A Risk Component-Based Model to Determine Pipes Renewal Strategies in Water Distribution Networks

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Abstract

Among the main concerns of water companies is to maintain the optimal performance of pipes in Water Distribution Networks (WDNs); this is achieved by activities such as renewal works, maintenance actions, pressure management, and other improvement operations. Accordingly, determining the risk associated with pipes is useful when planning such renewal works. In this study, a model is developed to determine a Pipe Renewal Strategy (PRS) based on the Risk Components (RCs) of each pipe. Hence, comprehensive criteria relating to pipe characteristics are assessed to determine the RCs. The developed model is based on a fuzzy-based, multi-criteria decision-making method, known as RC-WDSR (Risk Component-based Water Distribution System Rehabilitation). This is an improved version of the WDSR model, which was presented in 2018 by the authors of this study. To investigate the accuracy of the analysis of this model, two known WDNs - Anytown and Two-loop - were examined. The results indicate that the PRSs determined for the Anytown network reflects the pipe renewal priorities obtained from the WDSR model. Furthermore, in the Two-loop network, the PRSs obtained corresponded with the technical conditions of the pipes. Hence, it reveals that the results of the RC-WDSR are reliable when determining PRSs in WDNs.

Keywords**:** Water Distribution Networks; Pipe Renewal Strategies; Risk Components; Decision Making Model; Multi Criteria Decision Making; Risk Component-Based WDSR model; Pipe Failure Probability; Pipe Failure Consequence.

Abbreviations

AC: Asbestos Cement

CI: Cast Iron

DI: Ductile Iron

DMM: Decision Making Model

LCC: Life Cycle Cost

MCDM: Multi-Criteria Decision Making

PFC: Pipe Failure Consequence

PFP: Pipe Failure Probability

PFR: Pipe Failure Risk

PRS: Pipe Renewal Strategy

PVC: Poly Vinyl Chloride

RC: Risk Component

RC-WDSR: Risk Component-based Water Distribution System Renewal

TOPSIS: Technique for Order Preferences by Similarity to an Ideal Solution

WDN: Water Distribution Network

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1. Introduction

Water Distribution Networks (WDNs) are among the main lifelines in human societies (Winkler *et al.* 2018, Minaei *et al.* 2019). Hence, one of the most important concerns for water companies is to maintain the optimal conditions for water supply (El-Abbasy *et al.* 2016, da Silva and Souza 2017). Water pipes are major components of WDNs and play a key role in achieving this goal; therefore, it is essential to determine appropriate pipe renewal strategies (Tscheikner-Gratl *et al.* 2016a, Abd Rahman *et al.* 2018). For instance, within Portugal, in Lisbon's metropolitan area, WDN aging has led the water company to consider a 2% network rehabilitation rate (Ferreira and Carriço 2017).

An appropriate plan for pipe renewal should lead to the periodical investigation of pipe conditions to determine which need to be repaired, renovated, or replaced (Giustolisi and Berardi 2009, Devera 2013, Harvey *et al.* 2013, Roshani and Filion 2013, Marzouk and Osama 2015). In the last decade, many studies have been conducted to determine the most appropriate WDN renewal plans. Table 1 shows some of these studies between 2009-2020.

Table 1 near here

From 2009 until 2020, some of the studies carried out in the WDN renewal field focused on ranking rehabilitation activities by using risk-based methods (Christodoulou *et al.* 2009, Bicik 2010, Devera 2013, Sargaonkar *et al.* 2013, Choi and Koo 2015, D'Ercole *et al.* 2018, Salehi *et al.* 2018b, Salehi *et al.* 2019). In particular, Pipe Failure Risk (PFR) was considered in some of these studies (Rogers and Grigg 2009, Bicik 2010, Harvey *et al.* 2013, Arsénio *et al.* 2015, Kakoudakis *et al.* 2017, Wilson *et al.* 2017, Mazumder *et al.* 2018, Winkler *et al.* 2018, Tang *et al.* 2019). The concept of pipe risk in WDNs refers to the multiplication of Pipe Failure Probability (PFP) and Pipe Failure Consequence (PFC) (Salehi *et al.* 2018b, AWWA 2014). To assess the risk in a WDN, it is essential to evaluate both the PFP and PFC of all pipes (Bicik 2010, Salehi *et al.* 2018b, Kakoudakis 2019). One of the most important objectives of risk assessment in WDNs is to determine the proper planning of pipe renewal (Sargaonkar *et al.* 2013).

Moreover, Decision-Making Model (DMM) methods have also been applied in WDN renewal (Ammar *et al.* 2012, Trojan and Morais 2012, Kabir *et al.* 2014, Tscheikner-Gratl *et al.* 2017, Salehi *et al.* 2018a, Minaei *et al.* 2019, Marques and Cunha 2020). Due to the complexity of WDNs, Multi-Criteria Decision Making (MCDM) models have been mentioned more than other DMMs. The advantages of these models include the simultaneous analysis of multiple criteria and alternatives (Kabir *et al*. 2014). Recently, it has been revealed that MCDM models are efficient when determining the renewal plans of WDNs (Scholten *et al.* 2014, Tscheikner-Gratl *et al.* 2017, Salehi *et al.* 2018a). Therefore, combinations of risk-based methods and DMMs have been examined in numerous studies over the last decade.

Giustolisi and Berardi (2009) presented a risk-based DMM to replace pipes. In this model, pipe renewal activities were ranked using economic factors as well as technical variables. Accordingly, a multi-objective evolutionary optimisation method was used to model pipe replacement scenarios. The case studied in this project was a WDN in the United Kingdom. Meanwhile, Rogers and Grigg (2009) introduced an MCDM model, to consider pipe renewal prioritisation based on risk and failure. All data used in this model can be obtained from water companies. This project was implemented in two real cases and calibrated by water company experts.

In comparison, Bicik (2010) focused his Ph.D. thesis on the development of a risk-based

DMM for WDNs. In this research, a method was developed to identify WDN events using a risk-based approach. Afterward, an online DMM was introduced for the operational activities of WDNs. Christodoulou & Deligianni (2010) found that the integration of both risk assessment and asset management was one of the main factors that enable the optimal management of WDNs. Accordingly, they stated that all economic parameters, as well as social/political variables, should be identified. Hence, they presented an integrated neuro-fuzzy DMM and assessed this model using WDN data from New York City and Limassol, Cyprus.

Furthermore, Cardoso *et al.* (2012) introduced a project called AWARE-P, in which the objective was to integrate risk-asset management along with an economic analysis in urban water supply and sewage collection projects. This project was undertaken in four water companies, and the WDN renewal decisions were determined using economic data, as well as WDN risks. At the same time, Ammar *et al.* (2012) presented research in which a DMM was introduced to determine the time that a pipe should be repaired, renovated, or replaced. This work investigated, a renewal strategy based on the lifetime of pipes; it included the ways in which renewal activities affect a pipe’s hydraulic performance and its structural condition. Moreover, Roshani and Filion (2013) developed an event-based DMM to determine pipe renewal planning in order to optimise the time intervals between pipe renovations. The usual pipes renewal strategies, namely replacement, duplication, lining, and installation, were also considered in this work.

However, Yoo *et al.* (2014) proposed a model to prioritise pipe renewal activities. The analytical process in this model was based on hydraulic indices, and the failure rate was the only factor considered in the prioritisation of pipe renewal. Accordingly, to determine these priorities a pipe-failure-based MCDM model was developed. In comparison, in the renewal model proposed by Nafi & Tlili (2015), WDN pipes were assessed based on capital as well as functional values after which, an optimised point was determined between these values. The functional values were composed of the event rate, leakage, and pipe failure. More recently, Pietrucha-Urbanik & Tchórzewska-Cieślak (2018) proposed a new approach in the field of risk assessment in WDNs. Their work was classified in four steps: a) An event analysis in the WDN; b) The determination of an event rate based on the pipe type and the time the event occurred; c) A risk assessment based on previous studies; and d) The provision of an improved method based on an MCDM model for risk analysis.

Moreover, Salehi *et al.* (2018b) proposed a hybrid risk-based DMM in which only the pipes' design parameters (no events data) were used to determine a future WDN renewal roadmap. This method was composed of three steps: 1) The determination/update of WDN pipe design parameters; 2) A quantitative risk assessment in WDNs; and 3) A WDNs qualitative risk assessment. However, Phan *et al.* (2019) believed that, to monitor the efficiency of water pipe performances, it is essential to use a risk-based DMM. Therefore, they proposed a risk-based analysis method to prioritise pipe renewal. This method adopted a fuzzy inference system in which the consequences of pipe failure were assessed. This model considered indices, such as pipe failures, hydraulic parameters, and renewal activity costs, as decision criteria.

By considering studies over the past 10 years, it can be concluded that the majority of WDN pipe renewal planning is undertaken based on the hydraulic and mechanical factors associated with pipe failure (Giustolisi and Berardi 2009, Tabesh *et al.* 2010, Ammar *et al.* 2012, Shahata and Zayed 2013, Yoo *et al.* 2014, Nafi and Tlili 2015, Pietrucha-Urbanik and Tchórzewska-Cieślak 2018, Winkler *et al.* 2018, Kakoudakis 2019, Phan *et al.* 2019). Although social, spatial, environmental, and operational criteria affect pipe renovation strategies, these impacts were less considerable than those of hydraulic factors. Therefore, it is essential to develop a model that provides comprehensive criteria for pipe renewal.

Although criteria were comprehensively acknowledged in the research of Salehi et al. (2018a), only the determination of pipe priority for renewal was considered in this work (not renewal strategies). Consequently, this research will supplement the model developed by Salehi *et al.* (2018a). For this purpose, the Risk Components (RCs) in each pipe are determined based on comprehensive criteria, and Pipe Renewal Strategies (PRSs) are provided. In addition to the 42 criteria considered by Salehi *et al.* (2018a), other criteria that are effective in pipe renewal are considered in this work. Therefore, economic and operational criteria are incorporated into this study's developed model; hence, the number of criteria considered total 48. Moreover, when modeling problems with numerous criteria, TOPSIS offers significantly greater capabilities than other models, such as AHP, PROMETHEE, and ELECTRE (Torkamani *et al.* 2012, Tscheikner-Gratl *et al.* 2017, Salehi *et al.* 2018a). Therefore, using a DMM, such as TOPSIS, is most applicable in the model developed for this research, in which the numbers of criteria total 48.

From another viewpoint, the majority of studies conducted in the field of Water Distribution Networks consider the concept of pipe risk on its mathematical definition (Christodoulou et al. 2009, Bicik 2010, Devera 2013, Choi and Koo 2015, D'Ercole et al. 2018, Salehi et al. 2018b, Phan et al. 2019). Accordingly, the risk value is determined by multiplying the probability and consequence of pipe failure. Although in some studies, only one risk component (probability or consequence) is taken into account. In this present research, the RCs are analysed independently, and their multiplication is not considered. This is important because, when multiplying probability and consequence (risk), the risk of two pipes may be identical with different probabilities and various consequence values. Thus, these pipes are ranked the same in terms of their operational importance and renewal strategy. In comparison, an assessment of these pipes based on independent RCs could mean they are ranked at different importance levels in terms of renewal. Accordingly, the main novelty of this work concerns independent analysis of pipes' RCs using comprehensive criteria to determine the PRSs.

In this research, an RC-based model is developed to determine the PRSs, and achieved by using a fuzzy-TOPSIS (Technique for Order Preferences by Similarity to an Ideal Solution) method. As the model developed in this work is an improved version of the WDSR (Water Distribution System Renewal) presented by Salehi *et al.* (2018a), it is named RC-based WDSR (RC-WDSR). Indeed, this model is a version of the WDSR model in which analysis is based on pipes' RCs. To verify the accuracy of the RC-WDSR performance, two networks - Anytown and Two-loop - are analysed. The PRSs derived from the RC-WDSR are compared with the priorities obtained for the pipes in the WDSR (Salehi *et al.* 2018a). The results indicate that the RC-WDSR is reliable when determining the renewal strategies of WDN pipes.

2. Materials and methods

The key concern of this work is to improve the accuracy of pipe renewal planning in WDNs. For this purpose, the range of effective criteria the Pipe Renewal Strategies (PRSs) is expanded, and then, to assess these criteria, a Risk Component (RC)-based DMM is developed. In this model, the RCs of pipe failure (probability/consequence) are investigated independently. The schematic of the method proposed in this work is illustrated in Figure 1.

Figure 1 near here

2.1. Expansion of the criteria effective in Pipe Renewal Strategies

2.1.1. Comprehensive criteria for pipe renewal

In general, pipe renewal in WDNs is assigned to activities that correspond to the repair, rehabilitation, and replacement of the pipes (Morrison *et al.* 2013). The objective of these activities is to improve the hydraulic performance, and the structural conditions of WDNs. Moreover, the qualitative properties of a water supply must be improved by implementing pipe renewal activities (AWWA 2014). Consequently, the planning of pipe renewal activities should be based on criteria, which can effectively improve the qualitative/hydraulic/structural specifications of WDNs (Engelhardt *et al.* 2000).

These criteria have been considered in many studies and investigated from various viewpoints. In some studies, the criteria corresponding to pipe failure are taken into account in WDN pipe renewal planning (Eisenbeis *et al.* 2004, Kropp and Baur 2005, Rogers and Grigg 2009, Yamijala *et al.* 2009, Bicik 2010, Bubtiena *et al.* 2011, Xu *et al.* 2011, Harvey *et al.* 2013, Kakoudakis *et al.* 2017, Winkler *et al.* 2018, Kakoudakis 2019, Phan *et al.* 2019). Whilst in other studies, other criteria, such as economic, social, and environmental variables, are also considered (Engelhardt *et al.* 2003, Dandy and Engelhardt 2006, Bubtiena *et al.* 2011, Trojan and Morais 2012, Shahata and Zayed 2013, Tee *et al.* 2014, Tscheikner-Gratl *et al.* 2016b, Bruaset *et al.* 2018, Salehi *et al.* 2018a, Cabral *et al.* 2019, Marques and Cunha 2020, Vieira *et al.* 2020).

Some researchers in the field of WDNs (Sadiq et al. 2008, Islam et al. 2013, and Salehi et al. 2018a) have emphasised qualitative criteria, whereas in other studies, the renewal of WDN pipes is based on operational criteria, such as the leakage index (Fontana and Morais 2013, Creaco and Pezzinga 2014, Abd Rahman *et al.* 2018). In this regard, the criteria effective in WDN pipe renewal planning could be categorised into the classes illustrated in Figure 2.

Figure 2 near here

In the study conducted in 2018, 42 comprehensive criteria were introduced for pipe renewal planning in WDNs (Salehi *et al.* 2018a). These criteria are also considered in this study. While Salehi *et al.* (2018a) considered these criteria for pipe renewal prioritisation, their impact on the RCs of pipe failure is considered in this work. Indeed, these effects are assessed to determine the PRSs. For this purpose, a model is developed in this research, called the RC-WDSR (Risk Component-based WDSR).

In addition to the 42 criteria considered in the WDSR (Salehi *et al.* 2018a), further criteria, including 2 operational and 4 economic, have been added to the analytical steps of the RC-WDSR. Hence, 48 criteria are considered in this work. Furthermore, the categorisation of these criteria in the RC-WDSR differs to the WDSR (Salehi *et al.* 2018a). Table 2 illustrates the 48 criteria considered in the RC-WDSR and their classification.

Table 2 near here

2.1.2. The criteria effective for Risk Components (RCs) in pipes

Regarding the formula presented in AWWA (2014), the RCs of the pipes failures are:

$$\text{Pipe Failure Risk (PFR)} = \text{Pipe Failure Probability (PFP)} \times \text{Pipe Failure Consequence (PFC)} \qquad (1)$$

In this research, the RCs (PFP and PFC) of each pipe are assessed independently in relation to comprehensive criteria. Accordingly, it is essential to specify which criteria are effective on these RCs. The effect of all criteria on RCs is presented in Table 2. It must be noted that the concept of failure in this research relates to all events, which leads to inappropriate conditions in the hydraulic/structural/qualitative properties of pipes (Morrison *et al.* 2013, AWWA 2014, ISO 2016). Accordingly, the effect of each criterion on the PFP and PFC is investigated by conducting an assessment of the relationship between criterion fluctuations and the occurrence of inappropriate pipe conditions. In regards to the PFP, the fluctuations of a criterion can affect (YES) or not affect (NO) the increased probability of inappropriate conditions occurring in the hydraulic/structural/qualitative properties of pipes.

In comparison, for the PFC, the consequence of the fluctuations of a criterion can worsen (YES) or not worsen (NO) inappropriate pipe conditions.

As shown in Table 2, amongst the criteria considered in the RC-WDSR model, 37 are effective on the PFP, whilst 31 are effective on the PFC. Alternatively, just 20 criteria are simultaneously effective on the PFP and PFC (shown as rows in a darker colour in Table 2). Furthermore, only 11 criteria have an impact on the PFC (rows in a lighter colour in Table 2), while, only 17 criteria are effective on the PFP (white rows in Table 2). It must be noted that the effects on RCs were determined on technical principles, which were obtained from valid references in the field of WDN design and operation (Farley and Trow 2003, Trifunovic 2006, Thornton *et al.* 2008).

Many meetings were held by the authors of this work to assess the criteria effects on RCs. For instance, it was found that the higher the pressure (code 01) of a pipe, the greater the PFP in that pipe. On the other hand, during the failure of a high-pressure pipe, the consequences were more severe, such as greater losses. In considering another criterion, such as code 48, the shorter the average distance of a pipe to a population centre such as hospitals, schools, or stores, the more likely it is to be affected by hydraulic fluctuations, and consequently the more likely hydraulic or qualitative failure (PFP) will occur. Meanwhile, the greater effect of this pipe on the supply of water to public centres (due to its proximity to these centres) mean that failure occurrences can lead to a higher PFC.

For criterion code 38, it was found that, when the lifetime of buildings in the area of the pipe, is older, the PFC can be far greater. However, the old age of the buildings in this area may not necessarily increase the PFP. The opposite was determined for some criteria, such as code 04 (pipe age); thus, it was found that increasing the age of the pipe can increase the PFP, but the age of the pipe does not necessarily affect the PFC.

2.2. Development of a risk-component based DMM to determine the PRSs

In this work, a risk component-based DMM, known as RC-WDSR (Risk Component-Water Distribution System Renewal), is developed to determine the PRSs. As previously mentioned, the RC-WDSR model is the developed version of the WDSR presented by Salehi *et al.* (2018a). The main differences between these models are as follows:

1. The capability of the WDSR only focused on pipe/zone prioritisation in the rehabilitation in WDNs; in comparison, the RC-WDSR is a supplementary model that can provide the PRSs in WDNs;
2. Pipe prioritisation in the WDSR is based on the fluctuation of characteristics in a pipe's performance in relation to the comprehensive criteria; in comparison, in the RC-WDSR model, the PRSs are determined based on the RCs in each pipe;
3. In the WDSR, economic criteria were omitted due to the complexity of analysing these parameters; this shortcoming is improved in the RC-WDSR and economic criteria have been added to the model. Additionally, operational criteria are added to the RC-WDSR, thus, the total number of criteria in this model is 48.
4. In the WDSR model, a template layer is used to assess the importance of pipes in association with various criteria; this layer is derived from standards and various references in the field of WDN design and operation (Farley and Trow 2003, Trifunovic 2006, Thornton *et al.* 2008). Meanwhile, it is possible to localise this layer to the conditions of the study area and increase the accuracy of pipe differentiation whilst improving pipe prioritisation. The objective of the RC-WDSR model is only to provide the PRSs by analysing each pipe (and not by comparing the pipes together). Accordingly, the localisation of a template layer in the RC-WDSR model could provide an inaccurate or incorrect PRS for each pipe. Therefore, to

prevent the presentation of the wrong results, localisation is not included in this model.

The similarities between the RC-WSDR and WDSR models include the following:

1. The core analyser of the RC-WDSR is a DMM called the Fuzzy TOPSIS method, which is the same as the DMM used in the WDSR model. This method has been used in many studies in different scientific fields (Behzadian *et al.* 2012), due to its ability to model decision-making issues. It is most appropriate to use the TOPSIS method in the RC-WDSR (in which the criteria total 48), due to its capability of analysing numerous criteria simultaneously (Torkamani *et al.* 2012, Tscheikner-Gratl *et al.* 2017, Salehi *et al.* 2018a);
2. The layer of group decision-making used in the WDSR is also applied to the RC-WDSR model;
3. Similar to the WDSR, fuzzy logic is used as a fundamental method in the RC-WDSR to model uncertainties in the recorded data of water companies.

The major novelties of the RC-WDSR model are presented below:

1. In the analytical structure of the RC-WDSR model, the PRSs are determined by analysing the PFP and PFC independently. Indeed, the risk value, which is calculated by multiplying the probability and consequence, is not used in this model. This is because multiplying the probability and consequence of pipe failure might provide an inaccurate assessment. For instance, this process could present a similar risk value for two pipes with different conditions. In this regard, it is assumed that the PFP/PFC values in two different pipes are 40%/20% (pipe number 1) and 20%/40% (pipe number 2), respectively. Since the risks in these two pipes are calculated by multiplying the PFF/PFC values, these pipes will have a similar risk value (8%). In comparison, a pipe in a critical condition in terms of failure consequences (e.g. pipe

number 2) is more important than a pipe with a high probability of failure (e.g. pipe number 1) (AWWA 2014, D'Ercole *et al.* 2018, Pietrucha-Urbanik and Tchórzewska-Cieślak 2018). Therefore, it can be stated that comparing the risk values of two pipes cannot provide an accurate method to rank pipes and to plan their renewal activities. Subsequently, analysing RCs independently offers a novel and potentially preferable method to assess risk in WDNs, and is thus considered in the RC-WDSR model (present work);

2. In general, the probability/consequence values of pipe failures are calculated by statistical and probabilistic methods (Yamijala *et al.* 2009, Scheidegger *et al.* 2015, Faris Hamdala and Sagar 2016). In the RC-WDSR model, these values are determined by using a method other than the statistical and probabilistic techniques. The RC-WDSR uses the Fuzzy TOPSIS model, in which the probability values are determined by using a non-probabilistic method. This approach represents one of the novelties in this work. Therefore, the main reason for choosing a non-probabilistic method for the RC-WDSR model is the limitations of probabilistic techniques when modeling group decision-making. In addition, the weakness of these techniques in analysing the complexities and uncertainties involved in WDN data (Kahraman 2008, Anisseh and Mohd Yusuff 2011, Jiang *et al.* 2011, Torkamani *et al.* 2012, Yazdani *et al.* 2012, Marzouk and Osama 2015, Scheidegger *et al.* 2015) is another shortcoming of the probabilistic method. Therefore, in this research, fuzzy logic is used to analyse WDN data, and the Fuzzy TOPSIS DMM is applied to determine the PFP and PFC;
3. In DMMs, the results will generally be more comprehensive and accurate, and consider a larger number of criteria (Tzeng and Huang 2011, Tscheikner-Gratl et al. 2017). Accordingly, since the main purpose of this research is to improve the accuracy of pipe renewal plans, the range of effective criteria on pipe renewal works

is expanded. Thus, it is essential to develop a model with the ability to investigate numerous criteria and at different scales in the field of pipe renewal. Hence, one of the capabilities of the model developed in this work (RC-WDSR) is its ability to simultaneously assess 48 criteria in order to analyse the conditions of each pipe. Whereas in other studies, a smaller number of criteria are considered (Giustolisi and Berardi 2009, Tabesh *et al.* 2010, Sargaonkar *et al.* 2013, Yoo *et al.* 2014, Nafi and Tlili 2015, Așchilean and Giurca 2018, Bruaset *et al.* 2018, D'Ercole *et al.* 2018, Minaei *et al.* 2019, Salehi *et al.* 2019). However, this model is programmed in such a way that it is possible to remove a criterion from the analytical processes if no accurate data are provided from that criterion; thus, it is feasible to use the RC-WDSR model in any WDN and with any amount of data.

The analytical steps in the RC-WDSR are illustrated in Figure 3. As shown, the analytical processing in this model is undertaken in three steps:

Figure 3 near here

2.2.1. Step 1: Determine the linguistic/fuzzy value for the Risk Components (RCs) in each pipe

In the first step of the RC-WDSR model, the characteristics of each pipe are determined based on the data recorded by water companies. The properties of each pipe represent the data that are input to the RC-WDSR model, and accord with the 48 criteria. In this regard, it should be noticed that the RC-WDSR is programmed in a way that allows the transfer of WDN data from Excel files to this model. Also, as previously mentioned, it is possible for the RC-WDSR to fit the assessable criteria for each pipe with the data available in the WDNs. For instance, if the data recorded in a WDN are only involved in the hydraulic properties of the pipes, it is only feasible to run the RC-WDSR model with the hydraulic criteria in Table 2 (codes 01 to 03).

In the second part of the first step, the pipes' properties are investigated using the template layer in the RC-WDSR model. The basis of this layer accord with the template layer developed in the WDSR model (Salehi *et al.* 2018a). Afterwards, the linguistic/fuzzy values for the PFP and PFC of each pipe are determined in two separate processing methods. which relate to 37 and 31 criteria respectively. As the output of this step, two separate fuzzy decision-making matrices are obtained for the PFP and PFC, which detail the fuzzy values of each pipe for each criterion. Figure 4 illustrates the operational stages of the first step in the RC-WDSR model, including the questions and answers. The full version of the template layer of the RC-WDSR (as shown in Figure 4) is represented in Appendix 1.

Figure 4 near here

As illustrated in Figure 4, the linguistic values used for the description of the PFP/PFC in each pipe are categorised into seven classes for each criterion (very low, low, relatively low, medium, relatively high, high, and very high). These linguistic values corresponded to the fuzzy values, including (0,0,1,2), (1,2,2,3), (2,3,4,5), (4,5,5,6), (5,6,7,8), (7,8,8,9) and (8,9,10,10), respectively. For instance, the linguistic/fuzzy value of high or (7,8,8,9) would be assigned to the PFP and PFC of a pipe with an average pressure over more than 50 meters or less than 14 meters. This assignment only relates to criterion code 01, while other linguistic/fuzzy values are determined for this pipe based on its properties in relation to other criteria.

The seven classes introduced in this method can accurately cover the fluctuations of various criteria in different pipes. Moreover, the fuzzy values used in the RC-WDSR model are trapezoidal-triangular (hybrid) fuzzy numbers, which can efficiently cover criteria fluctuations and are more consistent with the seven linguistic classes compared with other fuzzy numbers. In this regard, four types of fuzzy numbers were assessed and after sensitive analysis, it was found that trapezoidal-triangular fuzzy values are most desirable in the RC-WDSR model. For this purpose, these different types of fuzzy numbers were used to analyse a similar network. The obtained results were then compared to the real conditions of this network. Finally, the numbers with a greater sensitivity to criteria fluctuations were selected as the most appropriate to analyse the WDNs. The fuzzy numbers chosen in this work are illustrated in Figure 5.

Figure 5 near here

2.2.2. Step 2: Fuzzy TOPSIS process to determine the Pipe Failure Probability (PFP) and the Pipe Failure Consequence (PFC) independently in each pipe

Since different scales of comprehensive criteria are considered in this research, it is essential to descale these criteria for simultaneous analysis. Hence, in the first stage of the second step in the RC-WDSR model, the fuzzy decision-making matrices from the previous step are descaled using a technique that relates to the Fuzzy TOPSIS method. In the next steps, the PFP and PFC of each pipe are then determined independently using Fuzzy TOPSIS analytical processes (Figure 2). The TOPSIS method was first introduced by Hwang and Yoon (1981) (Tzeng and Huang 2011), and, the Fuzzy TOPSIS steps of the RC-WDSR model are shown in Figure 3. In this model, the PFP and PFC are calculated by the same analytical process but using different criteria (as mentioned in part 2.1.2). Indeed, these processes are undertaken twice and independently from each other. The calculated indices (PFP/PFC) are numbers between zero and one, and the closer they are to number 1, and the more critical they are.

One of the capabilities of the RC-WDSR is to weight all effective criteria on the PFP/PFC by using a layer of group decision-making. As illustrated in Figure 3, the output of this layer is used in step 2-2 of the RC-WDSR model to weight the elements of the descaled fuzzy decision-making matrix. A group decision-making layer can significantly affect pipe renewal planning; for instance, less critical PFP and PFC values for a pipe can lead to its lower importance level in a renewal strategy. By relying on the viewpoints of expert decision-makers in the water company, the location of the pipe in a WDN would be particularly important; this makes it critical in failure consequences. Hence, by weighting the effective criteria on the PFC for group decision-making in the RC-WDSR, the final PFC value for the pipe is more critical than its PFP value, and consequently, the final PRS will be more accurate.

The layer of group decision-making in the RC-WDSR model is shown in Table 3. This table determines the numbers of experts who assign linguistic/fuzzy values to criteria. From this, the fuzzy value of each criterion weight is provided based on these viewpoints. However, in the RC-WDSR model, it is feasible to omit the criteria weighting process if desired.

Table 3 near here

2.2.3. Step 3: Determination of Pipe Renewal Strategies (PRSs) based on the PFP and PFC values

The PRS of each pipe is determined by using the output of the second step in the RC-WDSR model (PFP and PFC in each pipe). In this regard, AWWA (2014) is used to present the PRS of each pipe. Indeed, step 3 in Figure 2 is taken from this reference. Nevertheless, the PRSs mentioned in AWWA (2014) are expounded in this work, as represented in Table 4. The PRSs are divided into five classes; the most critical pipes are incorporated in the first class, while the pipes with the lowest critical condition are located in the last class. These classes range from the highest to the lowest importance, namely: “Fix now”, “Schedule renewal", "Assess proactively", "Monitor", and "Repair on failure" (Table 4). Moreover, PRSs should be updated after a period of the renewal implementation. Thus, it is essential to record the new condition of each pipe after the renewal works.

Table 4 near here

3. Assessment of the RC-WDSR model

3.1. The first analytical example: Anytown network

In this research, the Anytown network is chosen as the first example to assess the analytical processing of the RC-WDSR model and to verify its results. One of the main reasons for choosing this network is the availability of its pipe priorities for renewal activities, which were obtained from the WDSR model (Salehi *et al*. 2018a). In other words, the WDSR results can be used to assess the accuracy of the RC-WDSR results to offer greater reliability. Indeed, it is possible to compare the PRSs obtained from the RC-WDSR and the pipe priorities calculated from the WDSR (Salehi *et al*. 2018a).

The schematic of Anytown network with its pipe/zone renewal priorities and corresponding criteria concerning pipes properties are shown in Figure 6. Furthermore, this figure indicates the criteria weights that are determined by the group decision-making layer. The data involved in this figure are derived from the WDSR model (Salehi *et al*. 2018a). Accordingly, the Anytown network is composed of 4 zones and 32 pipes, which are mostly aged, particularly in zone 2. The pipes' hydraulic properties (e.g. pressure, flow velocity and pipe flow) in this network are determined using EPANet software. Furthermore, the mechanical properties of the pipes (e.g. pipe diameter and length) and the zones properties (e.g. urban structure and zone lifetime) are obtained from the study of Salehi *et al*. (2018a). Additionally, the type of pipes in the Anytown network is considered CI and DI (Salehi *et al*. 2018a). Nevertheless, it should be mentioned, that based on the recorded data of Anytown network, only 19 criteria are considered in the RC-WDSR model; the other criteria are omitted due to insufficiently complete data. However, it is possible to simultaneously analyse the 48 criteria in Anytown network by using the RC-WDSR model if the network data are adequate.

Figure 6 near here

3.2. The second analytical example: Two-loop network

A Two-loop network is assessed as the second analytical example to further investigate the accuracy modelling of the RC-WDSR. Salehi et al. (2019) previously assessed this network and its pipe renewal plan. Nevertheless, the RC-WDSR model work considers the Two-loop network to compare its analysis with Anytown network. Furthermore, the sensitivity of this model to fluctuations of renewal criteria in WDNs is assessed. It must be stated that data in the Two-loop network are more limited than the Anytown network as it only focuses on six criteria. Moreover, no group decision-making is used to present the different capabilities of the RC-WDSR when comparing the analysis of the Anytown network.

4. Results and Discussion

4.1. The analysis results of Anytown network

The analytical steps of the RC-WDSR model that determine the PRSs in Anytown network are illustrated in Figure 7. This figure is divided into three steps, as based on the aforementioned steps shown in Figure 2. In the first step, the linguistic/fuzzy value of each criterion (criteria with codes 01,02,03,04,05,06,08,09,10,11,12,13,14,15,16,26,38,44,45, as introduced in Table 2) was determined for each pipe. As stated, these linguistic/fuzzy values are categorised into seven classes (illustrated in Figure 7) that correspond to each criterion, as follows: VL: Very Low/(0,0,1,2); L: Low/(1,2,2,3); RL: Relatively Low/(2,3,4,5); M: Medium/(4,5,5,6); H: High/(5,6,7,8); RH: Relatively High/(7,8,8,9), and VH: Very High/(8,9,10,10). In step 2, the PFP and PFC of each pipe were provided by the values determined in the previous step. Finally, in step 3, the pipe PRSs was determined from the PFP/PFC values obtained for each pipe in step 2.

Figure 7 near here

Moreover, the distribution of the PRSs in Anytown network is illustrated in Figure 8. As shown in Figures 7 and 8, the PRSs provided for four of the network zones consist of two strategies: “Repair on failure” and “Assess proactively”. Furthermore, the method to determine the PRSs in two randomly selected pipes (pipes with numbers 11 and 26) is illustrated in Figure 7. These strategies were previously described in Table 4. A discussion of the results follows:

Figure 8 near here

1. As shown in Figure 7, the percentage of PRSs for pipes in various zones of Anytown network (last column) indicates the zone renewal priorities. Hence, the “Assess proactively” PRS was assigned to 66.67% of the pipes in zone 1, and shows that this zone has the highest importance for renewal planning. In comparison, for the pipes in zones 2, 4, and 3, these percentages are 50%, 40%, and 11.11%, respectively. These percentages show the relative importance of the zones for renewal activities. Moreover, by comparing Figures 6 and 7, it is obvious that the importance of the PRSs assigned to pipes in different zones of Anytown network (RC-WDSR model results) completely accord with the renewal priorities of pipes in all network zones (WDSR model results). Furthermore, the analytical structure of these models is different, and the pipes’ WDSR analysis is performance-based. In comparison, for the

RC-WDSR model, analysis is based on the pipes' RCs. Consequently, the matching of results in these models confirms the accuracy of the RC-WDSR model.

2. Zone number 1 is vital in the supply of water to other areas in the Anytown network. Hence, this zone is significantly more important than others, and any failure can practically affect others zones. This means the failure consequences could be critical for this zone, and it is reasonable to determine the critical PRS (Assess proactively) for 66.67% of the pipes in this zone by using the RC-WDSR model. On the other hand, the "Assess proactively" PRS was assigned to 50% of the pipes in zone 2, and shows the importance of this zone compared to the remaining two. It correlates to the properties of zone 2 in Anytown network (namely, the older age of the pipes and buildings and the high risk of failure in this zone). Moreover, the data available from Anytown network for zone 3 indicated that 88.89% of the pipes have a non-critical PRS (Figure 7). It represents a comparatively low risk urban location over zones 2 and 4. Additionally, the technical properties of this zone (e.g. excavation conditions) are better condition than those of zone 2. Thus, it is logical to determine a non-critical PRS ("Repair on failure") for most pipes in zone 3.
3. As shown in Figure 8, the distribution of critical PRS ("Assess proactively") mostly focuses on zone 2 and its nearby regions. This distribution seems associated with the realities of Anytown network; whereby older pipes and buildings and a higher risk of failure are more focused in the central network regions.
4. When comparing Figures 6 and 7, it is obvious that the "Assess proactively" PRS is assigned to the pipes (Figure 7), which thus represent high renewal priorities in each zone (Figure 6). Indeed, the priorities of the pipes in Figure 6 follow the PRSs determined for those in Figure 7; hence, it seems that the RC-WDSR model analysis is accurate.

5. Generally, in Anytown network, the “Assess proactively” PRS is determined for 37.5% of the pipes (12 of the 32 pipes in this network, as shown in Figure 7); thus, it is essential that the renewal planning of these pipes is carefully observed compared to other pipes. In practice, it is feasible to do this by using the RC-WDSR model.
6. As previously mentioned, due to the lack of recorded data available on the Anytown network, the PRSs of the pipes were determined using only 19 criteria. Although the results obtained from the RC-WDSR (Figure 7) follow the results of the WDSR model (Figure 6) and the realities of this network, by using more WDN data, the results of the RC-WDSR could be more accurate for renewal planning.
7. As previously stated, one of the novelties in the RC-WDSR model is the use of independent RCs (not in a multiplied form as risk) to determine the PRS of the pipes in WDNs. For a further assessment of the capability in the RC-WDSR model, the pipe rankings are presented in Table 5. These rankings accord with the PFP and PFC values, and the risk values of the pipes (PFR: Pipe Failure Risk).

Table 5 near here

8. In Table 5, it is obvious that the PFP value ranking of some pipes (Col. 4), is different to the PFC-based ranking (Col. 6), and the ranks obtained from PFR-based analysis (Col. 8). Accordingly, the different pipe rankings between the PFP-based and PFC-based analyses are more obvious (Col. 9) when considering other comparisons, namely columns 10 and 11. As shown in Table 5, in zones 2 to 4 of Anytown network, the similarities between PFP-based ranks and PFC-based ranks are 10%, 66.66%, and 40%, respectively (Col. 9). Moreover, the similarities of these ranks (PFP/PFC-based ranks) with those of the PFR-based analysis are 30% and 77.78% in columns 10 and 11. However, these similarities for zone 4 are 60% in column 10, and

80% in column 11. As a result, it can be concluded that renewal planning based on an independent analysis of the RCs seems different to risk-based renewal plans.

9. The same percentages for columns 10 and 11 in zones 1 to 3 were obtained from the different displacement of pipe ranks in the PFP/PFC-based analysis. For instance, in zone 2, 30% in column 10 is derived from the displacement of ranks for pipes 9, 17, 16, 18, 11, 13 and 14 in the PFP-based analysis (Col. 4) compared with their rankings in the PFR-based analysis (Col. 8). Moreover, the 30% similarity between the PFC-based ranks (Col. 6) and the PFR-based ranks (Col. 8) presented in column 11, is obtained from the ranking displacement for pipes 18, 11, 10, 16, 9, 12 and 13. As a result, these values only relate to the displacement of pipe ranks, and are not relevant to the similarities between the PFP-based and PFC values analysis. Moreover, it seems that, by increasing the number of the pipes in a network, there would be fewer similarities.
10. The pipe renewal ranks in zone 2, which are based on the PFP and PFC values, have only a 30% similarity with the risk-based ranks. In zones 3 and 4, the similarities of the PFP and PFR-based ranks are 77.78% and 60%, respectively. In comparison with the PFC and PFR-based ranks, the similarities are 77.78% and 80% in these zones. In zone 1, the pipe ranks obtained from different indices, are similar due to the low numbers. Therefore, when the pipe numbers increase and/or the conditions of the pipes are more critical for zone renewal planning (e.g. zone number 2 in Anytown network), differences will arise between independent RCs-based analyses and risk-based analyses. Moreover, in zones with fewer pipes and/or non-critical pipes, risk-based PRSs have a greater similarity with the PRSs, which are based on the PFP and PFC values (e.g. zones 1, 3 and 4 in the Anytown network). Therefore, since the majority of WDNs have complex conditions, like zone 2 in the Anytown network, the

independent assessment of PFP and PFC could lead to an accurate determination of the renewal strategies for pipes in WDNs.

11. The pipe renewal rankings are represented in Table 5, which suggests the consequence component is more important than the probability component when considering pipe risk. Indeed, the ranking of pipes based on consequence offers greater similarities to risk-based pipe rankings (Col 11) than rankings derived from probability-based analyses.
12. In Anytown network, the probabilistic indices, PFP and PFC, were determined for pipes. The use of a non-probabilistic method, based on a combination of fuzzy logic and DMM, produced an acceptable level of accuracy. The results provided for the Anytown network indicate that the combination used in the RC-WDSR model (fuzzy logic and DMM), can improve the many shortcomings of probabilistic models in complex issues, such as WDN operations.
13. One of the main concerns in water companies is how to allocate funds and financial resources to renewal activities in WDNs. In this regard, the results of the RC-WDSR model could be useful for financial planning. Hence, more funds could be assigned to pipes and zones with critical PRSs (e.g. zones 1 and 2 in Anytown network).

4.2. The analysis results of Two-loop network

To provide the PRSs in the Two-loop network, the analytical steps of the RC-WDSR model are presented in Figure 9. The data in this figure are taken from Salehi *et al.* (2019).

Figure 9 near here

As shown in this figure, although the pipe numbers in the Two-loop network are lower, the PRSs are more diverse than those in Anytown network. It shows the sensitivity of the RC-WDSR in modelling the various pipes with different conditions. Hence, due to the relatively similar conditions of the pipes in Anytown network, the PRSs focused solely on “Repair on failure” and “Assess proactively”. In comparison, in the Two-loop network, more diverse PRSs were determined, due to the significant differences between the pipe properties. In this regard, an essential PRS, such as “Schedule renewal”, was assigned to pipes 3 and 5. Hence, by investigating these pipes in the Two-loop network, as well as their flows and diameter, the selection of a critical PRS (e.g. “Schedule renewal”) by the RC-WDSR, is logical.

Moreover, by evaluating the mechanical properties of pipes 1, 2 and 7, it is clear these pipes have key roles for the Two-loop network. Thus, the selection of the “Assess proactively” PRS by the RC-WDSR for these pipes is accurate. The non-critical pipes in this network are numbers 6, 4, and 8. Therefore, it seems that the PRS selection “Repair on failure” and “Monitor” would be appropriate for these pipes.

5. Conclusion

One of the most effective components on the quality of urban water supply are the pipes in WDNs. Hence, the performance of these components needs to be continuously monitored in the operating activities of WDNs, and it is essential to determine a well-defined plan for the renewal of such pipes. Accordingly, in this research, a Risk Components (RC)-based DMM, called RC-WDSR, was presented as an applied tool to determine Pipes Renewal Strategies (PRSs). From the results obtained, the output of this model is reliable, meaning that the WDN pipes and zones, that need more urgent improvement could be identified. Furthermore, the renewal activities of the pipes in each WDN zone could be classified using the RC-WDSR model. This classification can significantly improve the renewal planning of the WDNs for water companies. In this regard, pipe renewal strategies are determined by only analysing independent components of risk (probability and consequence) in the RC-

WDSR model. This method contrasts with the technique that multiplies these components (known as risk), which may offer the misleading results.

In this research, two WDNs were studied. In the first WDN, the results indicate that the critical PRSs focused on the central regions of the Anytown network. This result follows the network realities. In the second network (Two-loop), the distribution of the PRS is associated with the importance of the pipes. In the RC-WDSR model, the risk components (probability and consequence) are not determined probabilistically. Indeed, these components are obtained using a Fuzzy-based MCDM model, called Fuzzy TOPSIS. This fuzzy method addresses many of the limitations of probabilistic models. These limitations generally include the modelling of group decision-making and the analysis of WDNs with data uncertainties.

Another feature of the RC-WDSR model is criteria weighting based on experts' comments, and it is also programmed to accommodate any amount of water company data. In other words, it is feasible to analyse with one criterion or as many as 48 criteria based on the data available from water companies. Therefore, if the field data of water companies are completed in the coming years, there will be no limit to the use of this model. However, the authors of this study are conducting further research to develop the capabilities of the RC-WDSR model. Hence, it must be acknowledged that the RC-WDSR model could be more efficient when using more effective criteria for pipe renewal planning. Therefore, it is recommended that this model be run in various cases with more criteria. Furthermore, since a cost-benefit analysis leads to the more practical planning of pipe renewal, it is recommended that further studies assess the economic criteria considered in this work to a real case for.

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