Optimization in Decision Making in Infrastructure Asset Management: A Review

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Featured Application: Infrastructure Asset Management is an important and popular research area, especially when the infrastructure networks are expending so quickly. Researchers developed a large number of optimization methods for its decision-making process. While they mainly focus on the individual algorithms and problems, a comprehensive knowledge, given the broad range of optimization methods, is hardly discussed and an analysis and graphical presentation of existing knowledge is necessary. This review is to discuss the current achievements on this subject, share the knowledge, avoid the repeated work, and guide the future research.

Abstract: Infrastructure assets, serving everyone's daily life, are an essential foundation of any society. Their management faces a wide range of challenges. Hence optimization methods are increasingly applied to assist making management decisions in infrastructure asset management (IAM). A large number of articles apply a broad range of optimization methods in their decision making (DM) and achieve great results. However, they mainly focus on individual methods and a comprehensive knowledge, given the broad range of optimization methods, is hardly discussed. Hence it is valuable to analyze and graphically present the existing knowledge on this subject. This paper, based on a total of 337 articles, provides an overall review of the applications of optimization when making management decisions in IAM, with the intension of enhancing the optimization application and method selection and guiding the future research in this field. More specifically, this paper introduces the application process of optimization when assisting DM in IAM, summarizes the previous application research, and discusses the popular optimization methods applied in DM in IAM. According to the literature review, this paper confirms optimization can effectively assist DM in IAM and a wide range of optimization methods are applicable to assist a variety of DM problems. The recommendations on the applications and selection of optimization methods in the context of IAM are also made to facilitate the applications.

Keywords: decision making; infrastructure asset management; optimization

1. Introduction

Infrastructure assets, including roads, bridges, pipelines, etc., are essential foundations for any country. They provide services that are necessary for everyone's daily life. However, they are highly capital intensive and sufficient investment is not always made [1,2].

Infrastructure asset management (IAM), also named asset management, is proposed to efficiently manage the infrastructure assets. Because of its broad coverage, IAM has diverse definitions with different focuses [3]. For example, New Zealand Asset Management Support (NAMS) defines IAM as "systematic and coordinated activities and practices of an organization to optimally and sustainably deliver on its objectives through the cost-effective life cycle management of assets" [4].

The Federal Highway Administration (FHWA) in the USA defines IAM as a business process that "incorporates the economic assessment of trade-offs among alternative investment options" and therefore makes "cost-effective investment decisions" [5]. Austroads, from Australia, defines IAM as "a systematic process of effectively maintaining, upgrading and operating assets" considering engineering principles, business, and economy in order to deliver optimal community benefits [6]. In general, it arranges management interventions e.g., maintenance and rehabilitation (M&R), update, etc., to an infrastructure project or an infrastructure network so that the project or the entire network is able to provide the required level of service, subject to the management requirements, e.g., maintenance budget.

Decision making (DM) is an essential part of IAM, which determines the management plan of interventions for the infrastructure asset project or the network. When generating different management plans, i.e., implementing different interventions to different network segments at different points of time, the management outcomes, e.g., management cost and infrastructure asset condition, are different. DM is required to find an appropriate management plan so that its outcomes satisfy the goals and requirements of IAM.

However, in modern society, DM is not easy as it faces a wide range of challenges, including large infrastructure asset networks, limited resources, various outcomes, conflicting goals, and uncertainties [7,8]. Hence, optimization is applied, and in more recent years, has become popular in DM. A large body of articles applies a broad range of optimization methods to a variety of DM problems. Firstly, the majority of these articles focus on the applications and improvements of individual methods in the context of a certain type of DM and a comprehensive knowledge, given the broad range of optimization methods, is hardly discussed. Secondly, with a growth of publications, it is valuable to analyze and graphically present the existing knowledge on this subject.

This paper aims at enhancing the knowledge of optimization methods and their applications when making management decision in IAM. Its main focuses are below as follows:

- Clarifying optimization methods and their abilities when dealing with DM problems in IAM;
- Summarizing and discussing the previous applications of optimization in DM in IAM, based on a total of 337 articles;
- Specifying the popular optimization methods applied in DM in IAM and making recommendations on their applications.

2. Background

DM attempts to find an appropriate management plan for a project or a network of infrastructure assets by assigning proper interventions to the project or the network segments during the analyzed period so that the management outcomes of the project, or the entire network, satisfy the goals and requirements of IAM. While the philosophy of DM may sound easy, it faces many challenges, including the following: A large number of alternative management interventions/strategies, especially at the network level and for long-term analysis, limited investments and resources, various outcomes with unclear relationship, conflicting goals, e.g., low management cost and good infrastructure condition, and risks originating from the uncertainties when planning the future.

As a consequence of the challenges, optimization is increasingly applied to assist DM. Optimization is a discipline of Operations Research, which applies scientific methods to "conduct and coordinate the operations" for DM problems [9]. Taking advantage of mathematical analysis, optimization has great strengths and high potentials to assist DM in IAM, as follows:

- With the help of powerful computers, optimization deals with large data, i.e., a large number of segments and alternative strategies/management interventions, so large networks and life-cycle analysis can be handled.

- Based on well-designed algorithms, optimization is able to find solutions for hard problems, e.g., allocating limited budget to a large network, and therefore promotes the best use of available resources.
- Optimization covers a variety of variables and formulae to describe different management outcomes and examines possible trade-offs accordingly.
- Optimization can involve multiple objectives, even the conflicting ones. The compromise of the conflicting goals is not necessary during the optimization.
- Optimization can also consider uncertainties with fuzzy variables, and can therefore help with estimating the uncertainties and controlling the risks during the management period.

A broad range of optimization methods have been introduced in DM in IAM. Even though the algorithms are different, their application process is similar when dealing with DM problems. Optimization methods cannot be directly applied to a practical problem and a mathematical description of the practical problem is needed, which is the so-called optimization model. Management outcomes are represented by variables and outcome relationships are described by formulae. One or several main management goals are defined as the optimization objective(s) and other goals and management requirements are defined as optimization constraints. Both objectives and constraints are formulated with related variables. Then, an optimization method is applied to solve the formulated optimization problem. A proper optimization method can effectively analyze an optimization problem, quickly generate high-quality solutions, and, therefore, better facilitates the management decisions in IAM [10].

After the optimization, a solution or a set of solutions are generated to help decision makers to understand their problems and make an appropriate management plan. The good solution(s) can offer accurate and reliable information about the addressed problem, while the poor solution(s) may lead to a wrong direction. Hence, it is important to select a proper optimization method that generates high quality solution(s) for a specific DM problem. However, a broad range of optimization methods are applicable in this field, each with different characteristics and application scope. Without a comprehensive understanding of these methods, the method selection can be hard.

3. Review of the Applications of Optimization Methods in Decision Making in Infrastructure Asset Management

To date, optimization methods are increasingly applied to assist DM and great achievements are obtained. However, a comprehensive knowledge, given the broad range of optimization methods in the context of DM in IAM, is still missing. In this section, a total of 337 articles, that apply optimization methods in this field, are reviewed. These articles, mainly journal papers and conference proceedings, were obtained from main literature databases with key subject words Infrastructure Management, Infrastructure Asset Management, Pavement Management, and Decision Making. They are listed in Appendix A. The following sections summarize these articles and discuss their applications.

3.1. Application History

As a terminology, IAM may sound new but, according to Sharma [11], it has a history of around three hundred years and has been employed by U.S. utilities for a long time. One of the earliest attempts was made in 1975 by Abelson and Flowerdew, who used dynamic programming to determine the least required to maintain a road project in Jamaica over 10 years [12]. Then, more optimization methods were introduced in this field. In the 1980s, the Arizona Department of Transportation officially implemented an optimization method in their pavement M&R system, the "Network Optimization System" [13]. In the 1990s, the subject of managing infrastructure assets expended from management systems of a single object to a broader orientation [14]. In the late 1990s, the idea of IAM was adopted in the USA to assist the management of infrastructure assets [15]. To efficiently manage infrastructure asset networks, the American Federal Highway Administration (FHWA) established the Office of Asset Management in 1999 and encouraged all state departments of transportation to apply rational methods when managing their infrastructure assets [16].

Figure 1 demonstrates the reviewed articles published by decades. It shows there is a jump in the 1990s and a big increase in the 2000s. The increase in the number of articles continues in the 2010s. Two reasons contribute to this increase, as follows: (1) IAM develops rapidly and their DM becomes too hard to be easily analyzed by conventional non-optimization methods and (2) optimization is developing and more optimization methods are applicable to DM in IAM. The authors need to point out that the number of articles the last decade of Figure 1 is not a complete summary, as the decade of 2010–2019 is not completed.
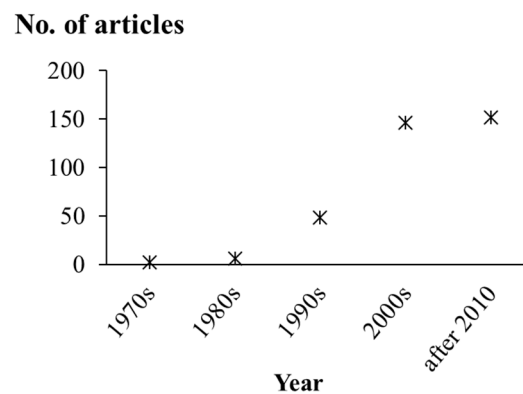
Figure 1. Number of articles published in decades.

Now optimization has become a fashion in IAM and not only the in academic world. Commercial companies also put large effort into to developing IAM software tools based on optimization. Many well-designed commercial software tools, including dTIMS [17], alden [18], TappetBox [19], and Confirm [20], are developed to assist IAM in the real world.

3.2. Levels of Decision Making

There are the following two levels of DM: Project- and network- level. The project-level DM only analyzes one infrastructure management project or considers an infrastructure network as a whole and only one management plan or strategy is generated for the project or the entire network. The network-level DM focuses on the segments of an infrastructure network and generates a management strategy for each segment of the network. In general, project-level DM only has a single object, while network-level DM has multiple objects. Figure 2 presents the number of articles published, in decades, focusing on the levels of DMs.
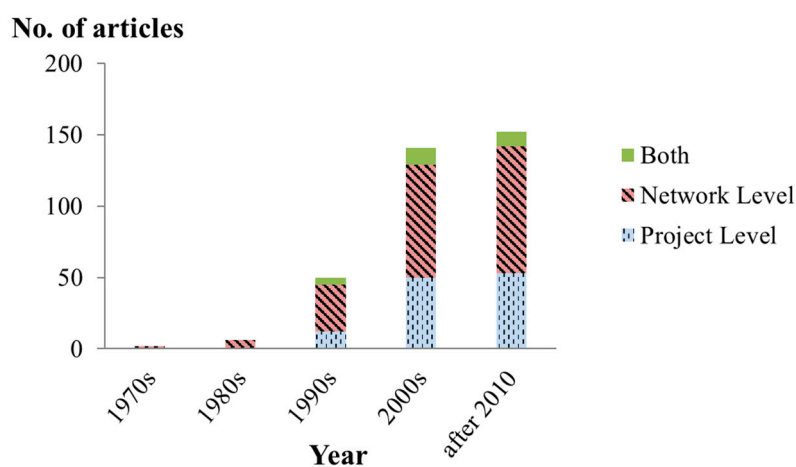
Figure 2. Levels of decision making.

As shown in Figure 2, among the reviewed articles, the majority of them study network-level decision making, while considerable amount of them are at the project level. Some articles consider both levels in their DM. The numbers of both project- and network- level DM are increasing with the growth of research interests in this field, though the network-level DM has a faster speed. It is important to notice that the discussion on M&R management is a dominating subject among the reviewed articles and most of the recent articles focus on the network-level DM, while the research on other management, e.g., update, often use the project-level DM. In terms of M&R management, project-level DM is often used to analyze a special project when the infrastructure, e.g., a bridge, is very important, when a complex model is established, or when complicated outcomes are analyzed [21–23]. Network-level DM considers not only the entire network but also analyzes the individual segments. It produces a management plan/strategy for each segment through the analyzed period so that the whole network can satisfy its management goal and requirements. It is more helpful when managing a network of infrastructure [24,25].

3.3. Types of Optimization

Optimization can be generally classified into two types, as follows: Single-objective optimization (SOO) and multi-objective optimization (MOO) [9]. Their relationship and targeted solutions are shown in Figure 3.
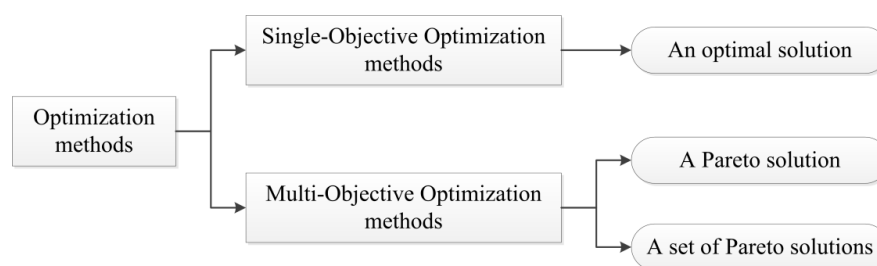
Figure 3. Types of optimization methods and their targeted solutions.

SOO optimizes only one optimization objective subject to optimization constraints. It aims at the optimal solution that produces the best value on the objective and satisfies all the constraints.

MOO optimizes multiple optimization objectives subject to optimization constraints. It aims at Pareto solutions, each producing the best objective values that cannot be improved without worsening the value of another objective. Additionally, all the Pareto solutions satisfy all the constraints. A MOO problem often has more than one existing Pareto solution. Some MOO methods can identify a set of Pareto solutions, while others only identify one Pareto solution, based on the decision makers' preference.

Figure 4 presents the application number of SOO and MOO on this subject. According to this figure, SOO was applied first and dominated in this field before the 2010s. Often a main management goal is defined as optimization objective and other goals and requirements are converted to optimization constraints. The commonly used SOO model is to minimize the M&R cost subject to the acceptable worst condition [26–28] or to improve the condition/condition-based benefit, subject to an annual budget [29–31]. By reviewing the articles, this paper finds out that, today, a considerable amount of articles still use SOO for their DM in IAM, while its orientation is moving to the hard DM problems, including huge networks [32,33], life-cycle analysis [34–36], complex non-linear models [37–39], and cross-assets [40,41].
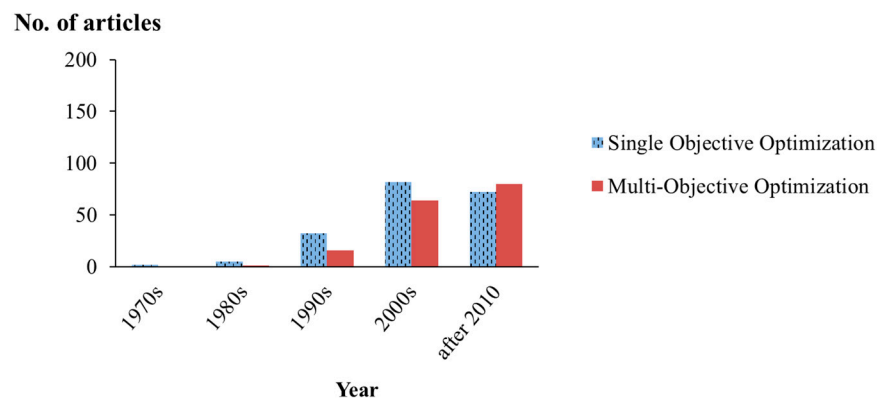
Figure 4. Types of optimization.

With the development of IAM, DM tends to consider multiple goals. When managing infrastructure, some management goals are commensurable and concordant, e.g., improving the network condition and increasing the level of service, and are often integrated into one objective and solved by SOO algorithms [42–44]. In this case, only one solution is obtained according to the integrated objective. However, often the management goals are incommensurable or conflicting, e.g., improving network condition and reducing management cost [45]. In this case the objectives cannot be simply integrated and this DM is formulated as a MOO problem and each incommensurable or conflicting goal is defined as an individual objective. MOO can describe practical problems in a more rational manner and leads to more informed decisions [7]. Hence, as shown in Figure 4, the application of MOO is increasing.

A MOO problem often has a set of existing Pareto solutions. However, not all of the optimization methods can obtain all the existing Pareto solutions. Figure 5 illustrates the percentage of the reviewed articles targeting at one Pareto solution or a set of Pareto solutions when adopting MOO in DM in IAM.
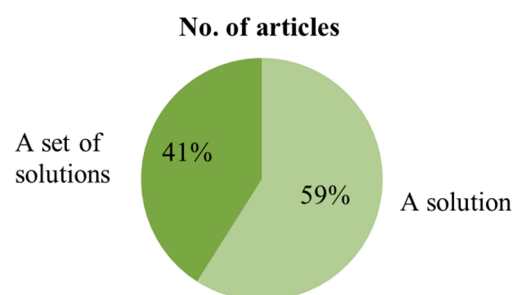
Figure 5. Number of articles targeting at different solution numbers for MOO.

Among the 337 reviewed articles that adopted MOO in their DM in IAM, 59% of them only produced one solution. These types of solutions require the input from decision makers, i.e., the preference on objectives, weighting of outcomes, expert experience, or practical consideration, and then, one solution is generated to match the decision makers' input. When decision makers have sufficient knowledge to give the input, obtaining one solution can largely simplify the solving procedure and speed up the optimization process.

In recent years, the attempt at a set of Pareto solutions is growing, according to the reviewed articles. This is mainly because the Pareto solution set not only offers the best solutions but also indicates the achievable best objective values, alternative trade-offs of objectives, and objective relationships, which can be used to clarify the problems at hand, balance the objectives, and lead to an informed decision [46–48]. Another interesting point found by the review is, even though MOO can analyze many objectives, 78% of the reviewed articles adopting MOO only define 2–3 objectives when making the management decisions. When more-than-three objectives are defined, the researchers

hardly generate a set of Pareto solutions but produce one solution based on specific preference or considerations [49–51]. The main reasons behind this include, (1) when more objectives are optimized, the generation of a whole solution set gets harder and (2) even if a set of solutions are generated, the solution interpretation can be complicated, as each solution corresponds to several objectives.

3.4. Applied Optimization Methods

Even as a broad range of optimization methods exist, they are generally divided into the following three classes: Deterministic methods, heuristics, and other methods and software. Deterministic methods are described by Moteleb as the "empirical or mechanic" algorithms that solve optimization problems based on the mathematical theorems and corollaries [52]. Heuristics are described by Silver et al. as "intuitive approaches", where an optimization problem is "interpreted and exploited intelligently to obtain reasonable solution[s]" [53]. Often, heuristics arise from the idea of relatively simple common sense and iteratively reproduce solutions based on identified ones [54]. With the exception of deterministic methods and heuristics, other methods are also proposed by hybridizing existing methods or ideas. Software is also developed based on specific algorithms. The commercial software tools often do not disclose the details of their algorithms or they may involve several algorithms. Hence, it is hard to simply classify these software tools into deterministic methods or heuristics. In this paper, these methods and software tools are classified into the third class while, if the software has a clearly introduced algorithm, its algorithm is classified into the deterministic method or the heuristic.

Figure 6 is a summary of the applied optimization methods. According to this figure, 44% of the reviewed articles use deterministic methods to help with their DM, followed by heuristics with a percentage of 35%.
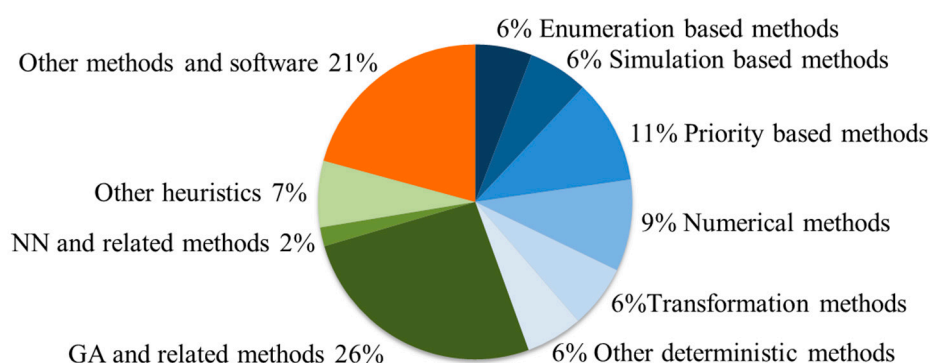
Figure 6. Optimization methods applied by the reviewed articles.

3.4.1. Deterministic Methods

The most popular deterministic methods are the priority-based methods, with an application percentage of 11%. They measure the priority of management options by exploring measurement criteria, weighting the criteria, and scoring the options accordingly. The highest-priority option is finally selected. These methods can be applied to SOO [21,55] and MOO, especially when optimizing several management criteria or objectives [56–58]. These methods can help in specifying the relationship of management outcomes in terms of measurement criteria. However, these methods require expert adjustment to make the rules of priority before or during optimization procedure and only produce one solution, based on the priority. They are recommended when sufficient knowledge is obtained to support the expert adjustment and to build the priority system. When the problems are complicated, a proper priority system may not be easily built.

Another popular group of deterministic methods in this paper is the so-called numerical methods. A total of 9% of the reviewed articles apply these types of methods in their DM. They build mathematical models and then compute the optimal solution following specific algorithms. They

have been applied to help with IAM since 1975 [12]. Different algorithms are proposed and applied, including linear programming [59–61], dynamic programming [62,63], dual programming [64], and branch and bound [65]. Additionally, with the help of powerful computers, numerical methods can efficiently solve decision making problems and obtain the optimal solution or Pareto solutions. They also can be incorporated in management software tools [66,67]. According to the reviewed articles, numerical methods are mainly applied to SOO or used as a solver for MOO. These methods often follow strict requirements and algorithms, which may result in a limited application scope. Hence, they are recommended for large-sized DM problems, especially when the outcome relationships are simple.

Enumeration based methods are one of the earliest and the most effective optimization methods when assisting IAM. They enumerate the possible options and select the best one(s). They can handle various DM problems, including complicated ones. Enumeration based methods can easily handle both SOO and MOO and guarantee to obtain the optimal solution (SOO) [68–70] or all the existing Pareto solutions (MOO) [71–73]. Compared to other deterministic methods the conventional enumeration-based methods, e.g., decision trees, are time consuming. Hence, they are recommended for problems with small networks and complicated problems where outcome relationships cannot be accurately described as mathematical formulae. The acceleration is necessary when analyzing large networks.

A total of 20 of the reviewed articles adopted transformation-based methods in their IAM. These methods transform a MOO problem into a SOO sub-problem or a set of SOO sub-problems and then solve the sub-problem(s) individually. Hence, they are widely applied to handle MOO problems for DM. The most commonly used transformation based method is the weighted sum method, which weighted sums all the objectives into one using a weighting system [74–76]. Transformation based methods can obtain a Pareto solution or a set of Pareto solutions. With the help of powerful computers, they can quickly analyze large problems, i.e., life-cycle analysis of large networks. However, these methods may not obtain the entire set of existing Pareto solutions. Additionally, these methods cannot directly solve an optimization problem but, rather, transform it into a sub-problem(s) and a solver is needed to solve the sub-problem(s). They are highly recommended for MOO, with a powerful solver, especially for hard DM, e.g., large-sized networks, life-cycle analysis, and complicated DM problems.

Similarly, simulation-based methods also contributed 6% of the applications among the reviewed articles. These methods simulate the behavior of the infrastructure assets after applying alternative management strategies/interventions and explore the uncertainties and risks during the management. A Markov chain is a popular choice for simulation based methods to simulate the infrastructure performance [77–79]. Simulation based methods can better describe the deterioration of infrastructure condition and, therefore, can consider the uncertainties during the optimization process. Yet, for large networks or complicated problems, the simulations may be too complex and these methods may not be efficient. Hence, these methods are recommended for small and simple DM, where infrastructure asset condition and uncertainties are important considerations in the DM.

In general, deterministic methods are the most popular choice for IAM among the reviewed articles. A main reason of their popularity is that they are effective and efficient when supporting management decisions. They can generate high-quality solutions for both SOO and MOO. According to the reviewed articles, their solution quality is stable and not affect by problem size and the restrictiveness of constraints. With the help of powerful computers, they are able to complete life-cycle analysis of large infrastructure networks in reasonable times. Considering the solution quality, deterministic methods are highly recommended for DM in IAM. However, deterministic methods follow specific algorithms with application limitations and restrictions. Hence, they may be ineffective for some types of problems in IAM.

3.4.2. Heuristics

Genetic algorithms (GA) and related methods are the most popular choice for MOO, with a percentage of 26%, as shown in Figure 6. These methods are based on the classic GA that defines

the management strategies or interventions as genes and then simulates the crossover and mutation of genes to create solutions [80]. For a better performance, improvements are proposed for the classic algorithm to handle SOO targeting at the optimal solution [48,81,82] and MOO targeting at a preferred Pareto solution [83–85] or a set of Pareto solutions [86–88]. The GA and related methods are flexible, easily controlled, and can handle a variety of DM problems, including the complicated ones. Comparing with other heuristics, GAs often generate better solutions and have higher efficiency. These methods are recommended when DM problems are too complicated to be easily handled by deterministic methods. When analyzing large-sized problems, these methods may produce poor solutions.

Neural networks (NN) and related methods are also applied in DM in IAM. They build a multi-layer network to analyze management outcomes and explore their relationships and their influence on the management plans. They can handle various objectives and constraints in terms of network inputs [89,90]. NN can effectively handle different management outcomes, even when the relationship of management outcomes is fuzzy or unclear. They are often applied for small infrastructure asset networks and may not be efficient for large ones.

Other heuristics are also introduced to assist management decisions for IAM, including Greedy heuristic [28,91,92], particle swarm optimization [93,94], and simulated annealing [95].

Heuristics, with 107 applications in the reviewed articles, are also a common choice for IAM. They are proposed as a general-purpose algorithmic framework, which largely increases their flexibility and robustness. Hence, they can handle a variety of DM problems, even the hard and complicated ones. Additionally, the understanding, application, and implementation of their algorithms is easy. However, the solution quality of heuristics is affected by a range of factors including problem size, constraint restriction, parameter calibration, etc. They may fail to obtain the optimal solution (SOO) and Pareto solutions (MOO), especially for the large-sized DM problems. Thus, heuristics are recommended when the problem cannot be easily solved by the deterministic methods. When applying a heuristic, several trials are suggested to confirm that the adopted algorithm calibration can produce the stable and good optimization result for the addressed DM problem.

3.4.3. Other Methods and Software

Other methods and software tools are developed to help with DM in IAM e.g., AASHTO software [96], GENEPAV-HDM4 software [97], OPTIPAV system [27], and feedback models [98]. These methods and software tools, especially the commercial ones, are well-organized with effective optimization algorithms. Some software tools even involve multiple algorithms. They are highly recommended when decision makers do not want to do the optimization by themselves.

3.5. Management Outcomes

DM in IAM may involve a wide range of outcomes and optimization methods can analyze various outcomes in terms of objectives and constraints. The financial expense of management interventions is the most popular and important outcome in IAM. Over 60% of the reviewed articles attempt to reduce the expense (objective) and around 40% of the articles have a management budget (constraint). The main types of expenses are infrastructure user cost [78,99,100], M&R treatment cost [101–103], asset management agency cost [87,100,104], and the total life-cycle cost [48,105,106]. However, the exact calculation of the expenses may vary from case to case. Optimization can also help in allocating limited funds across different types of infrastructure assets, working zones, or management projects [107–109].

Infrastructure asset condition is also an important outcome. The goal of IAM is to keep infrastructure assets in good condition in order to provide the required level of service. Around a quarter of the reviewed articles directly optimize infrastructure asset condition [110–112] or keep the condition at an acceptable level [44,87,113].

Level of service, as another criterion to assess the infrastructure, obtains increasing attention and applications [11,114,115]. Rather than an average index, it measures the performance of infrastructure in a better and more meaningful manner.

Besides the traditional outcomes, other outcomes are also analyzed with optimization, depending on the addressed problems, e.g., traffic [116–118], risk [49,119,120], investment efficiency [35,77,121], and greenhouse emission [48,63,91]. These outcomes indicate the deep and wide thinking when making management decisions. Presently, IAM does not only trade-off of expense and infrastructure condition but also looks at the needs of different parties and aspects. With the assist of optimization, the analysis of different outcomes becomes possible.

4. Conclusions and Future Research

This paper presents a comprehensive overview of the applications of optimization methods in DM in IAM. As a consequence of their intelligence, optimization methods are increasingly applied to assist DM and facilitate IAM. This paper, based on a review of 337 articles, introduces, summarizes, and discusses the achievements on this subject. According to the review, it concludes the following:

- Optimization can greatly assist DM in IAM. It analyzes DM problems even for the large infrastructure networks and life-cycle analysis and attempts to generate the best solution(s) under the goals and requirements of IAM. Therefore, DM becomes easier and more informed and its result is more reasonable and more objective.
- Optimization methods have been applied in DM in IAM for a long time and became popular in the 2000s.
- IAM has the following two types of DM: Project- and network-level, where the former is often used for a specific project and the latter is often used to analyze an infrastructure network when deciding the M&R management.
- DM problems can be defined as SOO or MOO depending on the number of the main goals. Optimization methods can handle both and generate one solution or a set of solutions accordingly.
- There are a broad range of optimization methods that can be applied to assist DM in IAM. This paper summarizes the popular optimization methods within the classes of deterministic methods, heuristics, and other methods and software. These methods have their strengths and weaknesses. The recommendations and suggestions on their applications are also made.
- DM may involve various management outcomes which can be analyzed by optimization methods in terms of objectives and constraints. The common outcomes include financial expense and infrastructure asset condition, while other outcomes are also considered.

Optimization is a useful tool for DM in IAM and great achievements are gained by the articles. Its significance is widely admitted by researchers and practitioners. However, with the development of IAM, DM becomes more complex. Firstly, an essential issue in IAM is to keep the infrastructure condition at an acceptable level. This requires an accurate model and prediction of the infrastructure deterioration, while the deterioration is affected by the changing environment and filled with uncertainties. Hence the prediction of infrastructure condition over the long-term is still a critical topic.

Moreover, private actors play an important role in IAM. Public agencies and private investors have different intention when managing infrastructure assets. How to consider their roles and satisfy their requirements in IAM is another important topic.

Additionally, each DM problem is unique and none of the optimization methods is a panacea. All of the algorithms have their strengths and limitations. Hence, the selection of a proper optimization algorithm depends on the addressed problem.

While optimization is mathematics and it tries to correctly describe practical DM problems, it is worth noticing that there is always a gap between practical problems and mathematical models. Decision makers should carefully examine their problems and tailor the optimization results in order to make more practical decisions for the addressed DM problems.

This paper is based on a total of 337 articles, while these articles do not cover all the published articles on this subject and some sound articles may be missed. This paper focuses on the optimization algorithms and other subjects are briefly discussed.

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Appendix A

In this paper, a total of 337 articles are reviewed and discussed to obtain a comprehensive understanding of the application of optimization in DM in IAM. The reviewed articles are listed below in the order of their published years.

1.	Abelson, P.W.; Flowerdew, A.D.J. Models for the economic evaluation of road Maintenance. *J. Transp. Econ. Policy* **1975**, *4*, 93–114.

2.	Friesz, T.L.; Fernandez, J.E. A model of optimal transport maintenance with demand responsiveness. *Transp. Res. Part B*. **1979**, *13*, 317–339.

3.	Kemp, F.O. Optimization of road maintenance in Sabah: accountants and engineers team up on cost accounting. Proceedings of the 4th Conference on Road Engineering Association of Asia and Australasia, Jakarta, Indonesia, 1983; Volume 4, pp. 81–103.

4.	Moghtaderi-Zadeh, M.; Kiureghian, A. Der Reliability upgrading of lifeline networks for post-earthquake serviceability. *Earthq. Eng. Struct. Dyn.* **1983**, *11*, 557–566.

5.	Cook, W.D. Goal programming and financial planning models for highway rehabilitation. *J. Oper. Res. Soc.* **1984**, *53*, 217–223.

6.	Way, G.B. Network optimization system for Arizona. Proceedings of the 1st North American Pavement Managment Conference, Toronto, Canada, 1985; pp. 16–22.

7.	Fwa, T.; Sinha, K.; Riverson, J. Highway Routine Maintenance Programming at Network Level. *J. Transp. Eng.* **1988**, *114*, 539–554.

8.	Jiang, Y.; Sinha, K.C. Dynamic optimization model for bridge management systems. *Transp. Res. Rec.* **1989**, 92–100.

9.	Azis, I.J. Analytic Hierarchy Process in the benefit-cost framework: A post-evaluation of the Trans-Sumatra highway project. *Eur. J. Oper. Res.* **1990**, *48*, 38–48.

10.	Male, J.; Walski, T.; Slutsky, A. Analyzing Water Main Replacement Policies. *J. Water Resour. Plan. Manag.* **1990**, *116*, 362–374.

11.	Jacobs, T. Optimal Long-Term Scheduling of Bridge Deck Replacement and Rehabilitation. *J. Transp. Eng.* **1992**, *118*, 312–322.

12.	Lansey, K.E.; Basnet, C.; Mays, L.W.; Woodburn, J. Optimal maintenance scheduling for water distribution systems. *Civ. Eng. Syst.* **1992**, *9*, 211–226.

13.	Li, D.; Haimes, Y.Y. Optimal maintenance-related decision making for deteriorating water distribution systems. *Water Resour. Res.* **1992**, *28*, 1053–1061.

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