

**STOCHASTIC MULTI-MODE RESOURCE-
CONSTRAINED PROJECT SCHEDULING
PROBLEM UNDER RESOURCE CALENDAR AND
RISK-NET PRESENT VALUE**

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CONSTRAINED PROJECT SCHEDULING
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RISK-NET PRESENT VALUE**

by

ZHANG QIAN

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LIST OF SYMBOLS

A_t	The set of activities in progress at the moment t
Bk_d^m	The dth transfer probability matrix of resource k under mode m
C	The total cost of the project
C_{ik}^m	The cost of activity i in execution mode m with resource k
C_i^m	Cash flow of activity i in mode m
$Cal_k^m(q)$	Calendar for resource k in mode m on day q
$Cal_i^m(q)$	Calendar for activity i in mode m on day q
$Cal_k^m(t)$	Calendar for resource k at moment t in mode m
$Cal_i^m(t)$	Calendar for activity i at moment t in mode m
$cycle_k^m$	A cycle of resource k in mode m
d_i^m	Activity i duration in mode m
DD	Due date
E_i^m	The set of resource types that are used to carry out activity i in mode m
f_i^m	Completion time of activity i in mode m
$I_{going}(q)$	The set of activities in progress on day q
m_i	Execution mode of activity i
R_k	The supply of resource k
R_k^m	The supply account of resource k in mode m
r_{ik}^m	The use of resource k by activity i in mode m
s_j	Start time of activity j
s_i^m	Start time of activity i in mode m
x_i^m	Execution of activity i in mode m

δ Discount rate per unit time ($\delta = 0.95$)

LIST OF ABBREVIATIONS

RCPSP	Resource-Constrained Project Scheduling Problem
M-RCPSP	Multi-mode Resource-Constrained Project Scheduling Problem
S-RCPSP	Stochastic Resource-Constrained Project Scheduling Problem
FM-RCPSP	Fuzzy Multi-mode Resource-Constrained Project Scheduling Problem
SM-RCPSP	Stochastic Multi-mode Resource-Constrained Project Scheduling Problem
AoN	Active on Node
NPV	Net Present Value
VaR	Value at Risk
NPVaR	Net Present Value at Risk
CNPVaR	Condition Net Present Value at Risk
NSGA-II	Non-dominated Sorting Genetic Algorithm II

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Appendix A	The program code of Model 1 solution
Appendix B	The program code of Model 2 solution
Appendix C	The program code of Model 3 solution

**MASALAH PENJADUALAN PROJEK TERHAD SUMBER
BERBILANG MOD STOKASTIK DI BAWAH KALENDER SUMBER DAN
NILAI KINI BERSIH RISIKO**

ABSTRAK

Disebabkan oleh fenomena ketidakpastian, masalah penjadualan projek terhadap sumber berbilang mod stokastik (SM-RCPSP) telah menjadi masalah penyelidikan yang ketara. SM-RCPSP menjadualkan aktiviti dengan berbilang mod pelaksanaan di bawah bekalan sumber dan terhadap hubungan keutamaan aktiviti dalam persekitaran stokastik berdasarkan teori pengaturcaraan bukan linear dan teori pengaturcaraan berbilang objektif. Objektif pertama tesis ini adalah untuk membina Model Pertukaran Masa-Kos bagi SM-RCPSP di bawah kalendar sumber tetap dengan meminimumkan masa dan kos penyiapan projek. Dengan mengandaikan bahawa tempoh aktiviti ialah pembolehubah stokastik, Model Pertukaran Masa-Kos dibina di bawah kalendar sumber tetap, bekalan sumber, mod pelaksanaan dan terhadap hubungan keutamaan. Objektif kedua tesis ini adalah untuk membina Model Rantaian Markov untuk SM-RCPSP di bawah kalendar sumber stokastik dengan meminimumkan masa dan kos penyiapan projek. Dengan mengandaikan bahawa tempoh aktiviti ialah pembolehubah stokastik dan rantai Markov digunakan untuk menerangkan kalendar sumber stokastik, Model Rantaian Markov dibina di bawah kalendar sumber stokastik, bekalan sumber, mod pelaksanaan dan terhadap hubungan keutamaan. Objektif ketiga tesis ini adalah untuk membina model tukar ganti nilai kini bersih risiko bagi SM-RCPSP dengan meminimumkan nilai kini bersih keadaan projek berisiko dan memaksimumkan nilai kini bersih. Dengan mengandaikan bahawa tempoh aktiviti dan aliran tunai adalah pembolehubah stokastik, Model Trade-off Risiko - nilai kini bersih dibina di bawah

bekalan sumber, mod pelaksanaan, hubungan keutamaan dan terhad tarikh akhir. Mengikut ciri-ciri model, algoritma yang mengintegrasikan algoritma genetik penyisihan tidak didominasi II dan simulasi Monte Carlo direka. Projek HVAC bangunan China Dongguan Jinyun Centre 5# digunakan sebagai kes untuk mengesahkan keberkesanan model dan algoritma. Model 1 dan Model 2 meningkatkan masa penyiapan masing-masing sebanyak kira-kira 17% dan 38% berbanding dengan model tradisional, dan kosnya tidak banyak berubah. Model 3 meningkatkan CNPVaR sebanyak kira-kira 48% dan nilai kini bersih sebanyak 47% berbanding dengan model tradisional. Keputusan menunjukkan bahawa model yang dicadangkan dalam tesis ini lebih dekat dengan projek sebenar, dan mempertimbangkan kalendar sumber boleh menjadikan pelan penjadualan lebih stabil dan mengurangkan pembaziran sumber dan masa yang disebabkan oleh rancangan yang tidak boleh dipercayai, memandangkan masalah risiko dapat mengelakkan potensi risiko secara berkesan. dan mengurangkan kerugian. Model boleh membantu membimbing penjadualan projek sebenar.

**STOCHASTIC MULTI-MODE RESOURCE-CONSTRAINED
PROJECT SCHEDULING PROBLEM UNDER RESOURCE CALENDAR
AND RISK-NET PRESENT VALUE**

ABSTRACT

Due to the uncertainty phenomenon, the stochastic multi-mode resource-constrained project scheduling problem (SM-RCPSP) has become a significant research problem. SM-RCPSP is scheduling activities with multiple execution modes under resource supply and activity priority relationship constraints in the stochastic environment based on non-linear programming theory and multi-objective programming theory. The first objective of this thesis is to build a Time-Cost Trade-off Model for SM-RCPSP under a fixed resource calendar by minimizing the project completion time and cost. Assuming that the activity duration is the stochastic variable, a Time-Cost Trade-off Model is constructed under the fixed resource calendar, resource supply, execution mode, and priority relationship constraints. The second objective of this thesis is to build a Markov Chain Model for SM-RCPSP under a stochastic resource calendar by minimizing the project completion time and cost. Assuming that the activity duration is the stochastic variable and the Markov chain is used to describe the stochastic resource calendar, a Markov Chain Model is constructed under the stochastic resource calendar, resource supply, execution mode, and priority relationship constraints. The third objective of this thesis is to build a risk-net present value trade-off model for SM-RCPSP by minimizing the project condition net present value at risk and maximizing NPV. Assuming that the activity duration and cash flow are stochastic variables, a Risk-NPV Trade-off Model is constructed under resource supply, execution mode, priority relationship, and deadline constraints.

According to the characteristics of the above models, the algorithms that integrate non-dominated sorting genetic algorithm II and Monte Carlo simulation are designed. The China Dongguan Jinyun Centre 5# building HVAC project is used as a case to verify the effectiveness of the models and algorithms. Model 1 and Model 2 increase the completion time by about 17% and 38% respectively compared with the traditional model, and the cost does not change much. Model 3 increases CNPVaR by about 48% and NPV by 47% compared with the traditional model. The results show that the models proposed in this thesis are closer to the actual project, and considering the resource calendar can make the scheduling plan more stable and reduce the waste of resources and time caused by unreliable plans, considering risk problems can effectively avoid potential risk and reduce the loss. Models can help guide the scheduling of actual projects.

CHAPTER 1

INTRODUCTION

1.1 Overview

A project consists of several basic activities that must be completed, with a specific deadline, cost, and limited non-financial resources (such as workers and materials). Activities have the priority relationship that limits what can be done and when it can be done. According to the definition of project management association, a project is a unique set of coordinated activities, with a clear start and end point, undertaken by an individual or enterprise to achieve a specific objective within a defined time and cost (Gardiner, 2017; Project Management Institute, 2021). Typically, projects usually have three main objectives: (1) to be completed as quickly as possible, (2) to consume fewer resources (significantly minimize cost), and (3) to build a better-quality project (Heagney, 2016). In addition, a fourth objective - safety is added in aviation and railroads (Parsamehr et al., 2023; Sharma & Trivedi, 2022).

To achieve the project objectives, projects need to be managed. However, projects are one-time and unique and are becoming increasingly common across enterprises (Lock, 2020). Projects are large and complex, involving many stakeholders and specialized technical disciplines. As does the money involved, the project's importance within the enterprise increases. Profit can only be generated through a specific and rigorous management approach.

Project management is the application of knowledge, skills, tools, and techniques to meet stakeholder needs and project expectations (Project Management

Institute, 2021; Walker, 2015). Project management is the process of conceiving, designing, preparing, evaluating, scheduling, organizing, monitoring and controlling the transformation of a system from an initial state to a specific state, and motivating all relevant personnel to achieve objectives within the specified time, cost, and resource supply (Lock, 2020). The project can generate profit by rationally applying project management methods (Lester, 2006).

Project management emerged during World War II, initially focusing on large military and construction projects. Over time, project management has been successful in many projects, and many managers have become interested in project management. Subsequently, project management develops a knowledge system with a standard set of theories, principles, methods, and practices (Lock, 2020). In today's competitive business environment, project management's ability to schedule activities and monitor progress within time, cost, and performance guidelines has become increasingly important to gain a competitive advantage. Since the inception of project management, the project scheduling problem has been at the core of the field (Omamode et al., 2024).

The project scheduling problem is to reasonably arrange activities to achieve specific project objectives on the basis of satisfying the priority relationship between activities (Demeulemeester & Herroelen, 2006; Hartmann & Briskorn, 2022). Project scheduling is a key factor affecting the success or failure of the project, and effective scheduling is of great significance to the successful implementation of the project. A sufficient schedule can make full use of resources, and enable the project to be completed according to the scheduled plan. Poor schedule often results in activities

becoming incompatible, resulting in significant waiting time and wasted resources. The project scheduling problem is also closely related to cost. The execution of activities consumes resource and cost, and when some or all of the activity is completed, the project generates profit. A sufficient schedule optimizes cash flow over the life of the project. Conversely, an imperfect schedule plan can lead to insufficient project cash flow, which can sometimes lead to broken funding chains, halted projects, and damaged enterprise reputations.

Chapter 1 outlines the research focus and presents the essential issues that garnered much attention in the research field. It briefly depicts the research background, clarifies the research problem, points out the research questions, formulates the research objectives, identifies the research scope, and highlights the research significance. Chapter 1 further presents the research structure in the thesis outline.

1.2 Research Background

China is representative of developing countries (Wang et al., 2022). From 2016 to 2020, the reform and development of China's construction industry achieved remarkable results, with an average annual growth of 5.1%. This accounts for more than 6.9% of gross domestic product (GDP), an average annual growth of 12.5% in the contract value signed by construction enterprises, an average annual growth of 24.1% in the business income of survey and design enterprises, and average annual growth of 24.1% in the business of engineering supervision, cost consulting, bidding agencies,

and other engineering consulting services enterprises. In 2020, the total output value of the national construction industry reached 26.39 trillion-yuan, achieving an added value of 7.2 trillion-yuan, accounting for 7.1% of GDP, with a construction area of 14.947 billion square meters and 53.66 million people employed in the construction industry (China Government, 2021). The China Construction Industry Association released the "Statistical Analysis of Construction Industry Development in the First Half of 2024". Statistics show that China GDP in the first half of 2024 was 61,683.6 billion yuan, an increase of 5.0% over the same period last year. The added value of the construction industry in the first half of the year was 3,777.1 billion yuan, an increase of 4.8% over the same period last year. The added value of the construction industry accounted for 6.12% of the GDP (The China Construction Industry Association, 2024).

There are still many problems in the construction industry, such as improper project management methods, resource waste, and project delay. A project is considered to fail when it does not deliver what is required within the agreed budget and time. Statistic data shows that nearly 70% of projects fail, that is, up to 70% fail to deliver on their promises to the client. Enterprises that use project management knowledge correctly will increase the chance of project success by 50% (Lock, 2020). According to a survey by the Project Management Institute, only some enterprises are aware of the importance of project management and how to use its knowledge to solve issues (Zhang et al., 2023).

The correct use of project management knowledge can enable smooth project implementation, increase revenue, reduce cost, and minimize profit loss. Scholars regard the project scheduling problem as one of project management's most common and fundamental problems (Habibi et al., 2018). The resource-constrained project scheduling problem (RCPSP) started to develop due to the project's resource constraints and activity priority relationship constraints. RCPSP has become a classical problem that has been widely and intensively studied (Albayati & Aminbakhsh, 2023; Bahroun et al., 2023; Pérez et al., 2024). The classical RCPSP problem has three constraints to be satisfied under the objective of project completion time minimization (Brucker et al., 1999): i) satisfy the priority relationship constraint among activities; ii) satisfy the resource supply constraint of activities; and iii) satisfy the time constraint, that is, completing an activity during a given period.

Since the RCPSP was proposed, it has attracted continuous attention from many scholars (Ballestín, 2007; Coelho & Vanhoucke, 2011; Kong & Dou, 2020; Ortiz & Diaz, 2020). Much research has been done on the RCPSP in different contexts. In addition to the classical RCPSP, different RCPSP have been proposed, such as multi-mode RCPSP (M-RCPSP) (Alcaraz et al., 2003; Coelho & Vanhoucke, 2011), multi-project RCPSP (Issa & Tu, 2020; Wauters et al., 2016), multi-objective RCPSP (Ballestín & Blanco, 2011; Tirkolaee et al., 2019), stochastic RCPSP (S-RCPSP) (Ke & Liu, 2005; Lamas & Demeulemeester, 2016), and fuzzy RCPSP (F-RCPSP) (Long & Ohsato, 2008; Xu & Feng, 2014).

When planning the project schedule, the project manager must consider factors in uncertain environments. Uncertainty may come from within the project, the scope change, the unavailability of resources preventing the execution of planned activities, and rework. Uncertainty also exists outside the project, such as the weather makes it necessary to postpone activities. Due to uncertainty, the project manager prefers a stable execution capability of the baseline scheduling plan rather than constantly adjusting the plan to cope with the change (Herroelen & Leus, 2004). Therefore, the possibility that the project will be executed strictly based on the idea state baseline plan is extremely low.

Taking into account the influence of uncertainty and better formulating the project scheduling plans, stochastic multi-mode resource-constrained project scheduling problem (SM-RCPSP) combining S-RCPSP and M-RCPSP are considered in this thesis. S-RCPSP considers the randomness of the project during the planning stage. It assumes that the activity duration or cost is a stochastic variable that follows some distribution. M-RCPSP considers multi-execution modes of the activity. Each mode corresponds to a different activity duration and cost. If project managers want to minimize the project completion time, a higher cost is needed to achieve it - instead, a lower cost leads to a longer project completion time (Hamta et al., 2021). Managers can choose different plans to achieve project objectives in SM-RCPSP.

1.3 Problem Statements

The first project scheduling problem considered in this thesis is the SM-RCPSP under a fixed resource calendar. A calendar is constructed for the resource, which specifies when to work and when to rest (Kong & Dou, 2020), attempting to resolve deviations between the baseline plan and the actual execution of the project. In the traditional SM-RCPSP, when the resource usage does not exceed the resource supply, the resource is available, if the resource calendar is taken into account, the resource needs to meet both the resource usage does not exceed the supply and the resource is not in a rest state, that is, the resource is available when it is in a working state. However, in previous research, scholars assumed no rest time for resource in SM-RCPSP (Hartmann & Briskorn, 2022). This rule usually does not match the project requirements and is a significant cause of schedule deviations. In reality, resources cannot work all the time, and having resources at rest can make resources more stable during work hours.

The second project scheduling problem considered in this thesis is SM-RCPSP under a stochastic resource calendar. In order to further study the resource calendar, considering the different characteristics of different resources, some resources have flexible rest time, which is not necessarily the weekend or a specific day. For example, the rest time of the machine is determined by the machine's usage time, and the rest time of the worker is determined by the worker's physical condition. The second problem considers that the rest time of the resource is jointly determined by the number

of consecutive working days of the resource and the resource type. Therefore, a Markov chain is used to describe the stochastic resource calendar.

The third project scheduling problem considered in this thesis is SM-RCPSP under the balance of risk and net present value (NPV). While pursuing project profit, managers must also consider the risk caused by uncertain factors (Wałędzik & Mańdziuk, 2018). Previous studies have pointed out that conditional net present value at risk (CNPVaR) can be used to represent the risk that a project can bear, but it is limited to the scope of scenario analysis (Rezaei et al., 2020). This thesis extends CNPVaR from discrete situations to continuous situations and uses NPV to represent project profit. By balancing the CNPVaR and NPV, a more practical project scheduling plan is formulated to reduce project risk losses.

1.4 Research Questions

In line with the problem statements of this thesis, the primary research question is ‘How to schedule project activities in the stochastic environment?’. Specifically, this thesis has the following three questions:

1. How to model the SM-RCPSP under fixed resource calendar characteristics?
2. How to model the SM-RCPSP under stochastic resource calendar characteristics?
3. How to model the SM-RCPSP under the trade-off between minimizing CNPVaR and maximizing NPV?

1.5 Research Objectives

This thesis provides a theoretical basis and decision-making basis for project managers to formulate reasonable implementation plans, describe the uncertainty based on probability theory, avoid the potential risk of the project, and maximize project profit. This thesis outlines the following three objectives:

1. To innovate a Time-Cost Trade-off Model (Model 1) for SM-RCPSP under a fixed resource calendar by minimizing project completion time and cost.
2. To innovate a Markov Chain Model (Model 2) for SM-RCPSP under a stochastic resource calendar by minimizing project completion time and cost.
3. To innovate a Risk-NPV Trade-off Model (Model 3) for SM-RCPSP by minimizing CNPVaR and maximizing NPV.

1.6 Research Scope

This thesis focuses on the RCPSP in a stochastic environment. The project often does not proceed as planned due to uncertainty factors in the real world. To better achieve the management objectives, the factors affecting the project scheduling plan are analyzed, the reasons for project failure are deeply discussed, the profit is analyzed to minimize project loss from the risk-averse perspective, and optimization models under the stochastic environment are built.

This research scope is limited to projects that have resource constraint. Scholars found that early scheduling research did not consider resource constraint, which is inconsistent with reality (Habibi et al., 2018). Resource constraint is a

common phenomenon in the project because the resources are not endless. When resource is in sufficient supply, projects can be completed in a short time, but at an increased cost (Hamta et al., 2021). The amount of resource supply is closely related to the project objectives. Therefore, project scheduling problem with limited resource is worth investigating (Ortíz Pimiento & Diaz Serna, 2020).

The research scope focuses on time and cost objectives. Completion time and cost have always been the key objectives of managers' attention and have also been widely studied based on the RCPSP (Ballestín & Blanco, 2011; Sajadi et al., 2017; Yuan et al., 2021). The time and cost are often two mutually balancing objectives that cannot be achieved simultaneously (Polancos & Seva, 2023). This thesis will consider multi-objective optimization models to find the optimal solutions between time and cost. It applies to capital-intensive, technically challenging, and costly projects.

This thesis uses CNPVaR to describe project risk and NPV to describe the time value of money. In the previous SM-RCPSP studies, a few scholars focused on project risk and NPV objectives. Most of them are planned on how project managers can maximize profit. However, some project managers are risk-averse, and the objectives are to avoid risk as much as possible and reduce loss. From the perspective of risk aversion managers, maximizing profit and minimizing loss is a question worth investigating. Focusing on risk issues and the time value of money can lead to a plan as close as possible to reality.

The research applies to the Dongguan Jinyun Digital Park 5# project. This case project is located in Dongguan City, Guangdong Province, China. It mainly serves

financial securities service companies and large Internet companies. The use function is the data center (Class C workshop). The design service life is 50 years. The HVAC system is the most critical part of the construction of the computer room; the system is more complex and will face more problems. This thesis chooses the Dongguan Jinyun Digital Park 5# HVAC project as a case study.

1.7 Research Significance

This thesis investigates the fixed resource calendar, stochastic resource calendar, and risk-NPV, which enrich the theoretical research related to SM-RCPSP. The three newly built models can provide relevant guidance for project management.

For the theoretical significance, the thesis extends the stochastic theoretical study of the resource calendar. The SM-RCPSP has been the topic of much research. Scholars have typically focused on studying resource as a continuous work and have yet to consider the resource calendar in SM-RCPSP. However, the resource needs rest time. Most research on the resource calendar focuses on the deterministic environment and single-mode execution method, which are still in the elementary theoretical stage (Kreter et al., 2016; Nikaeen & Najafi, 2022). In this thesis, according to the range of model parameters is given in interval form based on the measured data of the project site, the predicted data in the project feasibility report and the expert data provided by the project manager, activity duration is assumed to be a stochastic variable and followed a uniform distribution for SM-RCPSP under the fixed resource calendar.

This thesis uses a Markov chain to describe the stochastic resource calendar to further investigate the characteristics and types of different resources. It assumes that the resource rest time depends on the duration of resource work and the resource type. The Time-Cost Trade-off Model and the Markov Chain Model are constructed under resource calendar, resource supply, execution mode, and priority relationship constraints. Intelligent genetic algorithms are designed to solve the Time-Cost Trade-off Model and the Markov Chain Model.

The thesis introduces randomness into the risk-NPV study, theoretically enriching the risk-NPV problem in the stochastic environment. As one of the most interested research fields of project management, the SM-RCPSP mainly focuses on obtaining the shortest project completion time and low cost but rarely involves the risk-NPV objective functions (Drexler & Gruenewald, 1993; Ramos et al., 2023). The NPV and CNPVaR are essential dynamic factors to measure the project failure. It takes into account the project risk and the time value of money. Assuming that activity duration and cash flow are stochastic variables, a Risk-NPV Trade-off Model with CNPVaR minimization and NPV maximization is constructed under the constraints of resource supply, priority relationship, execution mode, and completion time. An intelligent algorithm is designed to solve the Risk-NPV Trade-off Model and obtain the optimal results.

For the practical significance, this thesis aligns with the project's practicality, especially for scheduling projects with high schedule uncertainty and high cost, such as data center server rooms and large-scale multinational projects. In project

management, managers not only want the project to have the shortest completion time and lowest cost but also ensure the project is carried out according to the original plan as closely as possible. This thesis aims to improve plan stability due to the stochastic activity duration and cost based on fixed resource calendar constraint, stochastic resource calendar constraint, and risk-NPV trade-off. The data center is in Xiegang Town, Dongguan City, Guangdong Province, China. It is a modern data center project with complex construction steps, high construction period requirements, and significant capital requirements. The China Dongguan JinYun Centre 5# building HVAC project will be used as a real case to demonstrate the effectiveness of the models and algorithms. The results showed that the solution by adding the fixed and stochastic resource calendar is closer to the actual project completion time, and the scheduling plan is more stable and reliable. The results obtained by the Risk-NPV Trade-off Model can maximize profit and minimize loss. It can effectively avoid the occurrence of the risk, which is more in line with the psychological expectations of risk-aversion managers.

1.8 Definition of Key Terms

The key terms in the thesis are defined in Table 1.1. The definitions of activity schedule, Active on Node (AoN), CNPVaR, fixed resource calendar, NPV, resource calendar, risk, risk-NPV, SM-RCPSP, stochastic resource calendar, mutation probability, and crossover probability are given in Table 1.1.

1.9 Organization of the Research

The thesis is divided into 5 chapters. The organization of the research is shown in Figure 1.1. Chapter 1 Introduction provides the research background, questions, and objectives. The significance of the thesis is described from real-life applications and theoretical research perspectives. The establishment of organizational structure is based on the specific research methods and technical lines of the thesis. The main innovation points of the thesis are summarized. Chapter 2 Literature Review discusses the main problems involved in the thesis and the related methods. The relevant studies on the S-RCPSP, M-RCPSP, classical RCPSP, RCPSP under resource calendar, max-NPV RCPSP, and RCPSP under risk are systematically sorted out and summarized. The theoretical framework of the thesis is constructed.

Chapter 3 Research Methodology describes models and methods for solving SM-RCPSP. Firstly, to construct the model, the preparatory knowledge of the model and the assumptions of the model are given. Then, three multi-objective multi-mode optimization models are built under the fixed resource calendar, stochastic resource calendar, and risk-NPV problem, respectively. Finally, according to the characteristics of the model, intelligent algorithms are designed to solve three models.

Chapter 4 Results and Discussion discuss the model and algorithm performance. This thesis demonstrates the application of the models through a real case - China Dongguan JinYun Centre 5# building HVAC project. Through comparison with traditional models and actual project results, it is found that the

scheduling plans obtained from the Time-Cost Trade-off Model, Markov Chain Model, and Risk-NPV Trade-off Model are expected to have better stability.

Chapter 5 Conclusion summarizes the research contents and main findings, analyses the research implications. The limitations of the research, further extensions, and further prospects will be provided.

Table 1.1 The Definition of Key Terms

Terms	Definition
Activity schedule	The activity schedule contains each activity start and completion time and the sequence of activities (Brucker et al., 1999; Pellerin et al., 2020).
AoN	AoN is an acronym for the single code network diagram method, a method of scheduling activities in project management (Rose, 2013).
CNPVaR	The average loss value of a portfolio if the portfolio's loss exceeds a given net present value at risk (NPVaR) (Rezaei et al., 2020).
Crossover probability	The number of times a crossover occurs for chromosomes in one generation, i.e., the chance that two chromosomes exchange some of their parts (Hassanat et al., 2019).
Fixed resource calendar	In this thesis, fixed resource calendar means resource has the fixed working time and resting time.
Mutation probability	Mutation probability is a parameter in a genetic algorithm that determines the likelihood that an individual will undergo the mutation process (Alaminos et al., 2024).
NPV	The NPV of a project is the present value of current and future profit minus the present value of current and future cost (Leyman & Vanhoucke, 2016).
Resource calendar	The resource calendar sets out the working hours and rest for resource (Lu & Lam, 2008; Nikaeen & Najafi, 2022).
Risk	An uncertain event or condition that, if it occurs, has a positive or negative effect on a project objective (Wideman, 2022).
Risk-NPV	In this thesis, risk-NPV refers to risk and NPV of project, and CNPVaR is used to measure project risk.
SM-RCPSP	Scheduling activities in a stochastic environment and selecting an execution option for each activity in a resource-constrained project (Ramos et al., 2023).

Terms	Definition
Stochastic resource calendar	In this thesis, stochastic resource calendar is defined as resource has stochastic working time and resting time. Resource rest time is determined according to the number of consecutive working days and its type.

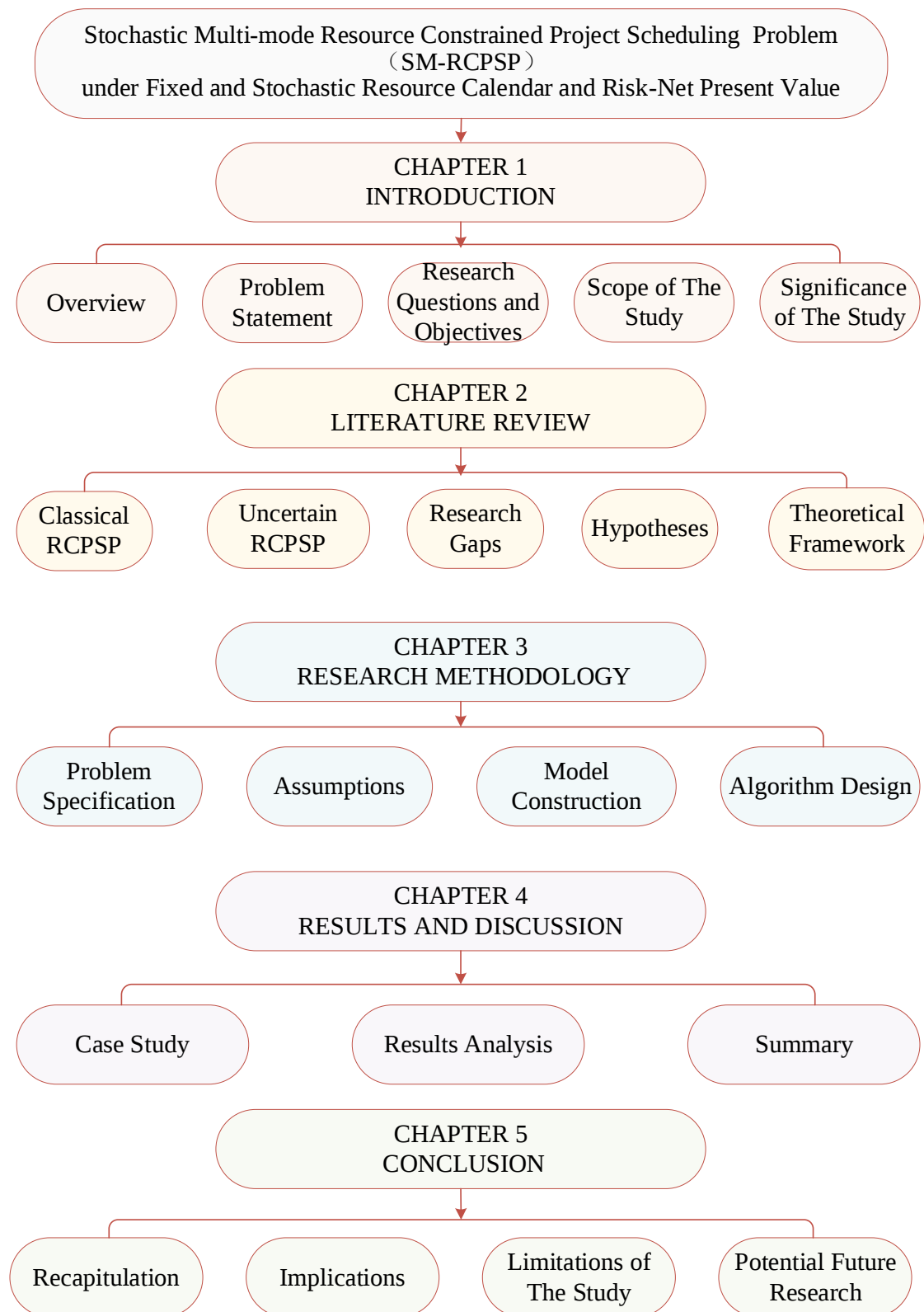


Figure 1.1 Organization of the Thesis

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The RCPSP has been at the heart of project management since its inception in the early 1900s (Demeulemeester, 2009). Chapter 2 reviews the literature on RCPSP according to classical RCPSP, uncertain RCPSP, M-RCPSP, max-NPV RCPSP, RCPSP under resource calendar, RCPSP under risk, and the current status of research on different RCPSP solution methods. Then, the research gaps in the RCPSP field, hypothesis, and theoretical framework are discussed. The flow chart for Chapter 2 is shown in Figure 2.1.

2.2 Classical RCPSP

The RCPSP was first introduced by Johnson (1968). The RCPSP comprises a set of task-specific activities and a limited set of resources, where the resource is divided into a renewable, non-renewable, and doubly constrained resource, as presented in Table 2.1. The renewable resource is available at each stage, and the amount available at each stage is limited. The non-renewable resource is based on the project duration, is limited in quantity, and cannot be renewed once consumed. The doubly constrained resource supply is prioritized during the project operations and whose total consumption is limited are usually replaced using renewable or non-renewable resource. This thesis mainly focuses on the renewable resource in RCPSP, which is more fixable than others. The RCPSP contains two essential constraints: (1)

priority relationship constraint: each activity must start once all the preceding activities are completed, and (2) resource supply constraint: activities can only start when the type and quantity of resource required are met (Golab et al., 2023; Hartmann & Briskorn, 2022).

Table 2.1 The Classification of Resource

Resource Types	Definition	Example	Reference (Authors, Year)
Renewable	The resource is available at each stage, and the amount available at each stage is limited.	Workers Machinery	(Böttcher et al., 1999)
Non-renewable	The resource is based on the project duration, is limited in quantity, and cannot be renewed once consumed.	Money Material	(Altintas & Azizoglu, 2020)
Doubly-constrained	Resource whose supply is prioritized during the project operations and whose total consumption is limited are usually replaced using renewable or non-renewable resources.	Workers and money are commonly constrained.	(Nudtasomboon & Randhawa, 1997)

Following the Hartmann and Briskorn's literature (2010), a classical RCPSP can be described using a single-codeword network diagram $G = (V, E)$ as follows: the project contains n activities and $V = \{1, 2, \dots, n\}$ is the set of all activities. $E \subseteq V \times V$ is the set of end-start logical relation between activities. $(i, j) \in E$ implies that activity j must be started after activity i is finished. The activity i duration is d_i . The completion time of activity i is f_i . Completing the project requires k renewable resource, $k = \{1, 2, \dots, K\}$ is the set of total type of resource, the demand of activity i

for resource k is r_{ik} , the total supply of resource k is R_k , The basic mathematical model of the classical RCPSP is given in Equations (2.1) to (2.3).

$$\min \quad f_n \quad (2.1)$$

subject to

$$f_j - d_j \geq f_i, \forall (i, j) \in E \quad (2.2)$$

$$\sum_{i \in A_t} r_{ik} \leq R_k \quad \forall t \in \{1, 2, \dots, n\} \quad k = \{1, 2, \dots, K\} \quad (2.3)$$

In the classical model, Equation (2.1) refers minimizing the objective function f_n , which is the project completion time. Equation (2.2) indicates that the activity j start time $f_j - d_j$ cannot be earlier than the activity i completion time f_i . Equation (2.3) shows A_t is the set of activities being executed at time t . Equation (2.3) indicates that the demand for any resource by an activity r_{ik} at any time cannot exceed the total supply of that resource R_k .

The objectives of the models are different depending on the project management objectives. These objectives are project completion time minimization, cost minimization, and resource supply minimization. Time and cost minimization are the most common objectives in classical RCPSP models (Ding et al., 2023).

This thesis classifies RCPSP from the following four contents, namely (1) resource type, (2) objective functions, (3) availability level of information, and (4) execution mode of activities. The RCPSP classification is shown in Figure 2.2.

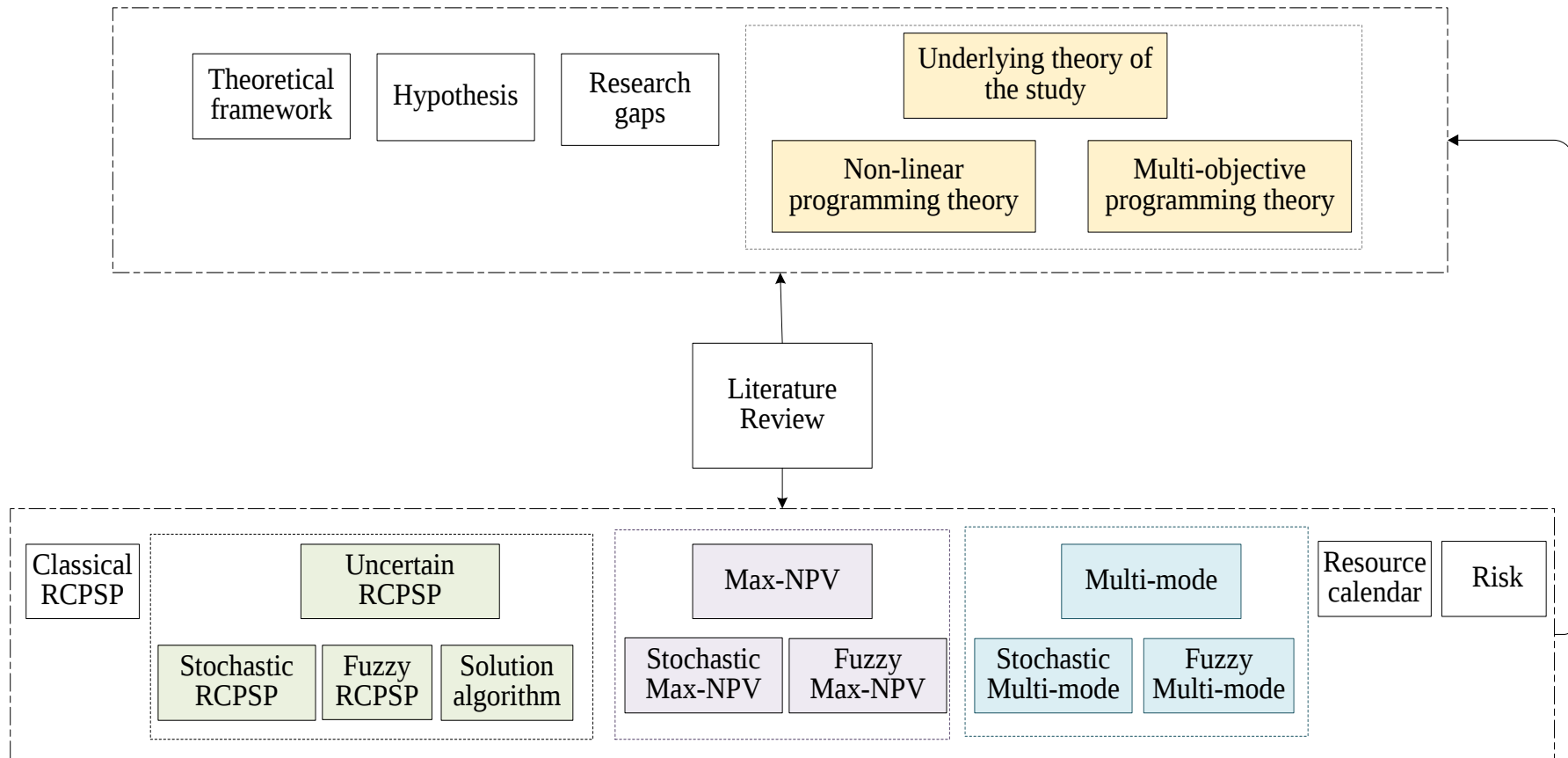


Figure 2.1 Flow Chart for Chapter 2

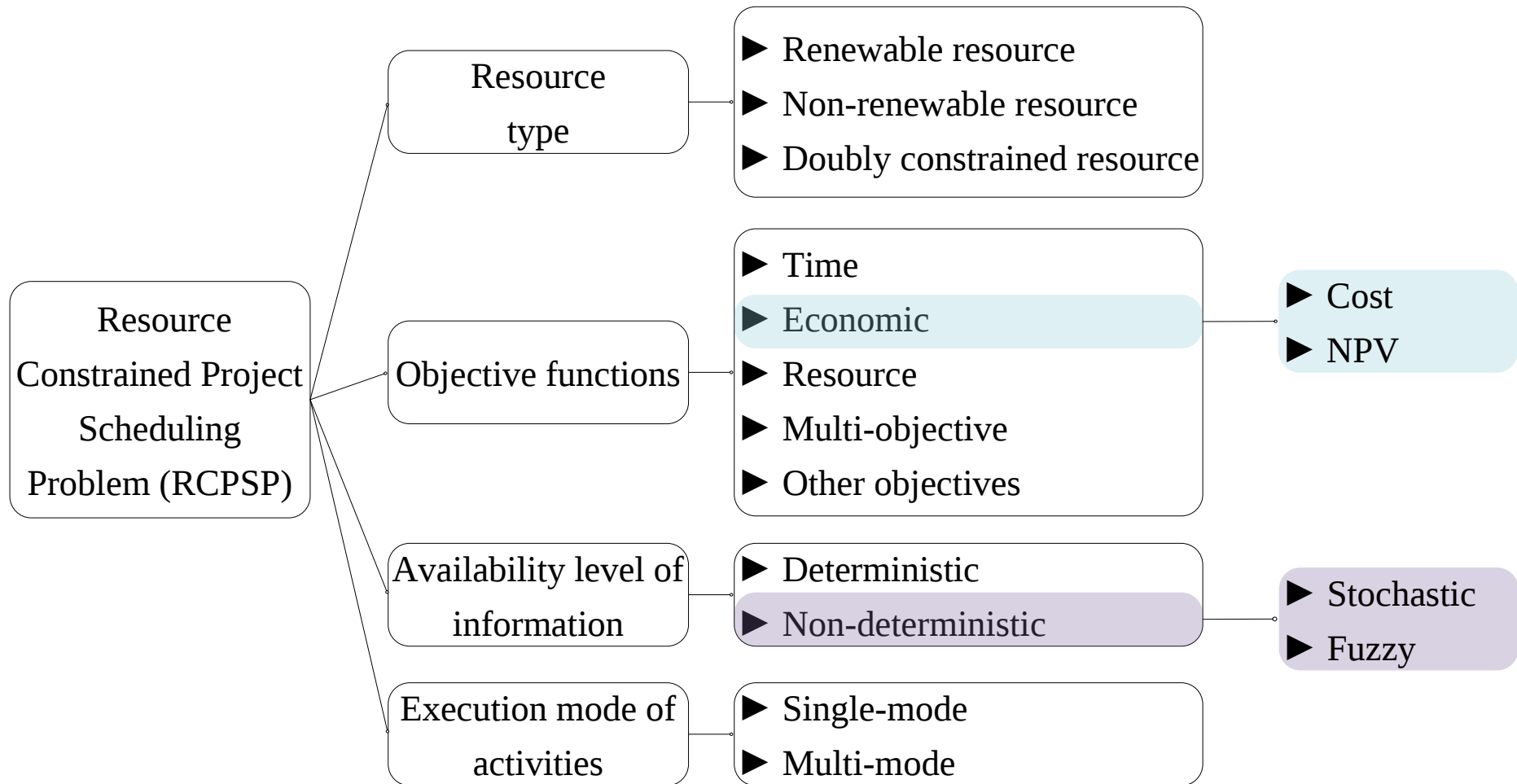


Figure 2.2 RCPSP Classification (Hartmann & Briskorn, 2022)

2.3 Uncertain RCPSP

Uncertainty is a natural characteristic of every project (Cleden, 2017). This characteristic exists from the project plan's development to the project's end. Uncertainties may come from within or outside the project. Uncertainties within the project include changes in objectives and scope. Uncertainties outside the project include the unavailability of raw materials and unexpected weather changes. A few early project scheduling plans have considered uncertainties. As a consequence, these plans are often only available in some special situations. In recent years, RCPSP in uncertain environments has gained more and more attention (Ballestín, 2007; Chen et al., 2021; Chen et al., 2018; Choi et al., 2004; Fernandez et al., 1998; Herroelen et al., 1999; Rostami et al., 2018; Sallam et al., 2021).

The uncertain RCPSP mainly includes S-RCPSP and F-RCPSP. The uncertainty is mainly reflected in the parameters, and the classification of uncertain RCPSP is given in Figure 2.3. The S-RCPSP is primarily reflected in stochastic cost, time, and resource supply, as well as both stochastic cost and time. The F-RCPSP is primarily reflected in fuzzy cost, time, resource supply, and both fuzzy cost and time.

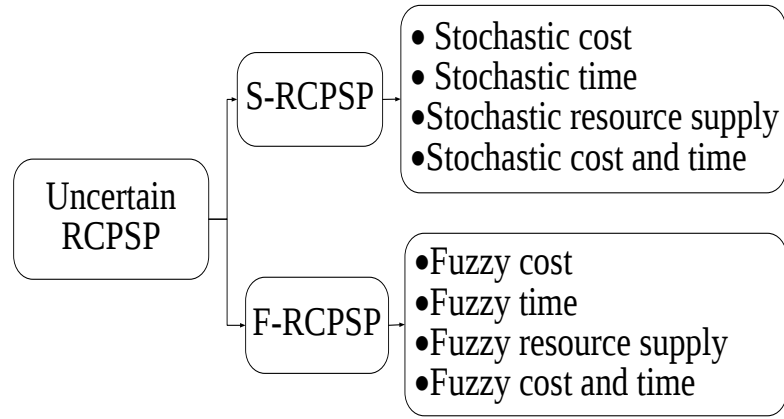


Figure 2.3 The Classification of Uncertain RCPSP (Ji & Yao, 2017)

2.3.1 Stochastic RCPSP

The S-RCPSP based on stochastic activities relies on the RCPSP and differs from the classical RCPSP, where the activity duration is changed from a constant to a stochastic variable. Most research in S-RCPSP is focused on stochastic activity duration and cost (Liu et al., 2024). Various stochastic models are considered to deal with the S-RCPSP, such as expected value models (Alipouri et al., 2020; Ortíz & Diaz, 2020) and chance-constrained programming models (Hazır & Ulusoy, 2020; Liu et al., 2022).

Freeman (1960) introduced probability theory to the project scheduling problem to minimize the project completion time. To correctly estimate the completion time and develop a reasonable schedule, scholars assumed that activity duration was a stochastic variable following different probability distributions (Peng et al., 2023). Lootsma (1966) assumed that activity duration was a stochastic variable with gamma distribution, and optimistic, median, and pessimistic activity duration estimates determine the parameter values. Then, Britney (1976) assumed that activity duration