

1 *Whether and When to Invest in Transportation Projects: Combining Scenarios and Real Options*
2 *to Manage the Uncertainty of Costs and Benefits*

3

4 **Abstract** - Transportation infrastructure projects are a cornerstone of economic growth.
5 However, the issue of whether new transportation infrastructure projects deliver the expected
6 benefits has come under considerable scrutiny. The growing economic uncertainty and the
7 tightening of budget constraints have made the design, evaluation, and selection of such high-
8 cost projects particularly critical. There are disagreements as to how project decision-makers can
9 evaluate the long-term costs and benefits of infrastructure projects. The objective of this paper is
10 to address such disagreements. We develop and apply an innovative methodological approach
11 that combines real options with scenarios to help policymakers assess the costs and benefits of
12 transportation projects. While these techniques have been widely adopted in corporations, there
13 is little empirical evidence regarding their combined use by project decision-makers dealing with
14 complex infrastructure projects. In this paper, we fill this gap in the planning and project studies
15 literature. We show that scenarios and real options can be very helpful in developing a more
16 comprehensive understanding of long-term impacts of major infrastructure projects and thus in
17 selecting the most relevant projects. Overall, our study assists the debate on the management of
18 the uncertainty of long-term costs and benefits of infrastructure projects and helps cope with
19 such uncertainty.

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21 **Managerial relevance statement** - In this paper, we design and apply a new methodological
22 approach aimed at helping project decision-makers cope with the uncertainty of transportation
23 infrastructure projects by enhancing decision-makers' ability to assess long-term effects on
24 economic development and growth. Specifically, the innovative methodological approach we
25 illustrate in this paper is designed to allow policy-makers to develop a shared understanding of
26 investment potential of major investment projects in transportation infrastructure, select projects
27 that are most likely to contribute to economic growth and focus their resources on such projects
28 while reducing the financial risks inherent in major investment projects by regarding such
29 projects as consisting of different steps, each entailing the right but not the obligation to proceed
30 forward to the next step. Overall, the methodological approach we propose in this paper helps
31 governmental institutions facing tightening budget constraints optimize the use of their budgets
32 and their overall strategy for economic growth.

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34 **Index Terms** - Transportation projects; Decision-making under uncertainty; Project planning;
35 Scenario planning; Real options

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I. INTRODUCTION

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Public infrastructure and construction projects are major tools for enhancing economic growth [1] [2]. However, the growing turbulence of the economy and the tightening of budget constraints have made the design, evaluation, and selection of such high-cost projects particularly critical [3] [4], thus underscoring the challenge of optimizing the use of public money by selecting the most beneficial projects for local communities and regional growth [5]. Project decision-makers have acknowledged high uncertainty and incomplete control in dealing with the long-term challenges of transportation infrastructure projects and deciding on their implementation [6] [7]. In the broadest sense, when the key characteristics of major infrastructure projects in terms of their ambition, social and organizational relations, temporality, timescale and impact [8] are considered, uncertainty can be defined as a state of not knowing or a lack of certainty [9].

Although discounted cash flow (DCF) techniques such net present value (NPV) and internal rate of return (IRR) have long been applied by practitioners for evaluating investment alternatives (e.g., [10]), these techniques have been criticized because of being inadequate and incomplete in assuring a rational decision process able to capture ‘intangible’ project attributes and the value of future flexibility (e.g., [11] [12]). In response, scholars have clearly emphasized the difficulties inherent in the ex-ante evaluation of transportation infrastructure benefits [13] [14] and developed ad hoc techniques for coping with the growing uncertainty of investment decisions. Among such techniques, scenario planning and real options have become quite popular [15][16]. Scenarios (also referred to as scenario planning hereafter in the paper) are alternative views of the future in the form of different configurations of key drivers of change. Their rationale is not to predict the future but rather to enable decision-makers to revise assumptions about the future

61 and mental models [17]. Apart from scenarios, another key approach to uncertainty management
62 is that of real options, which showed that corporate assets can be valued using option pricing
63 techniques. Real options theory emphasizes the idea that many initial investments provide firms
64 with opportunities (but not obligations) to make subsequent follow-up investments [18].
65 Real options are traditionally based on the same models that have been used to value financial
66 options, that is, the Black-Scholes [19] and Merton [20] option pricing formula, and the binomial
67 option valuation method [21] and the Monte-Carlo method [22]. Both financial options and real
68 options use volatility, i.e., the degree of fluctuation in price of a market or security, in their
69 treatment of uncertainty, by assuming that the volatility or risk of the underlying asset can be
70 determined accurately and readily. However, whereas for traded financial assets this would most
71 probably be the case, as there is likely to be sufficient historical data available to assess the
72 underlying asset's volatility, this might not be the case for large, one-off real assets as those of
73 infrastructure projects, for which there would be little or no historical data available. Recently,
74 some new approaches to real option modeling have thus been developed which help to cope with
75 the difficulty inherent in the assessment of the volatility of real assets, namely fuzzy logic and
76 fuzzy sets [23].
77 Even though scenarios and real options have complementary strengths and weaknesses, the two
78 streams of research have rarely crossed [24] [25]. While both of these techniques have been
79 adopted separately (and largely) in different industries, little evidence exists as to their
80 integration, especially due to the different inputs they provide [26] [27].
81 In real options modeling, alternative scenarios have the potential to help estimate changes in the
82 present value of investment decisions, particularly when there are favorable and unfavorable
83 events that can impact the expected value of future free cash flows. On the other hand, the main

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A. Uncertainty management of transportation infrastructure projects: conventional investment analysis techniques

Previous studies have emphasized that improvements in transportation infrastructure yield significant benefits to direct users. According to Vickerman et al. [28], such improvements consist of shorter travel times and better scheduling, which create new location advantages, reduction of travel costs as a result of shorter distances, ease of traffic flow, reduced congestion, and higher speeds [29]. Transportation infrastructure services also reduce fuel consumption, air pollution, and capital and labor costs (e.g., [30] [31] [32]). Scholars have also explored the short- and long-term effects of transportation infrastructure on the economy, which manifest in increases in employment during the development of the infrastructure and enhanced convenience for households and increases in real estate prices if land values rise due to a trade-off between transport costs and accessibility [33] [34]. Venables [35] emphasizes that all such ‘wider economic benefits’ should be considered in an ex-ante evaluation of long-term returns of such projects.

However, the uncertainty of long-term effects of transportation infrastructure projects represents a key challenge for national and regional governments – a challenge that is particularly severe because of lifecycle length and the complexity (a broad range and diversity) of the outcomes of such projects [36] [37]. Coping with uncertainty has been observed to be a vital element of major infrastructure planning and development processes, in which both the lack of relevant and reliable data (‘known unknowns’) and the nature and range of future socially constructed events (‘unknown unknowns’) pose a significant threat to major infrastructure evaluation and approval (e.g., [38] [39]).

131 In this respect, growing uncertainty has driven project management research toward new
132 opportunities and challenges [40] [41]. Despite the debate over the long-term effects of
133 transportation infrastructure projects, we still know relatively little about how to manage the
134 uncertainty of such effects. In particular, to date, scholars have focused on the use of
135 conventional investment techniques by highlighting the benefits – and at the same time, the
136 limitations – of such approaches.

137 Specifically, the most common techniques for assessing the long-term returns and costs of
138 infrastructure projects are ‘conventional’ investment appraisal techniques, i.e., payback (PB),
139 return on assets or investment (ROA or ROI), and capital budgeting tools, such as NPV and IRR,
140 based on DCF (e.g., [42] [43]). Among these approaches, DCF, NPV and IRR can be considered
141 the dominant methods. The main reason that justifies the widespread application of capital
142 budgeting tools to project investments is essentially related to the intuitive simplicity of the
143 go/no-go investment decision. DCF provides a single numerical outcome, the discounted net
144 present value of the project: if the DCF value is above zero, the project is a go, while if it is
145 below zero, the project is rejected [44].

146 The DCF approach calculates the value of an expected stream of cash inflows less an expected
147 stream of cash outflows discounted at a given rate. This method assumes that an investment
148 decision is made either at the beginning of a project or never [45]. This feature implies two major
149 limitations: first, DCF may take into account a random walk (statistical dispersion) of costs and
150 benefits, but not their respective volatility, because the degree of variation of trading prices over
151 time are unavailable; second, it ignores the opportunity to profit from new information about key
152 changes in the external environment as long as this information becomes available [46].

153 Major infrastructure investments have specific characteristics, particularly in regard to
154 uncertainty and capital budgeting over long periods of time [47] [8]. The application of
155 traditional financial investment appraisal methods fails to include the random probability
156 distribution of the critical inputs to the project value over time, and hence potentially results in
157 incorrect valuations of strategic long-term infrastructure investments [35]. In deterministic
158 valuation models, such as NPV and DCF, the output of the model is fully determined by the
159 parameter values and the initial conditions. In contrast, stochastic models (i.e., real options)
160 possess some inherent randomness. The same set of parameter values and initial conditions will
161 lead to boundaries of a ‘statistical space’ where the project value is free to float at each given
162 time [48]. The value of uncertainty and volatility embedded into large infrastructure investments
163 remains difficult to evaluate using conventional financial techniques, which suggests that the
164 management of such uncertain investments may particularly benefit from different approaches
165 based on stochastic models [49].

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167 *B. Alternative approaches to project evaluation: scenarios and real options*

168 *1. Scenarios*

169 A promising alternative approach to project evaluation relies on scenarios; it has been
170 used extensively by business strategists since the 1960s, with the most notable example being the
171 Shell case in the oil industry [50]. Since then, scenarios have been further used to increase the
172 robustness of long-term investment plans by leading firms of many different industries and by
173 policymakers in tourism (e.g., [51]), environmental studies (e.g., [52]), urban water infrastructure
174 (e.g., [53]) and urban planning (e.g., [54]). However, the application of scenario planning in
175 transportation research has only recently captured the attention of scholars and practitioners [55]

176 [56]. Due to computer simulation tools supporting spatial data visualization and interactive
177 analysis, considering scenarios has allowed decision-makers to explore the future outcomes and
178 benefits of selected transportation and water infrastructure projects. To improve the robustness of
179 Innovate UK's decision-making under uncertainty, in 2015/2016 it commissioned the
180 development of a set of scenarios to explore the role of future technology for future transport.
181 This approach was used to explore potential impacts on different stakeholders in the society and
182 consider policy interventions that were consistent across a range of scenarios [57]. Similarly, in
183 2020, Transport Scotland published its revised National Transport Strategy in which its
184 underlying thinking and formulation have been informed by a scenario planning tool and process
185 [58].

186 Instead of predicting the future, the main rationale of scenarios is to consider alternative views of
187 the future in the form of different (but internally consistent) configurations of key drivers of
188 change in the business (or project) environment [17]. The most common use of scenarios for
189 transportation and infrastructure projects has mainly shown deductive reasoning to be required to
190 focus on the arising uncertainties (i.e., new events or drivers of change) in the project
191 environment and then to select, among all of such arising uncertainties, the most critical ones to
192 be used as the basic premises of a small number of scenarios [59]. However, although the
193 potential of this method has long been emphasized by strategic scholars, its use in the
194 management of transportation infrastructure projects has been curbed by its recognized
195 limitations.

196 In this regard, the scenarios' value added depends strictly on their consistency, which relates to
197 the ability to capture coherently within each scenario the mutual influences of many drivers of
198 change. Despite the availability of different approaches to scenario building (e.g., deductive vs.

199 inductive approaches), consistency is strongly dependent on the knowledge and skills of the
200 managers involved in this process. While consistent scenarios are likely to help decision-makers
201 change the mental models they inherit from previous experience (and overcome the inertia
202 inherent in such experience), inconsistent scenarios are likely to contribute to organizational
203 inertia instead by leading to mental models that are not aligned with the real future [17]. Another
204 relevant limitation of scenarios is the lack of systematic approaches to measuring the future
205 outcomes of each scenario. The qualitative focus of scenarios often leads managers to overlook
206 the task of quantifying the future value of drivers of change, and the lack of quantitative data
207 ultimately reduces the vividness – and the value added – of scenarios [24]. Even in the case of
208 financial modeling and investment appraisal, where scenarios are meant to estimate changes in
209 the value of future cash flows, the need to consider different and multiple scenarios at the same
210 time leaves decision-makers with the difficult (and therefore often simply omitted) task of
211 reducing such multiple scenarios to a single “most likely” expected value of the investment [60].
212 Finally, it is worth noting that considering scenarios requires participants to be motivated,
213 involved and in a good disposition to prevent biased decisions and dominant personalities from
214 prevailing, which might limit the range of alternative scenarios that are eventually described and
215 fully considered [24].

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217 *2. Real options*

218 Further to scenarios, a key approach to uncertainty management increasingly emphasized
219 by strategic scholars and practitioners is that of real options. Although the literature has quickly
220 expanded to considering a large number of increasingly complex models for the analysis and
221 valuation of real options, its underlying reasoning is based on a quantitative approach rooted in

222 finance research (e.g., [45]). The real option approach extends financial option theory to
223 nonfinancial or ‘real’ assets. This perception places real options at the intersection of strategy
224 and finance, where the Black-Scholes model prices the right but not the obligation to make an
225 additional investment, based on five key factors, namely the exercise price, the asset value, the
226 time left until the expiration, the risk-free rate and the project’s volatility. Over time, a number of
227 different real option valuation models have been developed; however, all of them utilize an
228 algorithm similar to the Black-Scholes partial differential equation, which can only be used if the
229 expected variance of returns (the volatility) is known [61].

230 The real options technique is significantly different from the traditional discounted cash flow
231 (DCF) approach due to allowing managerial investment flexibility and the dominant role of
232 volatility in determining the future value of the investment. Real options theory emphasizes the
233 flexibility inherent in the opportunity (but not the obligation) to invest further in additional
234 assets, which thus allows decision-makers to profit from favorable outcomes and avoid losses.

235 The real options approach has been applied first to a wide range of domains, including the oil,
236 energy, pharmaceutical, and telecommunication industries, where the underlying project or asset
237 (e.g., oil, energy or medicines) is traded in perfect markets in which information about the asset
238 is available freely and is reflected in the asset price [16]. Although more examples of the use of
239 real option valuation have emerged in recent years in the field of infrastructure [62] [63], there is
240 still little evidence of this technique’s application to transportation projects, where DCF remains
241 by far the dominant investment appraisal method [42] [64]. The lack of a frictionless market for
242 infrastructure assets and, consequently, the difficulty of tracking daily market prices makes the
243 statistical determination of volatility unfeasible; consequently, a calculation of the solution of the
244 Black-Scholes partial differential equation remains impossible or largely subjective if we use

245 surrogate volatility data for similar ('twin') assets [23]. This quite likely represents the main
 246 barrier to the application of real options to appraisal of investments in transportation
 247 infrastructure, where the volatility of key parameters is unknown.
 248 As a result, although the real options technique has been increasingly used in valuing
 249 infrastructure investments, most of published cases focus on projects where the volatility of
 250 output prices and cost inputs can be determined or derived with the use of advanced statistical
 251 methods, such as Monte Carlo simulations [65]. In projects where the distribution and dispersion
 252 of key variables is unknown or unreliable, decision-makers have embraced real option reasoning
 253 to define the options attributable to the initial investment following an informal and heuristic
 254 process that can lead to future-proof outcomes [66].

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256 *C. Advantages and disadvantages of DCF, scenarios and real options*

257 Table 1 summarizes the main benefits and challenges of DCF, scenarios and real options
 258 for infrastructure projects' evaluation and the management of such projects' uncertainty.

259 **Table 1.** Benefits and challenges of DCF, scenarios and real options

Method	Benefits	Limitations
DCF	Intuitive simplicity of the investment decision rule: if $DCF > 0$ then go; if $DCF < 0$ then abandon [44] A simple and univocal link between a strategy and its financial value [67]	Historic volatility of costs and benefits is not available [45] Ignores the value of active management, and the ability to profit from new information [61]
SCENARIOS	Alternative visions of the future [17] Externally focused: scenario planning helps managers continuously explore opportunities and threats [68] Qualitative approach and system thinking [50]	Multiple scenarios cannot be easily reduced to a single "most likely" expected value of the investment [60] Need for internal consistency [17] Bias of participants due to the influence of dominant personalities [24]

	<p>Flexibility and adaptation of strategic investment decisions [69]</p> <p>Coordination and communication: creation of a language and shared understanding among decision-makers [70]</p>	
REAL OPTIONS	<p>The Black-Scholes model is one of the most important concepts in modern financial theory. It involves a stochastic equation that estimates the future value of capital investments, taking into account the impact of time and other risk factors [71]</p> <p>Emphasis on flexibility to postpone, stop or expand irreversible investments in real assets [72]</p>	<p>Difficulty of valuing options on real assets since doing so requires the calculation of volatility of the underlying asset price, which is the fundamental driver of real option value. The value of the volatility of real assets is unclear or is entirely unobservable. No option value can be determined without the knowledge of volatility [66]</p> <p>Loss of links to the environment: most of real option valuation models do not provide clear guidelines for selecting key drivers of change and exploring their likely evolution [24]</p> <p>Unrealistic assumptions about quantitative financial skills of decision-makers. Senior management usually lacks mathematical skills required to apply, understand and communicate real option valuation [73]</p>

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261 Overall, such benefits and limitations – coupled with the growing uncertainty of transportation
 262 infrastructure projects – call for the design and application of new management approaches
 263 integrating both strategic and financial analysis such as scenarios and real options, using ideas
 264 that might be borrowed and adapted from other research streams in management and economics
 265 [74].

266 The use of scenarios and real options in transportation management is particularly promising, as
 267 infrastructure projects are generally framed in terms of various sequential phases, i.e., planning
 268 and zoning, construction and post-construction [75]. This feature is consistent with the

269 underlying principles of real options and scenarios. It is therefore quite surprising that the
270 combined use of real options and scenarios has remained underexplored thus far by scholars and
271 practitioners in the field of transportation research.

272 In the following sections of the paper, we aim to bridge this gap in the existing literature by
273 developing a new methodological approach that systematically combines real options with
274 scenario planning. The method we propose aims to foster real option reasoning by simplifying
275 the use of the Black-Scholes option pricing model in a way that allows decision-makers to
276 calculate the financial value of alternative scenarios.

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278 III. COMBINING REAL OPTIONS AND SCENARIOS FOR EVALUATING TRANSPORT 279 INFRASTRUCTURE INVESTMENTS

280

281 The methodology we develop and illustrate in this paper builds upon the previous work
282 of Favato and Vecchiato [25], who already attempted to embed real options into scenarios for
283 assessing the long-term value of a new drug in a biotech start-up. Despite being rooted in the
284 same deductive approach of scenario planning and the payoff model of real options, the
285 methodology we propose in this paper is significantly different. First, although the underlying
286 real option reasoning is essentially the same as that in the published biotech case, the scenarios
287 elicited here reflect the specific economics of transportation infrastructure by considering the
288 idiosyncratic benefits and stages of development of investments of this type (as previously
289 identified in the review of the existing literature; see [28]). By doing so, we show that the payoff
290 model of pricing real options we use in this paper can be easily transferred to a variety of
291 construction industries and project specifications. Second, the biotech application priced a
292 staging option to develop an innovative medicine, where uncertainty was directly related to the

293 outputs of clinical testing and the consequent possibility of meeting regulatory requirements in
294 terms of efficacy and safety of the new medicine. In the case illustrated by this paper, we price
295 an option to expand an existing infrastructure project with already committed financing. We
296 retrospectively apply our methodological approach to the case of the north extension of the third
297 underground line in Rome (Line C). This transportation infrastructure case provides a
298 compelling research setting, given the uncertainty in the nature and the quantification of the
299 benefits to direct users. By doing so, we inherently demonstrate that the payoff model of pricing
300 real options, combined with scenarios, is a useful tool for managers of infrastructure projects
301 since it allows pricing all types of real options, including staging, expansion, abandonment,
302 delay, or switching of the infrastructure to a different use. Finally, while the biotech case
303 describes the method of making an investment decision by a privately held company that is free
304 to choose the valuation tools and the model inputs that it believes are better proxies of the
305 financial value of the project, in the transportation case we discuss here a publicly funded
306 project, where the investor was a public entity (the municipality of Rome), and the variables to
307 be included in the valuation of the incremental investment needed to expand metro Line C were
308 codified by national laws [76]. In this case, our model passed a severe test, since the degree of
309 freedom in choosing the value drivers was extremely limited. The value drivers were defined a
310 priori, hence the application of our proposed method to the case of the Rome underground's Line
311 C ('Rome Line C') suggests that this method has the flexibility to be adapted to virtually any
312 infrastructure investment decision.

313 In the remainder of this section of the paper, we illustrate first our overall methodological
314 approach to the integration of real options and scenarios; in the next Section 4, we then apply it

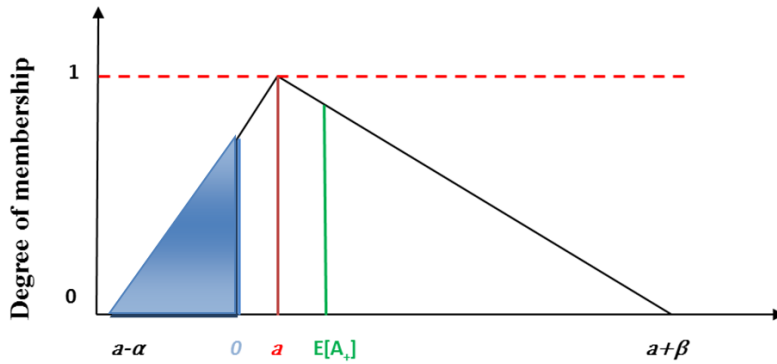
315 to the case of Rome Line C and compare the outcomes of our method with those of the
316 traditional DCF approach.

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318 *A. Payoff model for valuing real options of infrastructure projects*

319 Among the recent studies in the literature on real options, the payoff model developed by
320 Collan et al. [77] features a fuzzy logic approach to valuation of investments under uncertainty,
321 which makes it particularly suitable for cases in which input information takes the form of cash-
322 flow scenarios (fuzzy sets) and the volatility of cash flows is unknown or unavailable but can be
323 described with a degree of probability ranging from 0 (extremely unlikely) to 1 (certainty) [75].
324 These characteristics make the payoff model a good fit for the appraisal of investment in new
325 transportation infrastructure projects. This method calculates a real option value for a project
326 from the project's payoff distribution (an NPV distribution) that can be constructed from the
327 project's cash-flow scenarios. The created NPV distribution is treated as a fuzzy number.
328 According to [77], the method utilizes fuzzy sets to determine the possibilistic – as opposed to
329 probabilistic – expected value of a given investment project. The fuzzy distribution shown in
330 Figure 1 simplifies reality and assigns the highest degree of possibility (1, meaning 'fully
331 possible') to the 'base' case (or the middle case) and the lowest (approaching 0) degree of
332 possibility to the minimum and maximum values of the distribution. The result is a triangular
333 fuzzy distribution of returns on investment (hence, the payoff distribution).

334 **Figure 1.** Triangular distribution of the payoff model



335

336 The payoff distribution was originally created using three discounted cash-flow scenarios [77]:

- 337 1) A 'worst'-case scenario based on the lowest credible estimates of costs and benefits,
 338 2) A 'best'-case scenario based on the highest credible estimates of costs and benefits, and
 339 3) A 'base' scenario based on an intermediate outcome in which costs and benefits are
 340 neither maximized nor minimized.

341 The outcomes outside the worst-case and best-case scenarios will not be considered by the
 342 payoff model, and therefore the included values define the payoff distribution of the project's
 343 discounted cash flows, which is treated as a fuzzy set.

344 The choice of three scenarios (base, best and worst) is particularly relevant to the appraisal of
 345 infrastructure investments since previously published cases referred to a high, medium or low
 346 attractiveness of safeguarding such investments according to uncertainty and modularity of the
 347 empirical observables in transportation projects [78]. The adoption of the payoff method allows
 348 us to match real option reasoning with the development of distinct scenarios. The latter lead to
 349 the estimation of discounted cash flow values that are subsequently consolidated into a single
 350 univocal value of the investment under uncertainty. This value is calculated as the payoff value
 351 of fuzzy sets represented by the three scenarios (base, high and low), and the calculation of
 352 uncertainty does not require any measure of dispersion, such as volatility. The use of three
 353 reference scenarios, the ability to consolidate three discounted cash flows into a single value

354 under uncertainty, the applicability of the method to projects with unknown volatility, and the
 355 intuitive visual representation of the decision space (a triangle) represent the key advantages of
 356 this method for management of infrastructure projects.

357 Depending on the sign of the base case (positive or negative) and the sign of its relative distance
 358 from the best-case and worst-case scenarios, the real option's value can be calculated as shown
 359 below:

360 $E(A_+)$

$$\begin{cases}
 a + \frac{\beta - \alpha}{6}, & \text{if } 0 < a - \alpha & \text{'all NPV positive'} & (1) \\
 \frac{(\alpha - a)^3}{6\alpha^2} + a + \frac{\beta - \alpha}{6}, & \text{if } a - \alpha < 0 < a & \text{'some negative NPV; positive peak'} & (2) \\
 \frac{(\alpha + \beta)^3}{6\beta^2}, & \text{if } a < 0 < a + \beta & \text{'some positive NPV; negative peak'} & (3) \\
 0, & \text{if } a + \beta < 0 & \text{'all NPV negative'} & (4)
 \end{cases}$$

362 The real option value calculated from the fuzzy DCF is the possibilistic mean value of the fuzzy
 363 DCF values $E(A_+)$ multiplied by the positive area of the fuzzy DCF and divided by the total area
 364 of the fuzzy DCF:

$$\text{Real option valuation} = \frac{\int_0^{\infty} A(x)dx}{\int_{-\infty}^{\infty} A(x)d(x)} E(A_+) \quad (5)$$

366 In this equation, A represents the fuzzy DCF, $E(A_+)$ is the possibilistic mean of the positive area
 367 of the payoff distribution, $\int_0^{\infty} A(x)dx$ is the positive area of the payoff distribution, and
 368 $\int_{-\infty}^{\infty} A(x)d(x)$ is the total area of the payoff distribution. This calculation method is aligned with
 369 the real options' valuation logic, which implies that the management will interrupt or modify a
 370 project when its payoff becomes negative [76].

371 Due to the triangular distribution of fuzzy set A_+ , the positive value of its fuzzy mean $E(A_+)$
 372 can be obtained simply by calculating the negative area (the blue triangle in Figure 1) as a

373 percentage of the total area of the triangle $a-\alpha; 1; a + \beta$. This value can be easily determined
374 without integration. The missing value (Y' of the apex of the blue triangle) can be obtained by a
375 calculation using the linear equation of the line defined by two points: $X= a; Y=1$ and $X= a-\alpha;$
376 $Y=0$. Then, we must solve the linear equation for $X=0$ to obtain the Y value of the apex of the
377 blue triangle (Y' in Figure 1). Next, the negative portion of $E(A(+))$ can be easily calculated as $(a-$
378 $\alpha \times Y')/2$. The negative value as a percentage of the total can be obtained by simply dividing the
379 area of the blue triangle by the total area of fuzzy set A $(a-\alpha + a + \beta/2)$; then, the positive
380 percentage value of $E(A(+))$ can be obtained by subtracting the negative percentage from 1. If we
381 apply the last percentage value to the calculated $E(A(+))$, the option value will be obtained without
382 the use of integration: this approach offers a significant advantage for policymakers in terms of
383 modelling the distribution of the payoff model because, in contrast to the complexity of the
384 Black and Scholes [19] model, the mathematical hurdle of this approach is minimal.

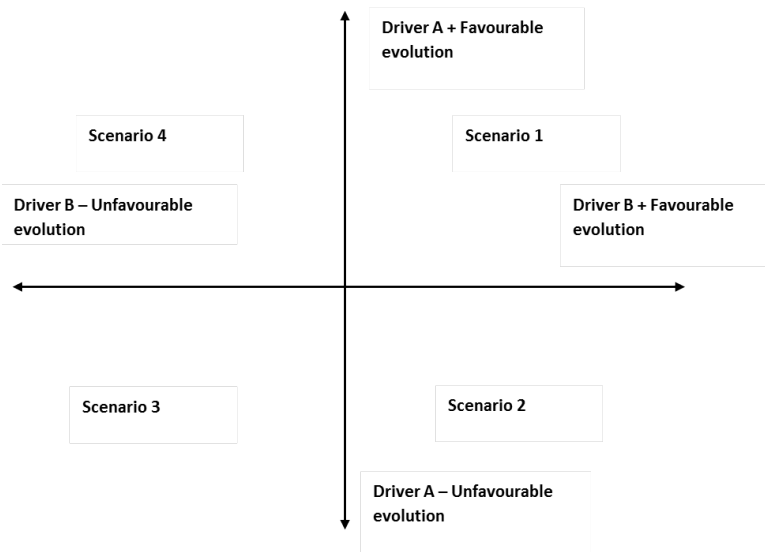
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386 *B. Deductive approach to scenarios*

387 The deductive approach to scenarios is particularly suited to the payoff model of real
388 option valuation [79]. This approach is based on the initial identification of the two most
389 important variables (i.e., drivers of change) that can affect the outcomes of a given strategic
390 investment decision [68]. As alternative (opposite) assumptions are formulated with regard to the
391 variables' future evolution pattern, these two critical variables become the axes of a 2x2 scenario
392 matrix, as shown in Figure 2. For simplicity, we generically name such key variables "Driver A"
393 and "Driver B". As indicated in Figure 2, while one assumption about future evolution usually
394 turns out to be the most favorable in terms of future outcomes, the other – namely, the opposite –
395 assumption may have a negative impact.

396

Figure 2. Structure of a 2x2 scenario matrix



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398 The 2x2 matrix provides a helpful framework for supporting the application of the payoff model.

399 Specifically, this matrix allows the identification of four scenarios with significantly different

400 impacts on the long-term return of an investment project.

401 Figure 2 shows that Scenario 3 is associated with the lowest expected DCF, and its 'double

402 negative' scenario is likely to represent the worst-case input to the payoff valuation model. In

403 contrast, the 'double positive' Scenario 1 represents the best-case input because it produces the

404 highest credible estimates of benefits and the most favorable cost expectations. Finally, the 'base'

405 scenario (i.e., that based on an intermediate outcome, where costs and benefits are neither

406 maximized nor minimized) might be represented instead by either the 'positive-negative' scenario

407 (Scenario 4) or the 'negative-positive' scenario (Scenario 2), depending on the different impacts

408 of the key drivers (variables A and B) on the future outcomes (NPV) of the strategic investment

409 decision.

410 Therefore, if the relative probabilities of occurrence of Scenario 2 (p') and Scenario 4 (p'') are
411 known ($p' + p'' = 1$), then the input for the base case can be obtained by calculating a probability-
412 weighted mean of the two discounted cash flows:

$$413 \text{'base case' DCF} = (\text{DCF Scenario 2} \times p') + (\text{DCF Scenario 4} \times p'')$$

414 If the relative probabilities are unknown, then the mean value of the DCFs stemming from
415 Scenario 2 and Scenario 4 is likely to be an acceptable approximation because it is assumed that
416 the two scenarios will share the same degree of possibility (full possibility = 1) in the fuzzy
417 distribution of project returns underlying the payoff model [76].

418

419 *C. Combining real options and scenarios*

420 By combining a 2x2 scenario matrix with the payoff model and real options' valuation,
421 project decision-makers can obtain a more comprehensive overview of the long-term effects of
422 major transportation infrastructure investments. The 2x2 scenario matrix described in Figure 2
423 can be seamlessly applied to the case of a transportation infrastructure project by exploring such
424 a project's different sources of revenues and costs and selecting two of such revenues and costs
425 as the basic drivers of the four alternative scenarios¹. Based on these scenarios, the payoff model
426 will enable the quantification of these revenues and costs and, ultimately, of the profits (value) of
427 the project itself in a relatively simple yet accurate way.

428 In particular, a key feature of construction projects that facilitates the application – and increases
429 the contribution – of the real options logic is that transportation infrastructure investments are
430 generally framed around specific and different phases. These phases also follow a precise order

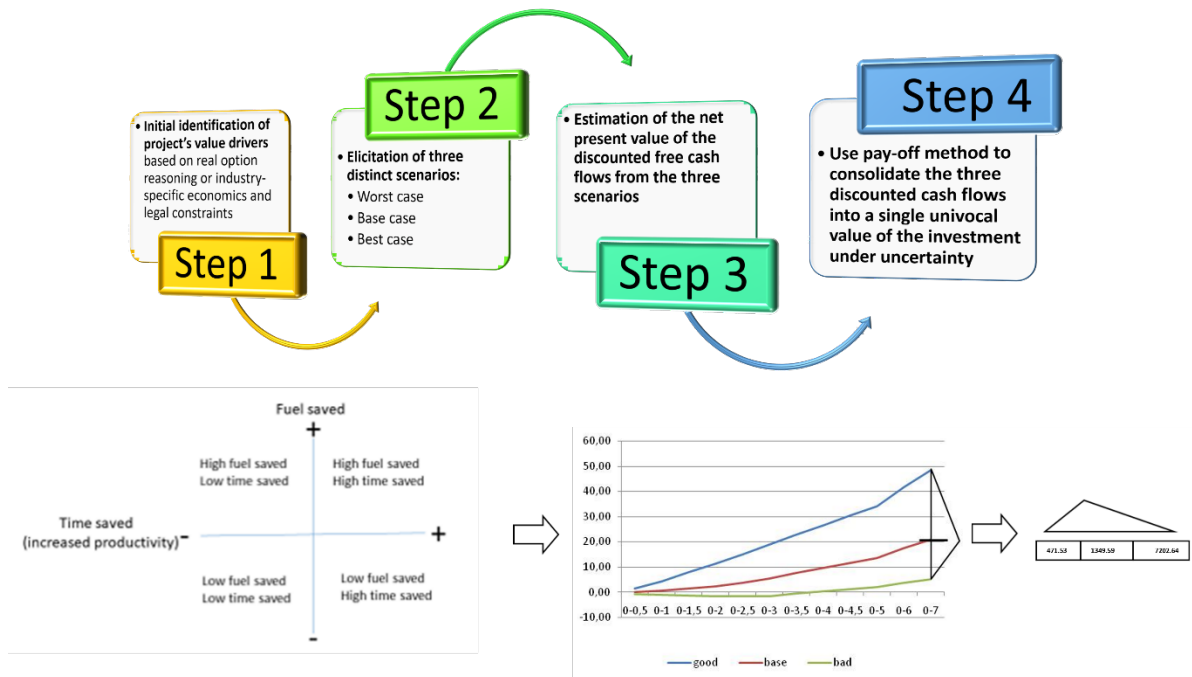
¹ The deductive approach would then explore the related evolution of the other drivers, in each scenario, in a way that is consistent with the assumptions made for the key drivers, thus allowing one to seamlessly increase the number of costs and benefits of transportation projects that are taken into account.

431 from feasibility studies, project definition, design, negotiation and pre-contract stages to
432 construction and commissioning. Specifically, beginning from owning the land on which
433 transportation infrastructure might be built, such a project can be divided into three main stages:
434 planning and zoning, construction, and post-construction [75]. A prerequisite for beginning a
435 transportation project is that the designated area be available for development. Land must often
436 be purchased or leased for the purpose of the project, and the profitability level of the potential
437 project to be built on the land determines the acceptable cost of obtaining the use of the land. The
438 planning and zoning phase (Phase 1) consists of investment in urban development prior to
439 construction and entails steps such as acquiring or leasing the land (where necessary) and
440 planning the area to be developed (e.g., designing the architecture, municipal engineering and
441 infrastructure plans). After Phase 1, the construction phase (Phase 2) begins when the zoning is
442 ready, and the construction permits are valid. This phase includes the construction and
443 development of municipal engineering and infrastructure for the newly connected areas (e.g.,
444 buildings, roads, pipelines, lighting, and parking areas) and the construction of the planned
445 transportation line. Finally, the post-construction phase (Phase 3) begins after the construction of
446 the transportation infrastructure is ready and operational. This phase includes 'owning' the
447 service and maintenance of the infrastructure constructs [75].

448 Each of the three phases requires specific investments and generates specific cash-flow revenues.
449 Furthermore, the duration of each phase is difficult to estimate accurately because of a number of
450 factors that are often associated with the high complexity and uncertainty of major infrastructure
451 projects [75]. Each phase gives policymakers the right – but not the obligation – to proceed to the
452 next phase. The real option logic – combined with scenario planning – is very helpful for
453 precisely capturing the value of this right and thus can provide policymakers with a more

454 accurate tool than the traditional DCF approach to help them decide whether to invest in a
 455 transportation infrastructure project.
 456 In Figure 3 we provide a flowchart summarizing the main steps of our methodological approach
 457 to the integrated use of scenarios and real options for infrastructure project.

458 **Figure 3.** Flowchart of the integrated use of scenarios (deductive approach) and real options
 459 (pay-off model) for infrastructure projects
 460



461
 462
 463 **IV. APPLYING OUR INTEGRATED APPROACH TO SCENARIOS AND REAL OPTIONS TO**
 464 **THE LINE C PROJECT OF THE ROME METRO**

465
 466 *A. Research setting: Extension of Line C of the Rome underground*

467 To illustrate our innovative methodological approach to the assessment of the long-term
 468 benefits of transportation infrastructure projects, we apply it to the case of the extension of the
 469 third metro line in Rome (Line C). This project, which was under consideration in 2007,

470 involved an estimated budget of approximately €1.6 billion and an estimated construction time of
471 eight years. The tender was assigned by Roma Metropolitane (the Rome Metro), operating on
472 behalf of the Municipality of Rome, and entailed the expansion of Line C's main route toward
473 the northwest by creating additional sections labeled T1 (from Clodio/Mazzini to Farnesina) and
474 C2 (from Farnesina to Grottarossa).

475 This project was framed around three phases; for simplicity, in this paper we focus on the first
476 and second phases: (1) urban development prior to construction and (2) the construction of the
477 new section of Line C underground. Specifically, we apply our methodology in the beginning of
478 the planning and zoning phase (Phase 1: urban development) to calculate the value of the option
479 to invest at that particular time and to eventually proceed with the construction of the two
480 sections T1 and C2 (Phase 2).

481 The dilemma faced by the Municipality of Rome was daunting and involved the questions of
482 whether to invest an estimated amount of €761.71 million to undertake Phase 1 and obtain
483 enough information to make an informed stop/go decision regarding the development of Phase 2,
484 and whether it would be worthwhile to proceed with the project and invest an additional amount
485 of €825.17 million, the direct estimated cost of building the new Line C extension. This decision
486 was critical for the Municipality of Rome, which aimed to improve the connection of the
487 northern part of Rome with the city center.

488 To decide whether the extension should be built, Roma Metropolitane and the Municipality of
489 Rome applied the traditional DCF technique using the NPV, which led to a negative value, and
490 the decision in 2007 to not proceed with this infrastructure project.

491 Note that the value obtained by our method combining scenarios and real options will be
492 compared at the end of this section with the NPV obtained by Roma Metropolitane. To fully

493 highlight the different outcomes of our method, we consider in its application exactly the same
494 official data that were used by the policymakers of the Municipality of Rome and the project
495 decision-makers of Roma Metropolitane when they calculated the NPV and made their final
496 decision. In contrast with the latter and the NPV method, we show that the uncertainty of the
497 project can be reduced by framing this decision as a real option: the amount of €761.71 million
498 should be regarded not only as an opportunity for the urban renewal of the northwest area of
499 Rome but also as the price of the option to proceed to the construction of sections T1 and C2
500 (Part 2). If the option value is greater than the cost of Phase 1 development (the option price), the
501 Municipality of Rome should invest; otherwise, the extension of Line C should be terminated
502 immediately.

503 To evaluate the costs and benefits of the extension of Line C, Roma Metropolitane performed a
504 thorough feasibility study in 2007, including a) mobility studies, b) forecasting demand for
505 transportation services, c) a simulation of the transportation network's services and traffic flow
506 calculations, and d) estimates of CO2 emissions and fuel consumption [80].

507 Along with quantitative mathematical models (e.g., automatic vehicle monitoring during peak
508 hours), qualitative interviews were used by the Municipality of Rome to determine citizens'
509 travel habits in the urban areas affected by Line C extension. The cost/benefit analysis was
510 performed over a project lifecycle period of 36 years (8 years of construction and 28 years of
511 operation) and included both infrastructure investments and operating costs. According to the
512 preliminary study performed in 2007, the overall investment required for Phase 1 amounted to
513 €761.71 million, while that required for Phase 2 amounted to €825.17 million. Roma
514 Metropolitane identified two key benefits of the proposed extension of Line C to users: (1) time
515 savings in the course of business travel (i.e., increased productivity) and (2) the reduced use of

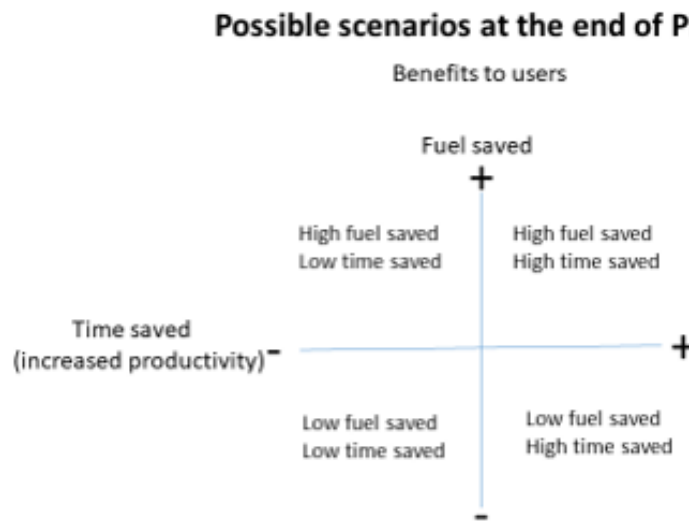
516 cars (i.e., fuel savings). These main categories of benefits were used by Roma Metropolitana to
 517 estimate the long-term value of the project and are consistent with the mainstream planning and
 518 project studies literature [34] [35]. Therefore, they are used in this paper as the cornerstone of the
 519 illustrative application of our methodological approach.

520

521 *B. Alternative scenarios for Line C of the Rome Metro*

522 The 2x2 matrix in Figure 4 describes the four possible scenarios for the development of
 523 the new northwest extension of the metro’s Line C at the end of Phase 1 (urban development
 524 prior to construction). The four scenarios result from different (alternative) courses of evolution
 525 of the future benefits for users, namely, increased productivity and fuel savings.

526 **Figure 4.** Possible scenarios for Rome Line C northwest extension at the end of phase 1



527

528 The scenario in which both benefits to users are large is the ‘best-case scenario’ (the upper-right
 529 scenario in Figure 4). The scenario in which both of these benefits are instead small is the ‘worst-
 530 case scenario’ (the bottom-left scenario in Figure 4). The 2x2 matrix also includes two
 531 intermediate scenarios: one assuming the attainment of large benefits of the project in terms of
 532 fuel saved and small benefits in terms of time saved in the course of commuting (the upper-left

533 scenario of Figure 4) and the other assuming the attainment of large benefits in terms of time
534 saved and small benefits in terms of fuel saved (the bottom-right scenario of Figure 4). The
535 ‘base-case’ scenario can be determined as an average state of these intermediate scenarios, i.e.,
536 the upper-left and bottom-right scenarios in Figure 4. For consistency, to determine the base-case
537 scenario in this paper, we considered the inputs used by Roma Metropolitane in 2007 [80] in its
538 DCF analysis to determine the value of the extension of Line C of Rome’s underground (as
539 described in the next section). The data were obtained directly from the cost-benefit study that
540 was available to the Municipality of Rome and the project decision-makers of Roma
541 Metropolitane in 2007 [80]. Additional inputs to the model included the incremental operating
542 annual costs (€-10.06 million), the negative externalities of extra time spent on local public
543 transportation (€-2.10 million), a discount rate calculated to be 5% and a VAT rate of 20% (as of
544 2007).

545 The relevant inputs for the direct drivers of benefits are summarized in Table 2 below.

546 The ‘worst-case’ scenario offers no significant benefits to the future users of Line C, and
547 therefore in this case the Line C expansion option should be discontinued.

548 **Table 2.** Inputs to DCF and the PAYOFF valuation. Source: [80]

DIRECT IMPACT	Base case	Downside (-)	Upside (+)	Source: [80]
INPUTS as % of BASE CASE values				
Time saved (increased productivity)	100%	40%	500%	Feasibility study by the Rome Municipality; page 171
Reduced use of cars (fuel savings)	100%	40%	500%	Feasibility study by the Rome Municipality; page 172
INPUTS' VALUE (€ millions actualized at 2008)	Base case: Rome Municipality's DCF valuation	Best scenario	Worst scenario	
Time saved (increased productivity)	105.89	529.43	42.35	Source of the base case: cost/benefit analysis by the Rome Municipality

Reduced use of cars (fuel savings)	30.10	150.50	12.04	Source of the base case: cost/benefit analysis by the Rome Municipality
SCENARIO ANNUAL VALUE (€ millions)	<i>135.99</i>	<i>679.93</i>	<i>54.39</i>	
ADDITIONAL INPUTS TO THE MODEL	Values			
Incremental operating annual costs (€ millions)	-10.06			Feasibility study by the Rome Municipality; page 169
Negative externalities (extra time spent on TPL - € millions)	-2.10			Feasibility study by the Rome Municipality; page 171
Discount rate	0.05			Feasibility study by the Rome Municipality; page 169
TOTAL INVESTMENT	1322.40			Feasibility study by the Rome Municipality; page 169
Total investment including VAT at 20%	1586.88			
Capex attributable to Metro construction (Phase 2)	687.64			Feasibility study by the Rome Municipality; page 169
Capex including VAT at 20%	825.17			

549

550

551 *C. Using scenarios to apply the payoff model and calculate the value of Line C extension*

552 In 2007, once the feasibility study and the collection of documentation related to Line C

553 extension were completed (in the beginning of Phase 1), the Municipality of Rome had a clear

554 expansion option. The latter can be defined as an embedded option that allows the organization

555 that purchased a real option to expand its operations in the future at little or no cost [72]. The

556 expansion option, unlike typical options that gain their value from an underlying security, gains

557 its value from the flexibility it provides to a company. Once the initial stage of a capital project

558 has been completed, an expansion option's holder can decide whether to proceed with the

559 project.

560 As indicated earlier in this section, we used the DCF projections used by the Rome Municipality

561 to appraise the investment opportunity as our base case. The DCF model is shown below in

562 Table 3.² The values are actualized at the 2008 value; hence, the columns are identical. All years
 563 have been included in the discounted free cash flow model, and both the discounting and the
 564 total cash flows reflect the entire planned timeframe (36 years) of the investment. We maintained
 565 as terminal value the input used by the Rome Municipality (99 million euros) for all scenarios,
 566 discounted over 35 periods similarly to the last year of cash flows, following the common
 567 practice in DCF valuation [81].

568 **Table 3.** DCF valuation accepted by the Rome Municipality and the consequent no-go
 569 investment decision. Source: [80]
 570

Years after initial investment (2008)	Year 0	Year 8	Year 9	Year 10	Year 11	Year 12	Year 13	Year 14	Year 15	Year 16	Year 17	Year 18	Year 19	Year 20	Years 21-35 2029-2043	Year 36 2044	Year 37 RESIDUAL VALUE 2045
Actual calendar year		2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028			
Annual expected FCF		136.0	136.0	136.0	136.0	136.0	136.0	136.0	136.0	136.0	136.0	136.0	136.0	136.0		136.0	99
Incremental operating annual costs (€ millions)		-10.1	-10.1	-10.1	-10.1	-10.1	-10.1	-10.1	-10.1	-10.1	-10.1	-10.1	-10.1	-10.1		-10.1	
Negative externalities (extra time spent on TPL - € millions)		-2.1	-2.1	-2.1	-2.1	-2.1	-2.1	-2.1	-2.1	-2.1	-2.1	-2.1	-2.1	-2.1		-2.1	
TOTAL annual positive intake		123.8	123.8	123.8	123.8	123.8	123.8	123.8	123.8	123.8	123.8	123.8	123.8	123.8		123.8	99
Discount factor (Year 2008 = 0)		0.7	0.6	0.6	0.6	0.6	0.5	0.5	0.5	0.5	0.4	0.4	0.4	0.4		0.2	0
NPV of annual FCFs	-	83.8	79.8	76.0	72.4	69.0	65.7	62.5	59.6	56.7	54.0	51.5	49.0	46.7		21.4	17
Total DFCF	1587	-237															
Total capital investment (stage 1 + stage 2)																	

571
572

573 After the base case was chosen, the best and worst cases were obtained by varying the main
 574 inputs according to the expected volatility estimated by a feasibility study performed by the
 575 Rome Municipality prior to completing the investment's performance evaluation. Then, the
 576 payoff model was seamlessly used to calculate the value of the option to invest in Phase 1 (urban

² Please note that for conciseness, we do not report values from year 25 to year 31 after the beginning of the project.

577 development prior to the construction of the project infrastructure) of Line C extension. Table 4
 578 reports the main inputs used in the payoff model to calculate the real option value of the project.

579 **Table 4.** DCF of the 3 scenarios (worst, base and best) included in the real option valuation and
 580 calculation of the payoff value of the option to expand.

581
 582

Years after initial investment (2008)	Year 0	Year 8	Year 9	Year 10	Year 11	Year 12	Years 21-35	Year 36	Year 37 RESIDUAL VALUE
Actual calendar year		2016	2017	2018	2019	2020	2029- 2043	2044	2045
Annual Cash Flows: WORST CASE SCENARIO		54	54	54	54	54		54	99
Incremental operating annual costs (€ millions)		-10	-10	-10	-10	-10		-10	
Negative externalities (extra time spent on TPL - € millions)		-2	-2	-2	-2	-2		-2	
TOTAL annual positive intake		42	42	42	42	42		42	99
Discount factor (Year 2008 = 0)		0.7	0.6	0.6	0.6	0.6		0.2	0.2
Discounted Annual Cash Flows		29	27	26	25	24		7	17
Total Discounted Cash Flows	471.53								
Annual Cash Flows: BASE CASE SCENARIO		136	136	136	136	136		136	99
Incremental operating annual costs (€ millions)		-10	-10	-10	-10	-10		-10	
Negative externalities (extra time spent on TPL - € millions)		-2	-2	-2	-2	-2		-2	
TOTAL annual positive intake		124	124	124	124	124		124	99
Discount factor (Year 2008 = 0)		0.7	0.6	0.6	0.6	0.6		0.2	0.2
Discounted Annual Cash Flows		84	80	76	72	69		21	17
Total Discounted Cash Flows	1349.59								
Annual Cash Flow: BEST CASE SCENARIO		680	680	680	680	680		680	99
Incremental operating annual costs (€ millions)		-10	-10	-10	-10	-10		-10	
Negative externalities (extra time spent on TPL - € millions)		-2	-2	-2	-2	-2		-2	
TOTAL annual positive intake		668	668	668	668	668		668	99
Discount factor (Year 2008 = 0)		0.7	0.6	0.6	0.6	0.6		0.2	0.2
Discounted Annual Cash Flows		452	430	410	390	372		115	17
Total Discounted Cash Flows	7202.64								
Possibilistic value of Total Discounted Cash Flows	2178.8								
Less initial capital investment	-825.17								
= DISCOUNTED FREE CASH FLOWS	1353.63								
Less option price	-761.71								
= Real Option value	591.92								

583

584 As shown in a visual representation of the real option value of Phase 1 of the Rome metro's Line
 585 C extension, the possible cumulative DCF over a period of 28 years (€2,178,8 million) less the

586 capital investment required for Phase 2 (construction) of €-825.17 gives a possibilistic NPV of
587 Phase 1 of €1,353.63 million. Therefore, the possibilistic NPV-OPTION PRICE (the Phase 1
588 urban development cost of €761.71 million) implies a positive real option value (ROV) of
589 €591.92 million. The ROV embedded in the investment decision at the end of Phase 1 of the
590 planning and zoning of the Rome Line C extension is thus large and positive (€591,92 million),
591 contrary to a negative expected value of the investment (€ - 237,34) derived from a deterministic
592 DCF approach; hence, the investment should not be turned down since it could possibly
593 contribute to the economic development of the city of Rome.

594 Based on this evidence, in 2007 the Municipality of Rome should have committed €761.71
595 million to begin the extension of the metro's Line C (Phase 1 development). Not only should the
596 positive value per se of the real option embedded in the incremental capital investment have
597 convinced the management to go ahead with the investment project – but also the public
598 managers should have recognized that the outcomes were based on inputs with truly
599 unpredictable variability. Any new information about the benefits of the project can change the
600 set of assumptions underlying the DCF at any moment. This aspect is essentially related to the
601 undiversifiable risk that drives the returns on major infrastructure and transportation projects.

602 However, using the payoff model, public managers can set the upper and lower limits of the
603 estimates based on the current acceptable range of uncertain values. This 'space' determines a
604 possibilistic value of the real option including all possible values within the minimum/maximum
605 range chosen to define the scenarios. The main factor that should lead to a 'go' decision is the
606 confidence to connect managers' inputs (the DCFs of the alternative scenarios) with 'possible'
607 mean returns with a distribution that can be visualized in the shape of a simple triangle. The
608 intuitive representation of uncertainty about future returns obtained with the payoff model allows

609 the management to confidentially reason about the key drivers of value embedded in the DCF,
610 i.e., the benefits of the transportation infrastructure, and to blend their mutually exclusive
611 patterns of evolution (in the different scenarios) into a coherent and comprehensive measure of
612 value: the real option.

613 The approach combining scenarios and real options illustrated in this paper established a direct
614 and immediate connection between the main categories of benefits used by Roma Metropolitana
615 (i.e., benefits to users) and the four possible scenarios leading to the option value of the Rome
616 metro's Line C extension at the time of the investment decision (the beginning of Phase 1).

617 In the case of the Rome metro's Line C, the ROV calculated with the payoff model is large and
618 positive (€591.92); hence, the Municipality of Rome should have invested in the urban
619 development project (Phase 1); in doing so, it would have bought the option to proceed with the
620 construction of the new northwest line extension later (Phase 2). By investing in the first phase
621 of the project, the Municipality of Rome would have acquired the right but not the obligation to
622 eventually build the new Line C route by postponing the timing of the actual irreversible capital
623 investment necessary to construct the new infrastructure (Phase 2). Once the option to expand
624 had been purchased and the urban development had been completed, Roma Metropolitana, acting
625 on behalf of the Municipality of Rome, could periodically reassess the estimated values of the
626 indirect benefits; therefore, the city would have time to decide whether to proceed in building the
627 new Line C route. The extension would occur only if the benefits to the direct users were
628 positive.

629

630 *D. Line C extension: comparing the outcomes of the combined scenarios/RO approach with*
631 *those of the traditional DCF approach*

632 In 2007, the leading policymakers of the Municipality of Rome and the project decision-
633 makers of Roma Metropolitane based their understanding of the outcomes of Line C extension
634 on the traditional DCF approach, calculating the NPV in the beginning of Phase 1 [80].
635 Overall, the result obtained through the DCF model differed significantly from that of the payoff
636 model (as applied in the previous section of the paper). While the NPV was negative (-€237.34
637 million), leading to the decision to reject the investment in the extension of Line C, the real
638 option value (as determined in the previous section) was large and positive, and it should have
639 led to the opposite decision to carry out the investment instead.

640 This comparison thus clearly indicates the benefits of our innovative methodological approach
641 and, more generally, of the possibilistic – as opposed to probabilistic – expected value of a given
642 investment project. More precisely, the combination of scenarios and real options helps
643 policymakers capture new information about relevant changes in the economic landscape
644 surrounding a major infrastructure project as long as such information becomes available,
645 whereas the NPV approach ignores the benefits related to the ability to delay (or stop)
646 irreversible investment decisions. Therefore, a relevant difference is how the combined use of
647 real options and scenarios enables a systematic approach to transportation infrastructure project
648 evaluation that encompasses a broad range of benefits to different categories of stakeholders.

649 While our method identified four different scenarios arising at the end of the first phase of the
650 project, the DCF approach ignored the existence of different phases and treated the project as a
651 single irreversible scenario from the very beginning of the project. Such determinism inevitably
652 led to an underestimation of the overall benefits of the proposed Line C extension and,
653 ultimately, of its long-term value. Consequently, as of 2021, construction of Line C underground

654 remains to be completed, and the delay in the development of the main route of Line C
 655 contributed to a dismissal of the Line C extension.

656

657 **V. DISCUSSION**

658 In this paper, we design and apply a new methodological approach aimed at helping
 659 project decision-makers cope with the uncertainty of transportation infrastructure projects by
 660 enhancing their ability to assess the value of long-term effects (costs and benefits) of such
 661 projects. Specifically, the innovative approach that we illustrate in this paper is designed to allow
 662 project decision-makers to (1) develop a shared understanding of the potential benefits of major
 663 investment projects in transportation infrastructure, (2) select projects that are most likely to
 664 contribute to economic growth and focus their resources on such projects, and (3) reduce the
 665 financial risks inherent in major investment projects by regarding such projects as consisting of
 666 different steps, each entailing the right but not the obligation to proceed forward to the next step.
 667 Overall, the methodological approach we propose in this paper helps project decision-makers
 668 and policymakers facing tightening budget constraints optimize their long-term investment plans
 669 [7] [35] [37].

670 Table 5 summarizes the main advantages of our innovative methodological approach by
 671 comparing it with the techniques of scenarios and real options used separately to manage
 672 transportation projects.

673 **Table 5.** Comparison of our combined methodological approach to using scenarios and real
 674 options with (the limitations of) each individual technique
 675

Limitations of scenarios and real options (when used separately)	Advantages (integrated use of scenarios with real options)	Source of benefits
---	---	---------------------------

Difficulty of valuing options on real assets (real options: [66])	The payoff model does not require managers to evaluate the volatility of the future benefits and costs of the transportation infrastructure (contrary to the case of established methods such as Black-Scholes)	Payoff model
Timing of exercise (real options: [66])	The 2x2 scenario matrix combined with the payoff model allows project decision-makers to obtain a flexible analytical framework for deciding when to proceed with the next phase of development of the transportation infrastructure	2x2 scenario matrix combined with the payoff model
Loose links to the external environment of the project infrastructure (real options: [24])	The 2x2 scenario matrix provides a clear narrative about future costs and revenues (benefits). Based on these dynamics, project decision-makers can clearly link real options analysis with the likely evolution of the transportation infrastructure	Scenarios: qualitative approach/data
Unrealistic assumptions about managerial skills (real options: [16])	The payoff model requires relatively simple statistical and mathematical skills	Payoff model
Biases (scenarios: [24])	Quantitative data provide a more objective basis for identifying the long-term value of transportation projects	Real options: quantitative approach/data
Lack of quantitative data (scenarios: [17])	Real options provide quantitative data that enable managers to turn the narrative of scenarios into the financial effects of external changes and new events affecting the future evolution of a transportation project	Real options: quantitative approach/data
Lack of consistency (scenarios: [24])	Quantitative data helps check the internal consistency of each scenario (e.g., by comparing the value of the same driver of change in the four alternative scenarios related to the long-term evolution of the project)	Real options: quantitative approach/data

676

677 The integration of scenarios and real options approaches might offer a viable solution for
678 minimizing project decision-makers’ bias by directing their attention toward the most beneficial
679 projects. The methodological approach discussed in this paper requires the explicit disclosure of
680 the choice and value of key project’s drivers used to inform the three scenarios. By doing so, the
681 assessment of competing investment decisions becomes necessarily more transparent and
682 reduces potential bias in project planning and approval (e.g. [2] [3]). Using this approach,

683 managers can explore the long-term patterns of evolution of the effects of alternative
684 transportation infrastructure projects and convert different future scenarios into clear cash flow
685 projections in a systematic yet relatively simple way by supporting strategic discourse and a real
686 option reasoning approach (e.g., [63] [66] [78]). In particular, the main contribution of real
687 options is highlighting how transportation infrastructure projects can evolve over time and
688 providing an opportunity to obtain and process new information that creates value for users. The
689 application of real options – especially the payoff model combined with scenarios – has the
690 potential to offer a more disciplined decision-making process than the traditional DCF approach
691 for not only the evaluation of transportation projects but also their timing. The NPV logic is
692 biased in favor of the early investment commitment because it considers only the risk of waiting
693 (preemption of scarce assets) without recognizing the advantages of waiting (a reduction of
694 uncertainty). In the case of Line C extension, taking into account the possibility of modifying
695 (i.e., postponing) major investment decisions based on the new information that becomes
696 available over time might allow the managers of Roma Metropolitane to reconsider the choice to
697 invest in Phase 1 (planning and zoning) and thereby to acquire the right – but not the obligation –
698 to proceed with Phase 2 (construction) later.

699 The combined use of scenarios and real options can also help prevent the occurrence of cases in
700 which uncertainty stops or causes the denial of approval of projects that in fact have the potential
701 to create long-term value for users [82]. As a result, we hope that our research will ignite the
702 debate over the costs and benefits of transportation infrastructure investments in relation to the
703 nature, size and timing of such costs and benefits [28] [29] [30] [31]. The combined use of real
704 options and scenarios can help improve the transparency and collegiality of decision-making
705 processes of different project stakeholders by preventing the dominant players and personal

706 interests from prevailing and by fostering a dialog among different institutional players,
707 especially direct users [83]. On the one hand, our innovative methodological approach to
708 assessing the long-term benefits of transportation infrastructure builds upon the previous work of
709 Favato and Vecchiato [25], who initially explored the topic of combining the payoff model of
710 real options and the deductive logic of scenarios. However, the above study was focused on the
711 specific case of a biotech company in which the identification of the key variables for the axes of
712 the scenarios was straightforward and idiosyncratic. In the biotech industry, the long-term profits
713 of a new drug depend on its efficacy and safety compared with those of the main drug that is
714 currently the dominant product (or standard of care). The variables of efficacy and safety were
715 thus used as the main axes of the scenarios [25]. In addition, the above study focused on the
716 idiosyncratic phases related to the development of new drugs (i.e., preclinical testing, studies
717 involving patients to estimate efficacy, and clinical studies entailing a comparison to the current
718 best-available treatment).

719 Despite sharing the same roots of the payoff model and the deductive logic of scenarios, this
720 paper develops a different approach that is unique to the specific case of transportation
721 infrastructure. First, it considers the idiosyncratic phases (i.e., the planning and zoning phase, the
722 construction phase and the post-construction phase) of such investment projects. Second, and
723 more importantly, it focuses on the assessment of the long-term value of the costs and benefits of
724 infrastructure projects by leading to a more accurate and comprehensive estimate of such costs
725 and benefits.

726 The application of our methodology to the case of the northwest extension of Line C of the
727 Rome underground also revealed several limitations of this methodology. First, it is important to
728 recognize that the quantification of future benefits of transportation infrastructure projects still

729 depends on the knowledge of experts involved in the preliminary analysis of such benefits. In
730 other words, our methodology is meant to assist project decision-makers in exploring the data on
731 benefits and assessing their future value; the identification of such benefits (e.g., their nature and
732 likely size) is a fundamental prerequisite for the effective use of real options and scenarios
733 themselves.

734 Second, a critical issue in the application of our methodological approach entails the conversion
735 of the intermediate scenarios of the 2x2 scenario matrix (i.e., scenarios ‘+;-’ and ‘-;+’) of Figure
736 3 into the base scenario for the payoff model. In the proposed example, we identified the base-
737 case scenario on the basis of the main estimates proposed by Rome Metropolitane itself in
738 calculating the NPV of the project. In the absence of a framework for deriving the base-case
739 scenario or assessing the relative probabilities of the intermediate scenarios of the 2x2 scenario
740 matrix, policymakers can assign the same likelihood (i.e., 50%) to the intermediate scenarios
741 themselves and then determine the base-case scenario of the payoff triangle as a simple average
742 of the two. However, this simplified approach might lead to an inaccurate – albeit slightly so –
743 estimate of the value of the real option.

744 Third, the Line C extension was a relatively easy project. For the sake of simplicity, we also
745 applied our integrated scenarios and real options approach to the first and second phases of the
746 Line C extension, thereby ignoring the costs and benefits related to the service and maintenance
747 of the infrastructure constructs (Phase 3: see [75]). Furthermore, for our illustrative case to be
748 consistent with the available data, we based the application of our method on the same costs and
749 benefits used by Roma Metropolitane in 2007 to calculate the NPV of this project. On the one
750 hand, we might thus have overlooked the impact of some other costs and benefits which are
751 recognized in the extant literature on transport projects (e.g., benefits due to reduced pollution or

752 an increase in real estate value) [35]. On the other hand, the flexibility of the scenario planning
753 approach allows us to seamlessly increase the number of costs and benefits of transportation
754 projects that are taken into account by our proposed method.

755 Finally, it is worth mentioning that our methodological approach has never been used (ex-ante)
756 on infrastructure projects, and no data was empirically collected on the feelings and beliefs of
757 decisionmakers on its applicability.

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759

VI. CONCLUSIONS

760 The aim of this paper is to contribute to the planning and project studies literature by
761 exploring how the integrated use of scenarios and real options might support investments under
762 uncertainty, by allowing project decision makers to better select the new transportation projects
763 in which they should spend their limited budget resources (e.g., [26] [27]). Our paper fills a
764 practical gap in relation to the embedding of real options in scenario planning as well as a
765 theoretical gap.

766 So far, scenarios and real options have generally developed as separate approaches to uncertainty
767 management, with these methods having different theoretical premises and nature (i.e.,
768 scenarios: qualitative approach based on expert's and managers' opinions; real options:
769 quantitative approach based on the collection and use of formalized data) and different
770 objectives (scenarios: fostering a strategic conversation process which allows decision makers to
771 adapt their mental models; real options: improve the accuracy of the calculation of future
772 investment outcome). Our paper contributes to the extant literature by discussing how the
773 combined use of scenarios and real options help advance each individual technique, by
774 complementing their different (qualitative vs. quantitative) premises and objectives.

775 The outputs of scenarios and real options have been found to be more reliable and effective when
776 these techniques are integrated, as the weaknesses of one technique turns to be the strength of the
777 other [16] [17] [24] [25].

778 Our work has some clear limitations, including its retrospective use in past projects rather the ex-
779 ante application in future ones. However, we hope that, despite these limitations, future research
780 efforts might improve the accuracy and reliability of our framework by applying it to different
781 types of infrastructure projects. More generally, we hope that our work might spur the
782 investigation of innovative approaches which move away from traditional (static rather than
783 dynamic) DCF-based methods of project evaluation, by driving project studies research toward
784 new opportunities and challenges [40] [41].

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