ASCE Journal of Management in Engineering

Flexible Infrastructure Design: A Real Options Reasoning Approach to Navigating Uncertainty in Large-Scale Projects

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DOI: 10.1061/JMENEA/MEENG-5678

Abstract – This study addresses the imperative of enhancing design flexibility in large-scale infrastructure projects to effectively navigate emerging uncertainties. Current appraisal methods often prioritize risk mitigation over uncertainty management, which hinders the implementation of flexible designs. Instead, this research explores the integration of design flexibility through real options reasoning (ROR) to create flexible infrastructures. As a result, a conceptual framework is proposed that draws from contemporary industrial practices such as modularization and project safeguards. Modularization, grounded in the alignment of functions and components, bolsters flexibility. Project safeguards, operationalized as passive or active measures, embed options in project outcomes. A proposed method emerges that synthesizes real options, modularization, and project safeguards into four guiding steps and nine helpful heuristics. These steps, enriched by heuristics, offer a structured approach to grasp, strategize, and implement design flexibility, transforming it from theory to impactful project management. Case-based and numerical validation was conducted to validate the proposed method. The proposed approach is illustrated through a case study of Heathrow Airport's £14 billion expansion. The research implications include the exploration of improved appraisal methods for large infrastructure projects, the advancement of ROR and application of heuristics in engineering management, and additional investigation into the integration of modularization and safeguards to enhance design flexibility in uncertain environments.

Practical application – This study presents a new methodological approach that offers a structured framework for effectively communicating the advantages of design flexibility in managing uncertainty during the appraisal process of large-scale infrastructure projects. The approach empowers project leaders tackle uncertainties intrinsic to large-scale projects. It fosters design flexibility's benefits, guides project selection aligned with growth goals, and manages uncertainties by conceptualizing projects as sequenced steps. This method comprises four sequential steps, each pivotal for enhancing design flexibility. It begins by translating strategic needs into tangible options, enhancing adaptive decision-making. The subsequent step involves selecting optimal product types and modularization options to fortify flexibility. Operationalizing risk, modularization, and safeguards in the third step cements flexibility into project architecture. The final step involves cost-benefit analysis, aiding informed investment decisions. These steps, enriched by simple heuristics, offer a structured approach to grasp, strategize, and implement design flexibility, transforming it to impactful project management. Ultimately, this approach guides projects towards a more adaptive future. The proposed approach is ideal for intuitive executive decision-making through practical shortcuts, particularly when analytical modeling faces limitations.

KEYWORDS: Design flexibility; Real options reasoning; Heuristics; Project appraisal; Modularity; Safeguards

1 Introduction

Infrastructure asset owners must prioritize flexibility to navigate future environmental uncertainties (de Neufville and Scholtes 2011). For example, unexpected changes render technological systems, like airport terminals, swiftly obsolete due to unanticipated uncertainties. To counter this, designing modular airport terminals with adaptable waiting areas may enable adjustments for varying passenger flows and transportation modes. The Institute for Building Sciences estimates that investing a dollar in infrastructure flexibility yields six dollars in future savings, encompassing economic disruptions, property damage, public health crises, and extreme weather-related fatalities (National Institute of Building Sciences 2019).

Recent studies scrutinize conventional investment appraisal approaches such as Reference Class Forecasting (CRF), Net Present Value (NPV), Return on Investment (ROI), and Discounted Cash Flow (DCF) which primarily address anticipated risks rather than uncertainties (Di Maddaloni et al. 2022; Hoseini et al. 2020; Love et al. 2022a). The challenge lies in managing risk events with known probabilities and uncertainty events with unpredictable probabilities (Love et al. 2022a; Ramasesh and Browning 2014). While existing approaches focus on risk factors, they overlook uncertainty-related fluctuations in cost materials, design changes, and financial issues.

Design flexibility, however, encompasses both risks and uncertainties, mitigating losses, enhancing gains, and fostering resilient systems. It involves adapting systems to a range of potential uncertainties and risks (Habraken 2008; Saleh et al. 2009). The absence of design flexibility during the infrastructure planning phases often undermines its utility, value, and performance over time (Gil et al. 2015; Krystallis et al. 2022). Emerging developments in design flexibility have sparked renewed interest in modularization (Bertram et al. 2019; Thai et al. 2020). Modularization enhances construction industry efficiency, safety, and sustainability (Abdul Nabi and El-adaway 2020; Choi et al. 2020; Kluck and Choi 2023). Importantly, modularization's potential to enhance flexibility and manage uncertainty in large infrastructures is underexplored (Efatmaneshnik et al. 2020; Krystallis et al. 2015).

However, championing modularization and flexibility in large-scale projects poses challenges. Firstly, limited practitioner familiarity, resistance to depart from traditional methods, and perceived costs, hinder modularization adoption (Choi et al. 2019; Ghannad and Lee 2022; Paliwal et al. 2021). Secondly, conventional appraisal approaches prioritize risk mitigation and capital cost control, neglecting uncertainty management, thereby constraining design flexibility (Gil and Tether 2011; Swanson and Sakhrani 2020). These considerations guide the study's practical motivation: "How can design flexibility of large-scale projects be enhanced for future uncertainties?"

To address this question, Real Options Reasoning (ROR) is employed as a framework, leveraging logic and heuristics to present real options as an executive decision-making approach (McGrath 1997). ROR's suitability stems from its encouragement of proactive, flexible investment management based on contingent circumstances (Trigeorgis and Reuer 2017). ROR is qualitative, employs heuristics and focuses on the strategic aspect of decisions. Heuristics are specific guidelines or rules that provide a simplified way to make certain types of decisions within the larger framework of ROR (McGrath et al. 2004). Managers’ heuristics may be deficient, yet their patterns of strategic decisions may crudely approximate decisions informed by formal real option valuation approaches (McDonald 2000). Heuristics play an important role in ROR for several reasons: They simplify the decision-making process by offering practical guidelines or rules of thumb; enable faster decision-making; are flexible and adaptable to various situations; provide a common language for discussing real options; bridge the gap between theory and practice; can be refined and improved over time based on real-world feedback and experience (see also (Love et al. 2022a; b) for heuristics application in engineering management).

This study provides both methodological and theoretical contributions. Methodologically, it introduces an innovative approach grounded in modularization and project safeguards. Modularization, fostering a one-to-one function-component relationship, bolsters flexibility (Efatmaneshnik et al. 2020), while project safeguards integrate real options within project outputs (Gil 2007, 2009). These safeguards are either passive (design-oriented) or active (involving design and execution).

The research implications are threefold: firstly, a need to enhance existing appraisal approaches to encompass uncertainty alongside known risks in large infrastructure projects; secondly, a call for further development of Real Options theory to provide more structured and mature methodologies for decision-makers in construction contexts; and thirdly, an exploration of strategies to overcome industry challenges and promote the adoption of modularization and safeguards, enabling greater flexibility in infrastructure design and execution. The paper introduces its background and rationale before outlining the conceptual framework in Section 3. Section 4 illustrates the approach's effectiveness through the Heathrow Airport case. Section 5 discusses theoretical and managerial implications, with Section 6 offering conclusions and suggesting future research directions.

2 Background

2.1 Uncertainty and Design Flexibility

Design flexibility addresses limitations in human foresight recognizing the unpredictable nature of the future (de Neufville and Scholtes 2011). To effectively navigate this uncertainty, infrastructure must be designed to accommodate a range of potential scenarios.

Additionally, the "flaw of averages" fallacy, assuming average conditions for project performance, must be resisted (Taleb 2007). While conventional investment appraisal approaches handle anticipated risks well, they struggle with uncertainty (Love et al. 2022a). Changing requirements further complicate matters, especially in large-scale projects where the scale and complexity can render requirements unreliable and subject to change (Krystallis and Locatelli 2022; Seo et al. 2021).

Design flexibility is pivotal to handling uncertainty and adapting to evolving needs, uses, and capacities (Cardin 2014; de Neufville and Scholtes 2011). Its value stems from recognizing that investing in provisions that may not yield benefits due to unforeseen future scenarios is a risk (Gil and Beckman 2009). By enhancing a project's ability to change, design flexibility helps large infrastructure avoid future risks and seize opportunities (Gil et al. 2015; Jalali Sohi et al. 2021). This approach ensures that the project remains inherently flexible to accommodate change. For example the NATS case in the UK implemented a flexible architecture of the control tower (Gil and Tether 2011) and flexible contracts proved to be effective in the success of public-private partnerships in India (Delhi and Mahalingam 2020).

2.2 Insights from Real Options Theory in Capital Projects

Built-in options derive from Real Options theory, positing that the benefit of flexibility must outweigh the associated costs (Trigeorgis and Reuer 2017). Central to this theory is the concept of an option, granting the right but not obligation to take specific future actions at a specified cost. Real options theory comprises two approaches: Real Options Valuation (ROV) and Real Options Reasoning (ROR). While ROV employs formal analytical models to value options, ROR relies on verbal theorizing without analytical modeling. ROR is particularly applicable when key drivers of real options can be conceptually identified and synthesized (McGrath 1997).

ROR employs heuristics, representing real options as a way of thinking for executives, offering an intuitive and logical tool for maintaining options or exploiting them (Trigeorgis and Reuer 2017). While ROR is adopted informally by decision-makers to negotiate flexibility value, it lacks the formalization seen in ROV, and its application in construction is less mature (Gil et al. 2015; Krystallis et al. 2022).

2.3 Enhancing Design Flexibility with Modularization

Recent studies have demonstrated that design flexibility can be empowered through ROR and strategies like modularization, overengineered systems, and repeatable systems (Krystallis et al. 2022). These strategies enhance an infrastructure's ability to manage uncertainty. Modularization marks a shift toward industrialized construction, promoting controlled manufacturing and assembly of building components (Kluck and Choi 2023). Modularization literature is rich and provides insights on modularization strategies (Pan and Hon 2020; Pan and Zhang 2023), internal competencies (Lessing and Brege 2018), firm's choice to use external competencies (Zhou et al. 2023), and interfaces between modules and site-based work (Pan et al. 2023).

Limited research has explored its potential to enhance flexibility in large-scale infrastructure (Efatmaneshnik et al. 2020). Despite the benefits, industry reluctance to adopt modularization and design flexibility persists due to challenges such as unskilled labor, inadequate training, errors, and lack of coordination (Assaad et al. 2022, 2023; Choi et al. 2019) or logistical issues and unsynchronized information accuracy on construction sites (Wu et al. 2022).

2.4 Research gap

One significant research gap pertains to the limited familiarity among practitioners with modularization and flexibility concepts in large-scale projects. There seems to be a resistance to depart from traditional project management methods. This research gap implies that there is room for exploring strategies to increase awareness and understanding of the benefits of modularization and flexibility within the industry. Modularization is a promising strategy with transformative potential for the construction sector. Yet, the role of modularization in infusing flexibility into large-scale infrastructure, promoting easier maintenance and robust coping strategies against uncertainty, remains understudied. Despite recognizing their potential, the implementation of modularization and design flexibility is often perceived as costly, lacking clear returns.

The second research gap is the neglect of uncertainty management in conventional appraisal approaches for large-scale projects. Many existing project management methods prioritize risk mitigation and capital cost control but may not adequately address uncertainty, particularly in the context of design flexibility. In addressing these two points, there is room for developing and validating new approaches or frameworks that specifically incorporate uncertainty management, aligning with the principles of ROR and modularization. To address these concerns, a proposed framework is outlined next.

3 Conceptual Framework Development

Building on Gil (2009), this study introduces a novel methodological approach (Figure 1) that draws upon robust theoretical insights from the engineering management literature. The epistemological stance of this study follows a positivist paradigm to formulate a prescriptive model, aligning with the methodological orientations typically embraced by the engineering and scientific management communities (Svejvig 2021). The deductive framework comprises four distinct steps and nine heuristics, synthesized from the integration of previously fragmented aspects of engineering management research. Subsequently, these four steps are explained by outlining the relevant literature that forms the theoretical foundation for developing the nine heuristics. The proposed approach encompasses the following sequential steps:

- Step 1: Interpreting strategic needs of design flexibility into real options
- Step 2: Determining the type of infrastructure products and modularization options
- Step 3: Operationalizing ROR and modularization with safeguards
- Step 4: Estimating the cost of investment with and without design flexibility

Figure 1. Proposed methodological approach

We performed numerical validation to confirm the effectiveness of the proposed method, a comparative analysis was conducted to compare the traditional appraisal method and the proposed one by comparing the cost of investment with and without design flexibility. The advantages of the proposed method over the existing approach were also discussed through subjective assessment in Section 5.1. However, further data collection and analyses are needed to conclusively validate decision makers' perceived sense of the proposed method's results.

3.1 Step 1: Interpreting strategic of design flexibility needs into real options

The approach acknowledges that infrastructure project business cases frequently lack comprehensive and reliable data on the evolution of the infrastructure over 30 to 40 years post-handover (Whyte and Nussbaum 2020). To overcome this, the initial step simplifies the system's complexity. Complex systems present challenges in understanding all variables and their interactions (Andringa et al. 2022). Drawing from complexity literature (Ramasesh and Browning 2014), complexity comprises element and relationship aspects. Reducing these complexities involves conceptualizing the infrastructure as a hierarchical arrangement of interconnected subsystems, known as near-decomposability (Simon 1962). Near-decomposable systems allow encapsulating subsystem specifics into generalized parameters.

In line with design flexibility literature, these subsystems should have embedded options (de Neufville and Scholtes 2011). ROR assists when quantifying operational option values is challenging due to data limitations or organizational constraints (de Neufville and Scholtes 2011; Taleb 2016). However, such options often entail higher upfront costs while offering flexibility that could lead to cost reductions during the lifecycle of the infrastructure (Krystallis et al. 2022). ROR covers choices like expansion, deferral, switching, or abandonment (Table 1), forming the basis for the first heuristic.

Table 1. Option types considered in this study

Heuristic 1: Reduce complexity by subdividing the project into interrelated yet distinct near-decomposable subsystems. Each of these near-decomposable subsystems will possess its unique set of real options. Consequently, both element and relationship complexities are mitigated, making them more manageable, enabling us to concentrate on the collective interactions of the subsystems.

Next, project teams must consider environmental uncertainties surrounding near-decomposable subsystems. Uncertainties may fall into known unknowns and unknown unknowns (Ramasesh and Browning 2014). Known unknowns are managed conventionally, while unknown unknowns divide into unknowable and knowable unknowns (Ramasesh and

Browning 2014). Unknowable unknowns are unpredictable rare events (e.g., tsunamis). Knowable unknowns, foreseen by decision-makers but unaccounted due to cognitive barriers, are addressed here (De Meyer et al. 2002; Taleb 2016). The paper’s approach deals with this latter category. When evaluating flexibility in infrastructure projects, there are several factors and features to consider (Miller and Waller 2003): General Environmental Uncertainties: These encompass elements in the business environment, such as government policies, economic conditions, and societal trends, which have the potential to impact all projects in a specific location. Industry-Level Uncertainties are related to factors that affect the structure of the industry. This includes unpredictabilities concerning buyers, suppliers, and current or potential competitors. Firm-Specific Uncertainties are uncertainties that are unique to a particular company or organization. They involve aspects like internal operations, research and development, financing, and the behaviors of the company's management and employees (see Figure 1). Incorporating these considerations can help enhance the comprehensiveness of the evaluation and outlined decision-making process. From here, Heuristics 2, 3, and 4 emerge.

Heuristic 2: Assess the owner organization's strategic needs for design flexibility and how the project aims to address them, e.g., by analyzing the project's business case. Identify the statements that are specific to each of the subsystems identified in Heuristic 1. These statements serve as the basis of the study. To evaluate the strategic statement corresponding to each subsystem, assess: (1) the degree of foreseen uncertainty; and (2) the impact of foreseen uncertainty on the infrastructure design.

For (1): identify threats and alternative paths to achieve project outcomes. For example, qualitatively (e.g., high, medium, low), consider the volatility of market trends and the degree of uncertainty for each subsystem. If such market volatilities exist, consider whether and how the project can adapt to them, e.g., in terms of technology or new regulatory regimes.

For (2): Consider the impact of foreseen uncertainties on the infrastructure design of each subsystem as a function of prospective market changes (e.g., by considering shifts in demand and supply). Qualitatively assess the impact for each subsystem in its ability to become more responsive to change.

Heuristic 3: A set of options follows. The options need not be complex; they need to be actionable and have a precise aim. Use the real options typology (switch, alter scale, stage) to test which option might better correspond to each subsystem's foreseen uncertainties identified earlier.

Heuristic 4: Qualitatively assess each option that was derived in Heuristic 3 against the following three criteria: i. The strategic value of the option – ask what valuable functionality is added to the subsystem from exercising the option in the future; ii. The degree of likelihood of exercising the option; iii. The time frame for when the infrastructure owner may exercise the option. The timeframe is usually predicted by the infrastructure owner. Assume that options are perpetual, that is, each option shall stay open throughout the asset's design life. In this early stage, do not yet assess the exercise costs.

3.2 Step 2: Determining the type of infrastructure products and modularization options

This step employs modularization insights to exercise built-in options by swapping or adding modules. Modular systems inherently allow flexible evolution (Baldwin and Clark 2000; Efatmaneshnik et al. 2020). Modular product architectures feature a 1-to-1 mapping of functions to physical components and standard interfaces between them, while integral product architectures lack such flexibility due to complex mappings and tightly coupled interfaces (Ulrich 1995).

Modularization enables adaptive changes to product design without total reconstruction (Efatmaneshnik et al. 2020). However, challenges arise when modularization is seen as costly, potentially increasing as modules multiply (Assaad et al. 2022, 2023; Ethiraj and Levinthal 2004). In such cases, integral products might be necessary, despite their lack of flexibility due to numerous interconnected interfaces (Gil 2007; Ulrich 1995), yielding Heuristic 5.

Heuristic 5: For each option: (1) Identify whether subsystems should be integral or modular and define the functional mapping between them, be it 1-1, 1-many, or many-many. (2) Clarify the implications of the function mapping for each subsystem.

For (1), analyze:

i. Determine which functional elements could be modular from the project's start, such as technologies with limited standalone value but substantial impact when integrated into the infrastructure system.

ii. Identify elements that could be modularized in relation to other subsystems during construction, adhering to 'tight free' principles to allow flexibility.

iii. Recognize elements that should remain integral, constrained by interdependencies that would be uneconomical to break apart, especially when integral architectures are more practical than introducing modularization.

For (2), assess the depth and scope of modularization to be employed by:

i. Setting achievable limits for desired modularization to avoid navigating an excessively vast design space.

ii. Balancing benefits gained against time investments required for testing and integration phases.

3.3 Step 3: Operationalizing ROR and modularization with safeguards

Excessive investment in modularization can lead to sunk costs if unused (Gil and Tether 2011). Alternatively, safeguards can complement modularization by ensuring responsiveness to evolving changes in complex infrastructure (Gil 2007). Without modularization, safeguards like overengineering introduce flexibility to integral architectures (Krystallis et al. 2021). Safeguards operationalize ROR, integrating options into outputs (Gil 2007, 2009), facilitating prompt responses to anticipated or unforeseen changes with minimal disruption. Safeguards can be active or passive. Active safeguards involve design and execution. They suit low uncertainty and modularization, or high modularization to lower option exercise costs (Gil 2007). Passive safeguards involve design only for moderate-high uncertainty and low modularization. They reserve space for potential use, cost-effective compared to no safeguards (Gil 2009; Gil and Beckman 2009). Heuristics 6 and 7 derive from this.

Heuristic 6: For each option, define the foreseen uncertainty (Heuristic 2) and level of modularization (Heuristic 5). Evaluate whether the existing modularization sufficiently aligns with the option's objectives. Integrate safeguards to operationalize real options during design (passive safeguards) or construction (active safeguards). This step aids in identifying suitable safeguards that complement modularization.

Heuristic 7: In scenarios of high uncertainty and low modularization, implement passive safeguards. For cases of low uncertainty and low modularization, choose active safeguards. Employ active safeguards when both uncertainty and modularization are low. If both uncertainty and modularization are high, forgo safeguards.

3.4 Step 4: Estimating the cost of investment with and without design flexibility

Investing in flexibility is challenging due to high costs and large projects need significant capital for built-in options. While evidence supports their long-term value (Cardin et al. 2015; Gil and Tether 2011), financial priorities often clash. Sponsors aim to minimize initial costs (Krystallis et al. 2022). To incentivize flexibility investment, operational revenue gains are vital, resembling 'payment-by-results' (Krystallis et al. 2022). This step of the approach computes costs with and without flexibility and shows that options' cost outweighs potential unprotected costs. This derives Heuristics 8 and 9.

Heuristic 8: Identify the activities and resources required for each safeguard's implementation, treating each safeguard as an independent element whenever possible. Estimate the development costs associated with integrating these safeguards into the development process. For active safeguards, base cost estimates on similar projects that have used the materials or processes required to embed the safeguard. Adjust costs for current inflation rates. For passive safeguards, consider the cost of relevant land. Also, factor in administrative expenses linked to procuring land, especially if the land is outside the project's premises. Evaluate each option with cost-effectiveness in mind. Consider whether, if exercised, the option aligns with the concept of payment-by-results, meaning that the investment needed for flexibility would enhance revenue streams for the asset owner.

Heuristic 9: Calculate the cost of implementing the safeguards, including the additional expenses involved in integrating them into the system. Qualitatively assess the impact of embedding each safeguard (low, medium, high). Estimate the costs associated with exercising built-in options for flexibility without initial safeguard investment. Qualitatively evaluate the impact of exercising these options without safeguards. Determine the safeguarded infrastructure's cost as a percentage of the project's total allocated budget.

Calculate the total cost of modifying the infrastructure with design flexibility in place as a percentage of the project's total allocated budget. Finally, compute the percentage difference between these two values to emphasize the impact of design flexibility on the project.

4 Illustrative Case Study

In this section, the methodological approach is retrospectively applied to the case of Heathrow's airport expansion plans (Department for Transport 2016; Heathrow 2019) to critically evaluate the proposed methodology's main advantages and its implications for the management of large infrastructure projects. The Heathrow case provides a compelling research setting, given the uncertainty in the nature and quantification of the benefits to direct users. The case exemplifies a typical instance of a large-scale infrastructure project characterized by inherent uncertainty (Denicol et al. 2020). Predominantly, we managed to acquire the official project data, which serves as a well-defined foundation for applying our methodological approach. Notably, this project has also sparked controversy, as local communities have raised concerns and questioned its overall value (Robinson 2019).

In contrast, our method shows that the uncertainty of the project can be reduced by framing decisions as real options. Thus, when compared with traditional appraisal approaches, our method demonstrates how ROR may increase the overall value of the project, with minimal costs. Importantly, it demonstrates that modularization and safeguards are far more efficient measures against uncertainty compared to not having them at all and provides policymakers and projects stakeholders measurable results to compare against the original masterplan.

In the case illustrated, the main objective behind the expansion is to alleviate the pressure of the current twin runways operating at 99% capacity since 2012 (not counting for the pandemic). Based on official data, the master plan promises a 75% increase in passenger traffic from the pre-pandemic 80 million passengers per annum (MPPA) to the projected 143 MPPA by 2050 when the project is fully delivered (Department for Transport 2016). Upon careful evaluation, only four out of 10 subsystems would directly contribute to Heathrow's 2050 objective after reviewing the official data of Heathrow's masterplan and supporting documentation: (1) Airfield, (2) Terminals, Satellites and Aprons, (3) Rail and (4) Parking. The expansion involves ten subsystems (Table 2) across four phases (Table 3).

Table 2. Constituent areas of the expansion* (Heuristic 1)

Table 3. Phase breakdown*

4.1 Step 1: Interpreting strategic needs for design flexibility into real options

As Heathrow anticipates launching a mammoth £14 billion expansion, it is vital to embed design flexibility to extend the life and value of the project for as long as possible. In this step, the flexible design evaluation and proposals will take the form of six real options (Appendix 1). All of the proposed options stem from Heathrow Airport Limited (HAL) official statements. Therefore, each option is a tentative solution to HAL’s expression firmly stated in this consultation document.

4.2 Step 2: Determining the type of infrastructure products and modularization options

The 30-year projection for each option was estimated based on the probability of exercise, aligned with Phase 4 of the anticipated expansion delivery. Additionally, the modularization of each option was indicated (Table 4). This identification enables the project team to make informed assessments regarding which infrastructure products should be safeguarded and which ones can remain unaltered (as detailed in the subsequent step).

Table 4. Assessing the modularization of real options (Heuristic 5)

4.3 Step 3: Operationalizing ROR and modularization with safeguards

Next, the real options with the respected subsystems of the expansion were associated. In addition, each option is supported by an appropriate safeguard (Table 5). Together, options and safeguards are directly linked to each of the four expansion subsystems.

Table 5. Delivering real options with safeguards

4.4 Step 4: Estimating the cost of investment with and without design flexibility

Finally, the cost of safeguarding each option was assessed. This cost was juxtaposed with the potential expense the airport might incur if the option were required in the future but had not been safeguarded during the design phase (Table 6). This comparison serves to provide a clear understanding of the cost-saving advantages inherently associated with incorporating safeguarding mechanisms into the infrastructure's design.

Table 6. Cost of investment with and without safeguards

5 Discussion

5.1 Research implications for the appraisal of large infrastructure projects

When compared to traditional appraisal methods such as DCF, ROI, or NPV, the greatest utility of our approach lies in its capacity to assess embedded flexibility when structuring capital investments susceptible to uncertainty (Table 7). For instance, the study delved into six options that could be particularly advantageous for HAL as the expansion progresses through its four-stage implementation. Aligned with Heathrow's preferred masterplan, these options are directly associated with the four distinct sub-systems of the expansion. Within the proposed infrastructure, potential ways in which design requirements could benefit from increased flexibility were identified. Each safeguard and modularization component carries specific objectives aimed at extending the asset's lifespan and maximizing its value. The study challenges the prevailing paradigm of conventional appraisal methods, which assume project outcomes to be static and vulnerable.

While conventional appraisal approaches like DCF, ROI, and NPV are useful in accommodating risks, they often lack the ability to factor in a project's uncertainties through statistical methods (Love et al. 2022a; b). Risks and uncertainties, if uncontrolled, can lead to the rise of claims, conflicts, and disputes during the course of a project (Ahmed and El-Adaway 2023). Instead, this study advocates the importance of planning for uncertainty, enabling large infrastructure assets to adapt to a rapidly changing environment (Krystallis et al. 2016, 2021).

To fulfill these expectations, the study introduces a novel methodological approach to design flexibility, comprising four sequential steps. Each step is executed in sequence and operationalized through a set of practical heuristics, contributing to the vision of "homo-heuristicus" (Love et al. 2022b). Despite a lack of extensive research on the utilization of heuristics to enhance infrastructure project appraisal decision-making, this paper adds to the body of literature aimed at minimizing cost variance under uncertainty, advocating for the incorporation of heuristics in formulating infrastructure project appraisals (Love et al. 2022a; b).

Table 7. Comparison between conventional appraisal approaches and a design flexibility approach

5.2 Research implications for Real Options theory

This study has implications for Real Options theory which has garnered widespread recognition for its departure from probabilistic reasoning and its ability to encompass uncertainty within the realm of large infrastructure projects. Specifically, ROV is acclaimed as a viable solution to mitigate decision-makers' biases, guiding their focus toward the most advantageous projects (de Neufville et al. 2009). In contrast, ROR is still in its nascent stages. ROR demonstrates its highest utility in situations where mapping financial options theory into tangible investment decisions and their valuation, as emphasized in ROV, presents challenges (Trigeorgis and Reuer 2017). ROR finds value in contexts where analytical modeling assistance is limited, allowing decision-makers to formulate and test hypotheses by relying on straightforward heuristics (Gil et al. 2015; Krystallis et al. 2022).

However, ROR operates as a high-level heuristic strategy that guides executives toward satisfactory and adaptable solutions (McGrath et al. 2004). Notably, there currently exists no formal framework based on ROR that enables decision-makers to efficiently undertake design flexibility decisions within capital projects (Gil et al. 2015). The methodological approach presented in this study seeks to address this void by introducing a means for more objective assessments, quantifying uncertain payoffs against the initial costs of flexibility. Moreover, this approach aids organizations and executives in more effectively navigating creativity and ambiguity (Trigeorgis and Reuer 2017), accounting for the diverse spectrum of potential futures that their investments may align with.

While heuristics are valuable for simplifying complex tasks, they are not without their limitations, such as biases, errors, and overgeneralization. Next, we outline how research can overcome the common problems of heuristics:

- Identifying Biases and Cognitive Errors: Research can delve into the cognitive biases that often influence heuristic-based decisions. By studying these biases, such as confirmation bias (McGrath et al. 2004), researchers can raise awareness among decision-makers.
- Providing Empirical Evidence: Research can offer empirical evidence to support or challenge the effectiveness of specific heuristics (Yilmaz et al. 2016). By conducting experiments and analyzing real-world data, researchers can provide insights into when heuristics work well and when they might lead to suboptimal outcomes.
- Combining Heuristics with other Decision Strategies: Research can explore how heuristics can be effectively combined with other decision strategies, such as scenario planning (Miller and Waller 2003). Understanding when to rely on heuristics and when to use complementary methods is essential for better decision-making.

- Feedback Loops: Research can establish feedback loops in decision-making processes. This involves continuously evaluating the outcomes of heuristic-based decisions and adjusting the heuristics as needed (Triantis 2005). By gathering feedback and adapting heuristics over time, organizations can improve their decision-making effectiveness.

5.3 Research implications for modularization and safeguards

By placing modularization at the core of this innovative methodological approach, as exemplified by the Heathrow case, both modularization and safeguards emerge as fundamental elements within a design flexibility framework. As observed in the Heathrow case, five out of the six real options should be actively safeguarded, given their heightened susceptibility to alterations according to Heathrow's criteria. Although implementing safeguards incurs sunk costs, the degree of uncertainty associated with exercising these options remains relatively low. Given these circumstances and considering the prevailing uncertainty, it proves more advantageous for HAL to invest in safeguards at present rather than embarking on a potential future endeavor of reconfiguring the entire structure (Krystallis et al. 2023). This study's contribution extends to the field of modularization literature and the ongoing discourse concerning the costliness of modularization initiatives (Assaad et al. 2022, 2023; Efatmaneshnik et al. 2020). Demonstrating the merits of modularization, when accompanied by project safeguards, this study underscores its appeal to infrastructure owners who undertake strategic, long-term considerations in their investment decisions.

Second, this study posits that modularization and safeguards should act as the forerunners of a project's evolution. Consequently, the value of the infrastructure is no longer solely reliant on the vagaries of time. Instead, through the adoption of modularization and safeguards, change becomes a catalyst for the project's growth. Arguably, the combination of modularization and safeguards has the potential to transform the implications of change for large-scale infrastructure, shifting them from potentially detrimental to potentially adaptive, as depicted in Figure 2.

Figure 2. Project Value Over Time without modularization and safeguards (left) and with modularization and safeguards (right)

In this context, the methodological approach advocated by this study encourages policy-makers, developers, and supply chain embrace greater optionality capabilities, thereby enhancing the operational longevity of projects.

5.4 Managerial implications

The new methodological approach presented in this study offers a structured framework for effectively communicating the advantages of design flexibility using heuristics. Below, several recommendations are put forth:

- The methodological approach outlined in this article retains a degree of subjectivity and relies on the expertise and experience of decision-makers. Crafting flexibility within an infrastructure project is a nuanced task that involves a careful balance between managing the project budget and ensuring the asset's adaptability to uncertain requirements. It emerges as a delicate equilibrium between control (affordability) and flexibility.
- Decision-makers hold the responsibility to champion design flexibility from the project's inception. When the project client emphasizes design flexibility, it sets a precedent for others to follow suit. The supply chain endeavors to meet the client's stipulations; therefore, if flexibility is not explicitly outlined, it is unlikely to receive the necessary attention.

- Traditional assessments and invitations for tenders should integrate criteria to evaluate design flexibility assessments, which should be an integral aspect of the technical solution. For instance, the tender might specify the initial cost of flexibility and the potential advantages of incorporating flexibility into the commercial solution. This clarification serves to highlight the value of flexibility to both parties and enables clients to assess the benefits-to-costs ratio of incorporating flexibility.
- Infrastructure owners and developers should incorporate modular designs into their overall strategies for infrastructure delivery and asset management. This integration should encompass pertinent safeguarding measures, including both passive and active safeguards, to ensure that future infrastructure investments remain adaptable amidst uncertainty.
- The responsibility for selecting and implementing modularization techniques and safeguards within projects lies with the owner. The methodological approach could guide such decisions. Moreover, considering that infrastructure owners often prioritize a cooperative culture more highly than contractors when facilitating modularization (Choi et al. 2020), the methodological approach should encourage such collaboration by engaging both parties (clients and contractors) throughout each step of the approach.

5.5 Limitations

While we focused on Heathrow's case, we believe our findings extend to the wider airport industry and other build environment settings. Future research should compare our insights to other sectors like transportation and process industries, with varying uncertainties and sub-system complexities influencing flexibility strategies. Future research could explore additional possible factors or features that need to be considered as explained in Miller and Waller (2003) on evaluating flexibility with ROR.

This study employed heuristics for its approach, albeit not exhaustively. Given the complexity of large projects, more research is needed for a balanced approach combining control and design flexibility (Gil and Tether 2011) powered by heuristics (Love et al. 2022a; b). Further studies could test and expand our findings, using case studies to explore concepts like ROR, modularization, and safeguards. Additionally, it is important to note that our method was applied retrospectively, and its ex-ante application in future projects remains unexplored, with no data on decision-makers' perspectives.

Despite limitations, this study emphasizes modularization's potential impact on long-term infrastructure performance, however we acknowledge that more research is needed to understand the key risks impacting costs and schedule of modular construction projects (Abdul Nabi and El-Adaway 2021), collaboration requirements (Abdul Nabi et al. 2023) and use of smart contracts to achieve greater flexibility (Chen et al. 2023). Additionally, future research could assess design flexibility and modularization's prolonged effects on service life. For instance, operational readiness influenced by modularization has been studied (Al-Mazrouie et al. 2021). These efforts could extend to operations post-handover. Recent research highlighted modularization's adaptability to situations like pandemics (Pan and Zhang 2022), suggesting valuable insights for emergency management in construction.

6 Conclusion

The study proposes an innovative approach empowering project leaders to tackle uncertainties intrinsic to large-scale projects. The method fosters a shared understanding of design flexibility's benefits, guides project selection aligned with growth goals, and manages uncertainties by conceptualizing projects as sequenced steps. This method comprises four sequential steps, each pivotal for enhancing design flexibility. It begins by translating strategic needs into tangible real options, enhancing adaptive decision-making. The subsequent step involves selecting optimal product types and modularization options to fortify flexibility. Operationalizing risk, modularization, and safeguards in the third step cements flexibility into project architecture. The final step involves cost-benefit analysis, aiding informed investment decisions.

These steps, enriched by heuristics, offer a structured approach to grasp, strategize, and implement design flexibility, transforming it from theory to impactful project management. By intertwining these steps and heuristics, project leaders can tackle future uncertainties while optimizing resources and bolstering long-term investments. The approach, fueled by ROR and heuristics, facilitates intuitive executive decision-making through practical shortcuts, particularly when analytical modeling faces limitations. Ultimately, this approach guides projects towards a more adaptive future.

Acknowledgements

The authors would like to thank the Editor, Associate Editor and two anonymous reviewers for their constructive comments.

Data Availability Statement

All data, models, and code generated or used during the study appear in the submitted article.

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Figure 1. Proposed methodological approach

Figure 2. Project Value Over Time without modularization and safeguards (left) and with modularization and safeguards (right)

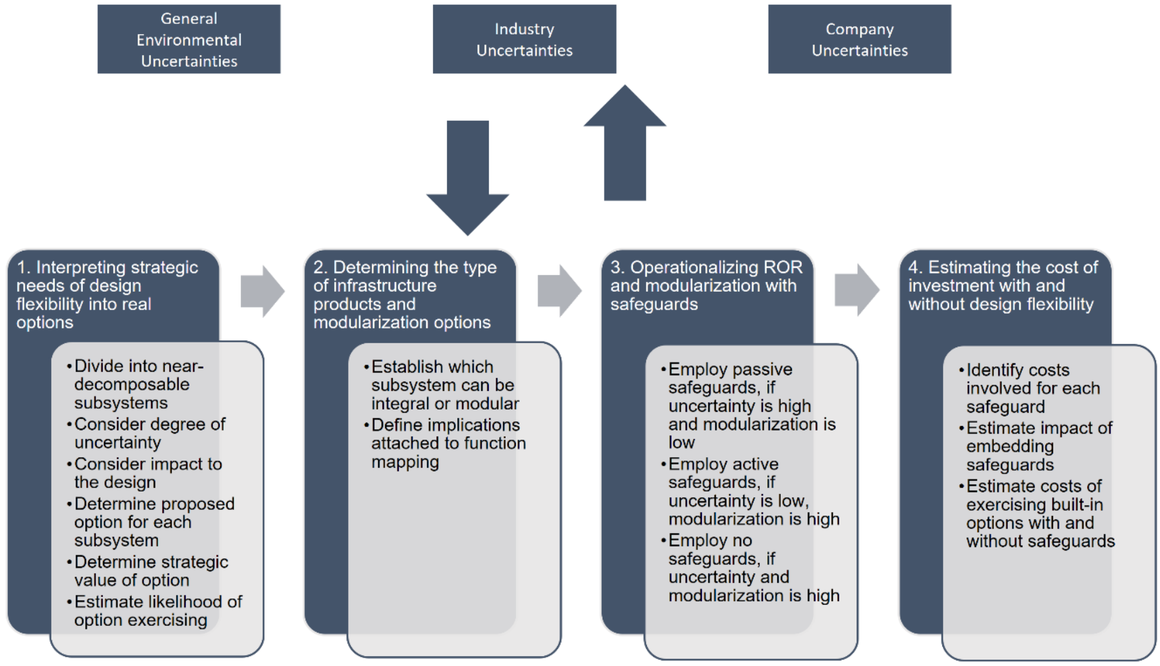

Figure 1. Proposed methodological approach

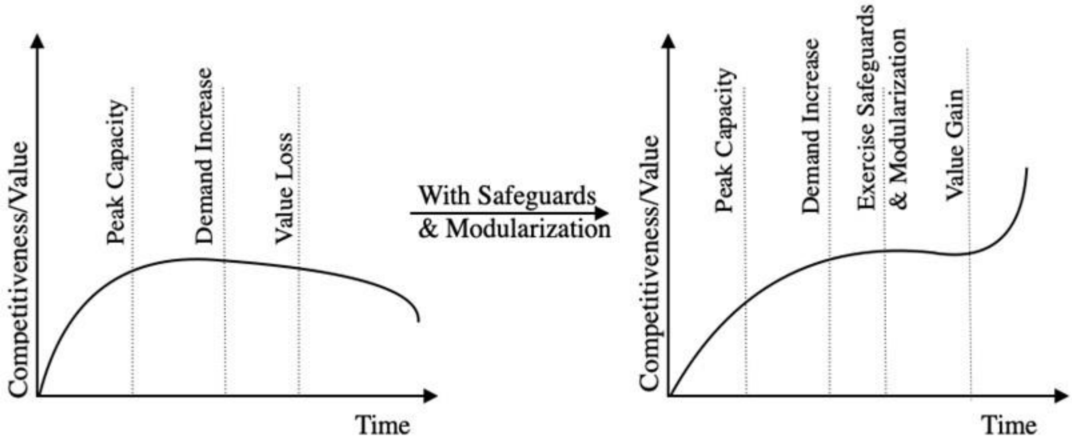

Figure 2. Project Value Over Time without modularization and safeguards (left) and with modularization and safeguards (right)

Table 1. Option types considered in this study

Option type	Description
Grow	Increase capacity in response to future events that will make growth economically justifiable
Stage	Delay or stage proceeding to the next stage, only after reassessing the costs and benefits of completing the previous stage.
Switch	Switch between production processes, functions, or outputs
Alter scale	Expand or contract if the project proves successful/unsuccessful.

Table 2. Constituent areas of the expansion* (Heuristic 1)

Airfield *(i.e. additional runways + taxiways)*	**Airport Supporting Development**
Terminals, Satellites and Aprons *(i.e. new terminal concourse T5X, its Satellite T5XN and corresponding aprons)*	**Parking** *(Only Northern and Southern Multistory Car Park facility)*
Roads and Rail *(Only rail link between T5X and T5XN + Link between T5 and T5XN)*	Displaced Land Uses and Community Facilities
Active travel	Landscape
Water Environment	Utilities

* The bold text marks the scope of this paper.

Table 3. Phase breakdown*

Phase 1 (2026)	Phase 2 (2030)	Phase 3 (2035)	Phase 4 (2050)
• Proposed new runway will be operational • New taxiway bypass from new terminal to Terminal 5 will be operational • Multistory Terminal 4 carpark will be completed	• First phase of terminal 5X satellite will be open (an expansion to the existing Terminal 5) • Southern Parkway will be available	• Terminal 5X satellite will be completed including northern extension. • First phase of Terminal 5XN (adjacent to the new runway) will be operational including additional aircraft stands	• Terminal 5X will be fully delivered • Northern Parkway will be fully built offering a multistory carpark (serving T2). • Additional taxiways will be operational providing access to the new terminals

*This table only contains information that is relevant to the subsystems addressed in this paper (Table 2) and is a direct quote from Heathrow's 2019 Preferred Master Plan (Heathrow, 2019)

Table 4. Assessing the modularization of real options (Heuristic 5)

Option	Subsystems	Modularization of Subsystem	Function Mapping	Implication
Option 1	Tarmac to Airside Terminal access is integrated	Integral	Many to many: Asphalt structure is fully embedded into the aerodrome and other surrounding systems	No changes can be made ex-post.
Option 2	Jet Bridge	Modular from Market	One-to-one: one jet bridge to one jet bridge docking mechanism	Understanding the function mapping can allow the project team utilize the mechanism to its fullest potential. i.e., ability to dock 2 aircraft instead of 1.
	Jet Bridge Mechanism (Docking Pillar)	Modular at Construction		

Option 3	Tarmac to Runaway access and other bypass taxiways	Integral	Many to many: Asphalt structure is fully embedded into the aerodrome and other surrounding systems	No changes can be made ex-post.
Option 4	ULTra Pods	Modular from Market	One to many: One pod will navigate on many guideways and pillars	As each modular pod will travel on all guideways, their construction must be realized as homogeneously as possible.
	Guideways and Supporting pillars	Modular at Construction		
Option 5	Steel Mezzanine	Modular at Construction	One-to-one: parking function to the steel mezzanine plate. As Growth is projected vertically, the integrity of the concrete frame is insignificant.	Allows the project team to build vertically to allow for additional capacity when needed.
	Concrete Frame	Integral		
Option 6	Steel Mezzanine	Modular at Construction	One-to-one: parking function to the steel mezzanine plate. As Growth is projected vertically, the integrity of the concrete frame is insignificant.	Allows the project team to build vertically to allow for additional capacity when needed, i.e. VIP lounge or retail
	Concrete Frame	Integral		

Table 5. Delivering real options with safeguards

	Heuristic 6		**Heuristic 7**	
Subsystem	**Option**	**Assessment**	**Safeguard (Active / Passive)**	**Development effort**
Airfield	**(1)** Equip T5XN ramp to service Code E aircrafts and the apron taxiway to support Code F aircrafts.	Uncertainty: MODERATE Modularization: INTEGRAL/LOW	**Active** - Reinforce the aerodrome to accommodate for the relevant aircraft specificities	Provision ramp with asphalt foundation to withstanding Code E specifications. Provision apron taxiway with concrete foundation to withstand up to Code F specifies aircrafts
	(2) Configure each T5XN gate with Dual jet way system.	Uncertainty: LOW Modularization: MODERATE	**Active** - Source and procure 28 dual jetways (46 jetways total)	Provision apron drive multi door passenger boarding bridge. Structurally equip the bay and the airside facing terminal gate to host such jetways.
	(3) Design new airfield more efficiently by increasing taxiway connections between the new northwestern runway and T5XN.	Uncertainty: HIGH Modularization: INTEGRAL/LOW	**Passive** - Secure space for one dual taxiway east of T5XN. Secure space for two additional Rapid Exit Taxiways (RET) connecting Northwestern Runway to both northern extremities of the T5XN apron.	Allocate land space to provision for extra taxi space. Possess budgetary allocations and produce topographic and architectural plans.
Inter terminal Rail	**(4)** Service a train line between T5X to T5XN.	Uncertainty: LOW Modularization: HIGH	**Active** - Physically allocate overground space for ULTra PRT system connecting T5 and T5XN	Procure concrete beams to serve as the foundation on which the rail tracks will sit on. Allocate enough space for the structure to comfortably blend into the airfield, including the arrival and departure PRT terminals. Design the passenger terminal in such a

				way to accommodate the PRT services.
Car Park	**(5)** Increase space for northern and southern multistory carparks.	Uncertainty: LOW Modularization: HIGH	**Active**- Reinforce platform to accommodate more load	Physically engineer and construct a concrete platform which can later accommodate the addition of more floors. (steel mezzanine)
Terminal & Satellites	**(6)** Accommodate for a prospective increase in passenger throughput capacity in line with phase IV of masterplan (> 143 MPPA).	Uncertainty: LOW Modularization: MODERATE	**Active** – Design to accommodate increased passenger traffic	Incorporate floor plates in T5X to accommodate additional passenger traffic when needed.

Table 6. Cost of investment with and without safeguards

Heuristic 8			**Heuristic 9**	
Option	**Safeguard**	**Investment**	**Option Exercising Costs**	
			With Safeguard in place	**Without Safeguard in Place**
1	Reinforce the aerodrome to accommodate for the relevant aircraft specificities.	RAMP = £83,584,120 Apron Taxiway= £19,957,640 Total = £103,541,760	£0	High Reinforcing the ramp will cost at least times three more. A non-operational stand can cost £2,300,000 per day.
2	Source and procure 28 dual jetways (46 jetways total).	£770,000 each. Total = £21,560,000	£0	Up to £2,300,000 a day while the stands are not operational as they are being refitted.
3	Secure space for one dual taxiway east of T5XN. Secure space for two additional Rapid Exit Taxiways (RET) connecting Northwestern Runway to both northern extremities of the T5XN apron.	Marginal cost must only allocate space during design phase.	(£69,300,000 for 2 taxiways at Code F specifications).	
4	Physically Allocate overground space for ULTra PRT system connecting T5 and T5XN.	£2,543,750 - £3,815,625	Marginal	High and will cause disruption to airport operations.
5	Reinforce platform to accommodate more load.	£460,000	Moderate £3,100,000-£6,160,000 Costs to install and insert pylons and dig foundation post-delivery.	Greater than £6 mil
6	Design to accommodate increased passenger traffic.	£385,000	£1,500,000 - £3,100,000 Cost for installation and manufacture.	Greater than £3 mil

Table 7. Comparison between conventional appraisal approaches and a design flexibility approach

	Conventional appraisal approaches	**Design flexibility approach**
Infrastructure	Fixed, fragile structures	Evolvable, antifragile structures
Key mechanism	Control	Design flexibility
Risk appetite	Risk-focused	Uncertainty-focused
Facilitators	Optimism bias, strategic misrepresentation, risk management	ROR, Modularization, Safeguards
Benefit-cost analysis	Cost efficiencies at CAPEX, increased spending at OPEX	Upfront increased investment at CAPEX, Managed spending at OPEX

Appendix 1

Table 8. Interpreting Heathrow's strategic needs for design flexibility into real options

Heathrow's Statement (Heathrow, 2019)	**Heuristic 2**			**Heuristic 3**		**Heuristic 4**	
	Degree of foreseen uncertainty	**Impact on the infrastructure design**	**Proposed Option**	**Option type**	**Strategic value of option**	**Likelihood of Option exercising**	**Timeframe**
A new satellite and apron will be constructed referred to as T5X North located between the existing central runways and the proposed new runway	Based on current observations of the airfield, 25% of bays are reserved for code F to service long haul flights. There is no indication that an exclusive switch to Code E bays is currently being considered for T5X.	HIGH - It is important to distinguish from an early stage which type of aircraft will be serviced by the terminal as this is a direct input that influences the structural design of the building. Other factors to consider is which destination will this terminal serve. Based off of this, the project team can have a better understanding of which aircrafts to mobilize at this new terminal.	**Option 1** - Equip T5XN ramp to service Code E aircrafts and the apron taxiway to support Code F aircrafts.	Switch	This option will allow the terminal apron to accommodate up to CODE E aircrafts barring the entrance to CODE F planes because the latter's demand is no longer of interest to airlines. Most importantly, this will give Heathrow the opportunity to reduce capital expenditure costs related to apron infrastructure because reinforcing the apron to CODE F standards is far more expensive.	MODERATE - Airliners have moved away from Code F aircrafts and are opting for more efficient Code E aircrafts. Accommodating them is vital to Heathrow's operations.	Phase 3

	Based on current observations of Heathrow's airfield (through google maps) 17% of Code E bays are only equipped with single jet ways. There is currently no evidence to suggest that Heathrow will not continue to implement single jetway infrastructure for new gates at T5XN.	HIGH - Aircraft bays are strategically designed for a specific aircraft type (or a selection of types if MARS is adopted). Placement geometries need to match perfectly with the type of aircraft assigned to the bay. The project team cannot assigned a CODE E aircraft to a bay that only has Code C capacities.	**Option 2** - Configure each T5XN gate with Dual jetway system.	Alter Scale	This option will allow the airport to process two CODE C aircrafts. In the absence of a CODE E aircraft, the dual jetways will branch out individually to service two sperate CODE C planes, allowing the airport to capitalize on tarmac space.	HIGH - Assuming passenger demand meets the target (which is expected by the masterplan), dual jet bridges will make airside operations more efficient by reducing turnaround times	
The new airfield will be made up of the new north west runway and related infrastructure, including taxiways	According to current design plans published by HAL, there appear to be a selection of missing taxiway arteritis that would prove beneficial to irrigate traffic. This design fault has also been picked up by Jacobs where they suggest the addition of two rapid exit taxiways.	MODERATE - There is direct positive correlation between the number of runways and the number of taxiways in an airfield. More taxiways are need to lead to an additional runway. While this is true, it will not change the design of the actual runway. The project team must only make sure that the taxiways are built strategically and efficiently	**Option 3** - Design new airfield more efficiently by increasing taxiway connections between the new northwestern runway and T5XN. (J)	Alter Scale	This option will equip the taxiways to handle traffic more efficiently by irrigating congestion during peak hours, growing the number of active aircrafts on the tarmac at any given point. Additionally, this option proposes the addition of two polar Rapid Exit Taxiways feeding traffic to and out of the runway directly from the T5XN Apron.	LOW - HAL would need to cease operations temporarily to build these taxiways, so it is unlikely	Phase 1
A new terminal and apron, T5X will be constructed and connected to the west of Terminal 5	Heathrow mentions that they are planning to connect T5 with T5X. Presently Heathrow connects all its terminals via underground rail using the Heathrow Express. There is no evidence to suggest that prospective terminal connections will use an alternate method. The option suggests	HIGH - It is important to distinguish at an early stage which type of aircraft will be services by this terminal as this a direct input that influences the structural design of the building. Other factors to consider is which destination will this terminal serve. Based on this, the project	**Option 4** - Connect passengers between T5 and T5X using ULTra Pods PRT system. (identical to the ones currently deployed to connect T5 to the southern carpark).	Stage	This option suggests a passenger link between the existing Terminal 5 and its projected extension Terminal 5X to streamline passenger movements between both buildings' operations are expected to follow similar flight hauls. The use of a modular private rapid transit system can be	MODERATE - According to Heathrow's preferred masterplan, passenger demand will justify the need for an increased level of transit facilities to accommodate for 143 MPPA by 2050. However, as the terminals are within walking distance, it may	Phase 3

	ULTra pods due to the proximity of the terminals and the efficiency tied to the use of this private rapid transit system.	team can have a better understanding of which aircrafts to mobilize at this new terminal.			considered for this. This is a stage option because T5X will only be delivered in phase 4	not be worth the investment.	
Northern Parkway - will be close to the M4 and will have a capacity for up to 23,000 spaces. Southern parkway - will have a capacity for up to 22,000 spaces. It will connect to the M25 and serve Terminal 5 campus**.**	Current provisions indicate a maximum capacity to both car parks at 23,000 for the norther carpark and 22,000 for the southern carpark. There is no measure put in place to increase this threshold should it be required by future demand. Especially considering that the carparks are open to all public (including non-travelers)	HIGH - This segment is heavily influenced by user demand. Should it increase beyond the forecast it would imply significant physical changes to the infrastructure.	**Option 5** - Increase space for northern and southern multistory carparks.	Growth	This option will provide the airport's carparks with additional levels of parking bays as the evolution of the expansion program progresses. By 2050, 143 MPPA are expected which is a 78% increase from 2019 annual passenger movements. This is a stage option as the car park's capacity will only need to be increased in function to the demand generated as the expansion progresses through its four-phase delivery.	MODERATE - This option may be exercised if Heathrow surpasses its target of 143 MPPA, as Heathrow has already provisioned for at least 46,000 new bays between the north and south parkway.	Phase 2
Terminal 5X will include…commercial developments and supporting facilities such as hotel and offices**.**	HAL mentions that Terminal 5X will include commercial developments but does indicate whether the terminal will be designed such that future expansions to the structure remain possible.	HIGH - The strategic outlook of the retail sector within the terminal has a direct impact in the way terminal's layout is arranged. For example, many airport build their retail wing around the duty-free section. Placing this section is essential in maximizing passenger footfall. Any changes to this can affect other sections of the retail and boarding operations.	**Option 6** - Accommodate for a prospective increase in passenger throughput capacity in line with phase IV of masterplan (> 143 MPPA).	Stage	This option will provide Terminal 5X with additional commercial spaces for trading as the evolution of the expansion program progresses. By 2050, 143 MPPA are expected which is a 78% increase from 2019 passenger annual passenger movements. This is a stage option as the terminal's commercial capacity will only need to be increased in function to the demand generated as the expansion	MODERATE - The development as stipulates Heathrow's masterplan, accounts for full 143 MPPA occupancy by phase IV, so it may not be the case that additional commerce is needed.	Phase 4

progresses through its four-phase delivery