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# Critical Drivers for Circular Economy Adoption in Construction Megaprojects: A Fuzzy Synthetic Evaluation Approach

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**ABSTRACT:** The pursuit of sustainability in complex and innovative construction megaprojects is increasingly urgent as these projects face mounting environmental, economic, and social challenges. The Circular Economy (CE) model has emerged as a transformative strategy, focusing on maximizing the value of materials and products through continuous circulation and minimizing resource waste. Transitioning to CE in megaprojects requires a nuanced understanding of CE practices across the project life cycle and the critical success factors that underpin effective implementation. This study identifies the Circular Economy Drivers (CEDs) for Construction Megaprojects (CMPs) in China through an extensive literature review and a large-scale survey of 379 industry experts. The drivers were categorized into five interdependent dimensions: Policy and Regulation (PR), Education and Awareness (EA), Business Models and Tools (BMT), Market and Economic Incentives (MEI), and Design and Construction Practices (DCP). Given the uncertainty in expert opinions, Fuzzy Synthetic Evaluation (FSE) is applied to assess the criticality and relative importance of each driver category. The findings highlight Policy and Regulation (PR) as the most influential driver, underscoring the importance of robust policy frameworks in advancing CE adoption. By unveiling the interconnectedness of CE drivers, this research provides actionable insights for policymakers, industry leaders, and practitioners aiming to embed sustainability into construction megaprojects.

**Keywords**
Circular Economy, Construction Megaprojects, Sustainability, Fuzzy Synthetic Evaluation, China, Sustainable Construction

## 1. INTRODUCTION

In today's rapidly evolving world, megaprojects have taken center stage as a driving force behind modern community development (Locatelli et al., 2017). As global populations age and economies expand at unprecedented rates, the demand for robust infrastructure services—from transportation networks to sustainable urban systems—has intensified. However, the definition of a "megaproject" remains fluid, shaped by economic contexts and governance frameworks. While the U.S. Department of Transportation sets a threshold of over 1billion, Flyvbjerg (2009) proposes a flexible range of 500 million to $1 billion for developed economies. In contrast, rigid monetary benchmarks prove impractical for developing nations with lower GDPs, prompting scholars like Hu et al.(2015) to advocate for adaptive criteria such as a cost-to-GDP ratio (e.g., 0.01% of a country's GDP). These varying thresholds underscore the need for flexibility in defining megaprojects, given their outsized role in socio-economic growth and sustainability goals (Shi et al., 2024).

Yet, despite their strategic importance, megaprojects face systemic challenges. Globally, investments in such ventures exceed $6–9 trillion annually—nearly 8% of the world's GDP (Flyvbjerg, 2014) but their track record is marred by cost overruns, delays, and underwhelming outcomes. For instance, 90% of megaprojects exceed budgets, with China's railroad projects averaging 30.6% cost overruns and 25% delays (Ansar et al., 2017). Compounding these issues, rapid urbanization has outpaced infrastructure development, leaving communities underserved (Gan et al., 2017).

To address these challenges, a paradigm shift is critical. While existing research explores Circular Economy (CE) drivers in general construction projects, megaprojects demand distinct analysis due to their unique scale, complexity, and stakeholder interdependencies. Unlike smaller projects, they involve massive resource consumption (e.g., steel, concrete), multi-jurisdictional governance, and long-term lifecycle impacts, amplifying both the risks of linear practices and the potential for circular strategies. Their extended timelines and high public visibility also elevate the urgency of sustainability, making CE adoption imperative to mitigate systemic risks and leverage opportunities for closed-loop systems through coordinated efforts among governments, investors, and communities (Alotaibi et al., 2024).

CE emphasizing resource efficiency, recycling, and waste minimization offers a transformative approach. By prioritizing lifecycle cost reductions and mitigating risks tied to resource scarcity, CE principles can counteract the inefficiencies of traditional linear models (Ghufran et al., 2022).The construction industry must move away from traditional practices and embrace sustainable solutions (Meshref et al., 2022). Enter the concept of "sustainable megaprojects" initiatives designed to be environmentally friendly and resource efficient. However, achieving this vision is easier said than done. One major obstacle lies in integrating circular CE principles into megaprojects. In many developing nations, including Saudi Arabia, limited regulation, education, and awareness hinder progress, leaving linear economy models firmly entrenched (Alotaibi et al., 2024), This outdated "take-make-dispose" approach not only depletes resources but also exacerbates environmental degradation. To break free from this cycle, the industry must adopt circular economy practices that prioritize recycling, reuse, and waste reduction. By doing so, it can transform waste into valuable resources, reduce environmental footprints, and support long-term economic growth (Ali & Shirazi, 2023). But the road to transformation is fraught with challenges, from high upfront investments to complex regulatory frameworks. Overcoming these barriers will require unprecedented collaboration between governments, private sectors, and communities. While research on circular economies in construction is growing, one glaring gap remains: understanding the drivers that encourage their adoption in megaprojects, especially in emerging economies like China.This study bridges this gap by introducing two novel contributions: (1) applying the Fuzzy Synthetic Evaluation (FSE) method to systematically prioritize CE drivers in megaprojects, addressing ambiguity and multi-stakeholder complexity often overlooked by traditional statistical approaches, and (2) contextualizing the analysis within China's megaprojects—a critical yet understudied setting given the country's global infrastructure leadership, rapid urbanization, and unique regulatory and economic dynamics. As a global leader in infrastructure development, China holds the key to unlocking scalable solutions for sustainable practices worldwide. This paper aims to address this gap by proposing a roadmap to seamlessly integrate circular economy principles into megaprojects, paving the way for a greener, more efficient future.

## 2. METHODOLOGY

Figure **1** presents a four-stage methodology for identifying CEDs in sustainable megaprojects. The stages encompass an extensive literature review, semi-structured interviews, questionnaire survey development, and Fuzzy Synthetic Evaluation (FSE). The flowchart illustrates a systematic and sequential approach to research, emphasizing the structured process of investigating the factors influencing the adoption of CE principles in sustainable megaprojects.

### 2.1 Stage 1: Literature Review

The literature review utilized the Scopus database for its extensive coverage and advanced citation tracking. Key terms such as "circular economy adoption," "implementation factors," "enablers," "drivers," and “megaprojects” or “construction industry” were used for targeted searches. Following Ibrahim et al. (2024), inclusion and exclusion criteria were applied to filter for peer-reviewed articles and review papers focused on CE drivers. Additionally, the snowballing technique was also used to identify additional influential studies by examining references and citations from key papers (Ibrahim et al., 2025). This approach is crucial for uncovering influential works that may not appear in the initial database search, thereby enriching the depth and breadth of the literature review (Ibrahim, Zayed, et al., 2024). After rigorous screening, a total of 76 papers were deemed relevant and included in the final analysis.

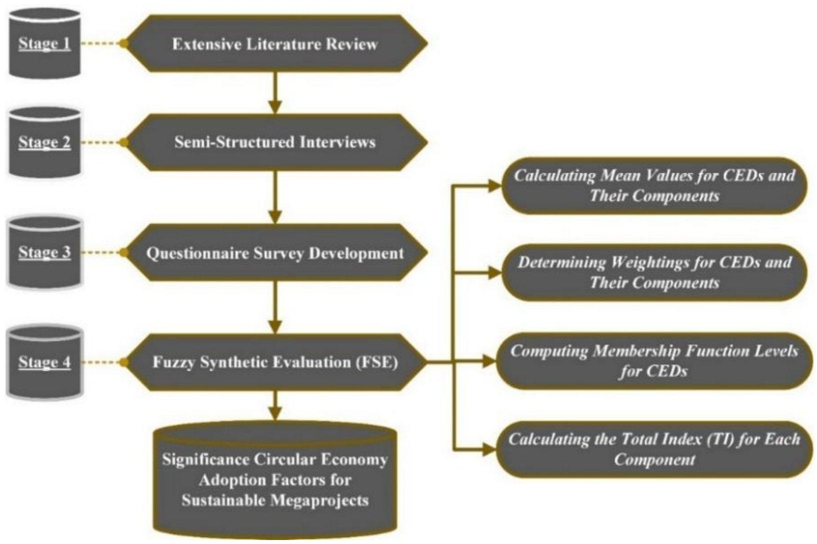


**FIGURE 1. RESEARCH METHODOLOGY**

### 2.2 Stage2: Semi-Structured Interviews

To gain deeper insights, semi-structured interviews were conducted with ten experienced practitioners specializing in megaprojects in China. These experts, with 11 to over 25 years of professional experience and advanced academic qualifications (master’s or Ph.D.), provided valuable insights into the drivers and their impacts on CE implementation. Based on the interview findings, the list of practices was refined, some variables were modified, and new variables (e.g., BMT9 and DCP5) were introduced. Additionally, the drivers were reorganized into five main categories, as shown in Table 1.

### 2.3 Stage 3: Questionnaire Survey Development

The study aimed to validate a proposed model and achieve research objectives through a questionnaire survey conducted in Mainland China and Hong Kong, regions chosen for their high number of CMPs and shared regulatory frameworks. The survey focused on large-scale projects with investments over 0.5 billion CNY outlined by Wang et al. (2021), targeting senior and middle managers with experience in such projects. Data collection occurred between March and September 2024 using stratified random sampling to ensure diverse representation. A pilot study refined the questionnaire based on feedback from 10 specialists, and the final version used a five-point Likert scale, with a Cronbach’s Alpha score above 0.971 confirming reliability. The survey garnered 379 responses, mostly from Mainland China (63.85%) and Hong Kong (36.15%), with participants primarily involved in residential (43.54%) and infrastructure/transportation projects (29.02%). Most respondents had 11-15 years of experience (55.15%), indicating a mature professional group, while fewer had 1-5 years (8.71%) or 16+ years (9.76%).

### 2.4 Stage 4: Fuzzy Synthetic Evaluation (FSE)

FSE provides a systematic framework for quantifying expert judgments through fuzzy logic and membership functions, making it well-suited for addressing complex research challenges.FSE is more appropriate than traditional statistical methods in scenarios involving uncertainty, multi-attribute evaluation, and subjective judgments. Its ability to handle complex, vague, and imprecise data makes it a valuable tool across various fields, from environmental management to education and corporate assessments (Saka et al., 2022). FSE's effectiveness in addressing construction industry challenges underscores its suitability for assessing the importance of CEDs in megaprojects. By combining traditional statistical techniques, like mean calculations, with fuzzy logic, FSE offers a comprehensive analytical approach structured into four key steps, outlined below:

Table 1. CEDs to adopting CE in Construction Megaprojects (Benachio et al., 2021; Khadim et al., 2022; Oluleye et al., 2023; Wuni & Shen, 2022)

| Category | ID | CEDs |
|---|---|---|
| **Policy and Regulation (PR)** | PR1 | Establish clear guidelines for adopting circular economy (CE) in construction and demolition waste management. |
| | PR2 | Require stakeholders to use secondary materials to promote circularity. |
| | PR3 | Conduct regular government inspections to ensure circularity in demolition projects. |
| | PR4 | Enforce penalties (e.g., fines) for non-compliance, such as illegal dumping of construction waste. |
| | PR5 | Promote waste classification and sorting practices. |
| | PR6 | Mandate reporting and documentation to support planning for CE initiatives. |
| **Education and Awareness (EA)** | EA1 | Integrate CE principles into university curricula and encourage related research. |
| | EA2 | Educate decision-makers on CE benefits. |
| | EA3 | Develop skills and roles necessary for CE adoption in the industry. |
| | EA4 | Facilitate expert workshops on CE principles and implementation. |
| **Business Model and Tools (BMT)** | BMT1 | Create circular business models and decision-support systems for waste management. |
| | BMT2 | Develop metrics and indicators to measure CE performance. |
| | BMT3 | Use BIM simulations to assess material reuse potential early in projects. |
| | BMT4 | Build data management platforms to drive value creation in CE. |
| | BMT5 | Apply life-cycle analysis during design stages to evaluate material reuse benefits. |
| | BMT6 | Leverage material stock data to enable reuse in new buildings. |
| | BMT7 | Encourage manufacturers to retain ownership of materials for future reclamation. |
| | BMT8 | Develop material passports to document detailed information on materials used. |
| | BMT9 | Use digital tools (e.g., BIM, IoT) to optimize processes, track materials, and improve resource management. |
| **Market and Economic Incentives (MEI)** | MEI1 | Allocate budgets effectively to support CE principles in construction (Governments lens). |
| | MEI2 | Build secondary markets for recycled materials and components (Manufacturers and industry bodies lens). |
| | MEI3 | Offer financial rewards (e.g., tax breaks, certifications) to stakeholders adopting CE principles (private-sector stakeholders' lens). |
| **Design and Construction Practices (DCP)** | DCP1 | Design structures for easy disassembly to maximize value recovery. |
| | DCP2 | Conduct pre-demolition audits to identify and recover resources. |
| | DCP3 | Ensure proper storage of waste to maintain the quality of recyclable materials. |
| | DCP4 | Design buildings with adaptability to facilitate future reuse. |
| | DCP5 | Choose materials based on durability, repairability, and recyclability. |

*(i) Calculating Mean Values for CEDs and Their Components*

The analysis begins by computing the mean scores (MS) for each driver using Equation [1]. This involves aggregating expert ratings on a 5-point Likert scale. The mean score for each driver is calculated as follows:

[1] $$MS = \frac{\sum(S \times Fr)}{N}, (1 \leq MS \leq 5)$$

Here, S represents the score assigned by an expert, Fr denotes the frequency of each rating (1–5), and N is the total number of responses for a given driver. The same process is repeated for each component of the drivers, culminating in the calculation of an overall mean for all components.

*(ii) Determining Weightings for CEDs and Their Components*

The next step involves assigning weights (*Wi*) to each driver and component. This study employs the normalized mean method due to its simplicity and reliance on mean scores. The weights for drivers (e.g., PR1, MEI2) and components (e.g., Policy & Regulation, Market & Economic Incentives) are calculated using Equations [2] and [3], respectively:
Equation [2]: Calculating sub-component (driver) weights

$$W_i = \frac{MS_i}{\sum_{i=1}^{5} MS_i}, 0 < W_i < 1 \; and \; \sum_{i=1}^{5} W_i = 1 \quad [2]$$

Here, $W_i$ represents the weight assigned to enabler i, and $MS_i$ is the mean score of enablers i as derived from the survey data.
Equation [3]: Calculating main component (category) weights

$$W_{Ci} = \frac{\sum_{i=1}^{5} MS_i \; for\ each\ component}{Overall\ MS_i} \quad [3]$$

$W_{Ci}$: Weight of main component (category) i, $MS_i$: Mean score of main components (category) i derived from survey data.

*(iii) Computing Membership Function Levels for CEDs*

The third step focuses on calculating membership function (MF) levels for each driver and component. The MF, which ranges from 0 to 1, indicates the degree to which an element belongs to a fuzzy set. The MF levels are determined using expert ratings on the Likert scale, as shown in Equation [4] provides the formula for calculating the MFs.

$$MF_{P_{in}} = \frac{P_{1_{in}}}{LS_1} + \frac{P_{2_{in}}}{LS_2} + \frac{P_{3_{in}}}{LS_3} + \frac{P_{4_{in}}}{LS_4} + \frac{P_{5_{in}}}{LS_5} \quad [4]$$

Here, $MF_{P_{in}}$ represents the membership function level for driver *i*, and $P_{1_{in}}$ to $P_{5_{in}}$ denote the percentages of respondents who assigned scores of 1 to 5, respectively. $LS_1$ to $LS_5$ denote the fixed Likert scale values (1 to 5) representing predefined agreement levels .
The MF levels for components $D_i$ are calculated using Equation [5], which combines the weighting function (*Wi*) with the fuzzy matrix of drivers (*Ri*):

$$D_i = W_i \otimes R_i \quad [5]$$

Here, ⊗ denotes the fuzzy composition operator, and Ri is derived from the membership functions of the drivers, as shown in Equation [6]. The degree of membership, $d_{in}$, is derived from the calculation of $D_i$ as shown in Equation [7].

$$R_i = \begin{vmatrix} MF_{Ei1} \\ MF_{Ei2} \\ \cdots \\ MF_{Ein} \end{vmatrix} = \begin{vmatrix} E_{1_{i1}} & E_{2_{i1}} & E_{3_{i1}} & E_{4_{i1}} & E_{5_{i1}} \\ E_{1_{i2}} & E_{2_{i2}} & E_{3_{i2}} & E_{4_{i2}} & E_{5_{i2}} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ E_{1_{in}} & E_{1_{in}} & E_{1_{in}} & E_{1_{in}} & E_{1_{in}} \end{vmatrix} \quad [6]$$

$$D_i = W_i \otimes R_i = (W_1, W_2, W_3, W_4, \cdots\cdots\cdots, W_n) \otimes \begin{vmatrix} E_{1_{i1}} & E_{2_{i1}} & E_{3_{i1}} & E_{4_{i1}} & E_{5_{i1}} \\ E_{1_{i2}} & E_{2_{i2}} & E_{3_{i2}} & E_{4_{i2}} & E_{5_{i2}} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ E_{1_{in}} & E_{1_{in}} & E_{1_{in}} & E_{1_{in}} & E_{1_{in}} \end{vmatrix} = (d_{i1}, d_{i2}, \cdots, d_{in}) \quad [7]$$

*(iv) Calculating the Total Index (TI) for Each Component*

The final step involves computing the Total Index (TI) for each component using the membership functions and the 5-point Likert scale. The TI is calculated using Equation [8]:

[8] $$TI_i = \sum_{i=1}^{n} D_{Ci} \times LS_i$$

Here, $D_{Ci}$ represents the fuzzy evaluation matrix of a component, and $LS_i$ denotes the Likert scale level. The TI provides a comprehensive measure of the criticality or significance of each component, enabling informed decision-making.

## 3. DATA ANALYSIS AND RESULTS

### 3.1 Calculation of Mean Values and Weightings for All CEDs and Their Components

Table 2 summarizes the mean values and weights of Circular Economy Drivers (CEDs) and their components within sustainable megaprojects. It includes mean values for each component, total mean values for the CEDs, and calculated weights for both the CEDs and their components. The results demonstrate the critical role of CEDs in driving Circular Economy (CE) adoption in Construction Megaprojects (CMPs), with all mean scores exceeding the benchmark of 3.50, reflecting strong agreement among experts on their importance. Key components such as PR, EA, BMT, MEI, and DCP are analyzed by their mean values and relative weights, providing actionable insights into their influence. These findings emphasize the strategic value of CEDs in integrating CE practices into large-scale projects, offering valuable guidance for decision-making and strategic planning.

Table 2. Mean Values and Weighting Results for CEDs and Components

| Component | Code | Mean Value | Total Mean Value | CEDs Weights | Components Weights |
|---|---|---|---|---|---|
| **Policy and Regulation (PR)** | PR1 | 3.683 | 22.158 | 0.1662 | 0.2240 |
| | PR2 | 3.702 | | 0.1671 | |
| | PR3 | 3.628 | | 0.1637 | |
| | PR4 | 3.739 | | 0.1687 | |
| | PR5 | 3.697 | | 0.1668 | |
| | PR6 | 3.710 | | 0.1674 | |
| **Education and Awareness (EA)** | EA1 | 3.591 | 14.525 | 0.2472 | 0.1468 |
| | EA2 | 3.707 | | 0.2552 | |
| | EA3 | 3.654 | | 0.2516 | |
| | EA4 | 3.573 | | 0.2460 | |
| **Business Model and Tools (BMT)** | BMT1 | 3.620 | 32.757 | 0.1105 | 0.3312 |
| | BMT2 | 3.683 | | 0.1124 | |
| | BMT3 | 3.660 | | 0.1117 | |
| | BMT4 | 3.591 | | 0.1096 | |
| | BMT5 | 3.689 | | 0.1126 | |
| | BMT6 | 3.686 | | 0.1125 | |
| | BMT7 | 3.620 | | 0.1105 | |
| | BMT8 | 3.599 | | 0.1099 | |
| | BMT9 | 3.609 | | 0.1102 | |
| **Market and Economic Incentives (MEI)** | MEI1 | 3.691 | 11.018 | 0.3350 | 0.1114 |
| | MEI2 | 3.641 | | 0.3305 | |
| | MEI3 | 3.686 | | 0.3345 | |
| **Design and Construction Practices (DCP)** | DCP1 | 3.683 | 18.459 | 0.1995 | 0.1866 |
| | DCP2 | 3.641 | | 0.1973 | |
| | DCP3 | 3.657 | | 0.1981 | |
| | DCP4 | 3.697 | | 0.2003 | |
| | DCP5 | 3.781 | | 0.2048 | |

The weighting for each driver was determined using Equation **[2]**. For example, the weight of MEI1 (with a mean score of 3.691) was computed as:

$$W_{\mathrm{MEI1}} = \frac{3.691}{3.691 \;\; + 3.641 + 3.686} = 0.3350$$

Similarly, the weighting for EA (total mean = 14.525) was calculated as:

$$W_{\mathrm{EA}} = \frac{14.525}{14.525 + 22.158 + 32.757 + 11.018 + 18.459} = 0.1468$$

### 3.2 Calculation of Membership Function Levels for All CEDs

Membership functions (MF2) were derived from survey participants' evaluations using Equation **[4]**. For example, the MF of PR1, rated as "very low" to "very high" by 2.6%, 5.5%, 31.7%, 41.2%, and 19% of experts, respectively, is expressed as:

$$MF_{\mathrm{PR1}} = \frac{0.026}{LS_1} + \frac{0.055}{LS_2} + \frac{0.317}{LS_3} + \frac{0.412}{LS_4} + \frac{0.190}{LS_5}$$

These results are summarized in Table 3.

Table 3. Membership Functions (MF2) for CEDs

| **Driver Codes** | | | **MF Level 2** | | |
|---|---|---|---|---|---|
| **PR1** | 0.026 | 0.055 | 0.317 | 0.412 | 0.190 |
| **PR2** | 0.029 | 0.061 | 0.301 | 0.398 | 0.211 |
| **PR3** | 0.024 | 0.098 | 0.322 | 0.340 | 0.216 |
| **PR4** | 0.021 | 0.092 | 0.282 | 0.335 | 0.269 |
| **PR5** | 0.016 | 0.106 | 0.280 | 0.364 | 0.235 |
| **PR6** | 0.024 | 0.061 | 0.325 | 0.364 | 0.227 |
| **EA1** | 0.026 | 0.108 | 0.296 | 0.388 | 0.182 |
| **EA2** | 0.034 | 0.082 | 0.256 | 0.398 | 0.230 |
| **EA3** | 0.026 | 0.084 | 0.298 | 0.391 | 0.201 |
| **EA4** | 0.026 | 0.108 | 0.322 | 0.354 | 0.190 |
| **BMT1** | 0.029 | 0.090 | 0.301 | 0.393 | 0.187 |
| **BMT2** | 0.016 | 0.084 | 0.311 | 0.377 | 0.211 |
| **BMT3** | 0.029 | 0.079 | 0.293 | 0.401 | 0.198 |
| **BMT4** | 0.029 | 0.108 | 0.298 | 0.372 | 0.193 |
| **BMT5** | 0.021 | 0.087 | 0.298 | 0.369 | 0.224 |
| **BMT6** | 0.032 | 0.087 | 0.272 | 0.383 | 0.227 |
| **BMT7** | 0.034 | 0.100 | 0.272 | 0.398 | 0.195 |
| **BMT8** | 0.024 | 0.103 | 0.298 | 0.401 | 0.174 |
| **BMT9** | 0.024 | 0.121 | 0.285 | 0.361 | 0.208 |
| **MEI1** | 0.029 | 0.069 | 0.301 | 0.385 | 0.216 |
| **MEI2** | 0.037 | 0.095 | 0.272 | 0.383 | 0.214 |
| **MEI3** | 0.026 | 0.095 | 0.266 | 0.391 | 0.222 |
| **DCP1** | 0.026 | 0.058 | 0.330 | 0.377 | 0.208 |
| **DCP2** | 0.024 | 0.119 | 0.280 | 0.348 | 0.230 |
| **DCP3** | 0.037 | 0.061 | 0.319 | 0.375 | 0.208 |
| **DCP4** | 0.037 | 0.079 | 0.277 | 0.364 | 0.243 |
| **DCP5** | 0.024 | 0.055 | 0.282 | 0.393 | 0.245 |

MF1 values were computed using weighting functions and fuzzy matrices. For example, the weighting function of EA $W_{\mathrm{EA}}$ (Table 2) and its fuzzy matrix $R_{\mathrm{EA}}$ (Table 3) can be expressed as:

$$W_{\mathrm{EA}} = (0.2472, 0.2552, 0.2516, 0.2460)$$

$$R_{\text{EA}} = \begin{vmatrix} MF_{\text{EA1}} \\ MF_{\text{EA2}} \\ MF_{\text{EA3}} \\ MF_{\text{EA4}} \end{vmatrix} = \begin{vmatrix} 0.0264 & 0.1082 & 0.2955 & 0.3879 & 0.1821 \\ 0.0343 & 0.0818 & 0.2559 & 0.3984 & 0.2296 \\ 0.0264 & 0.0844 & 0.2982 & 0.3905 & 0.2005 \\ 0.0264 & 0.1082 & 0.3219 & 0.3536 & 0.1900 \end{vmatrix}$$

Using Equation [5], MF1 of EA was computed as follows:

$$MF_{\text{EA}} = D_{\text{EA}} = W_{\text{EA}} \otimes R_{\text{EA}} = (0.2472, 0.2552, 0.2516, 0.2460) \otimes \begin{vmatrix} 0.0264 & 0.1082 & 0.2955 & 0.3879 & 0.1821 \\ 0.0343 & 0.0818 & 0.2559 & 0.3984 & 0.2296 \\ 0.0264 & 0.0844 & 0.2982 & 0.3905 & 0.2005 \\ 0.0264 & 0.1082 & 0.3219 & 0.3536 & 0.1900 \end{vmatrix}$$

$$= (.0284, 0.0955, 0.2926, 0.3828, 0.2008)$$

The MF1 values for all components are summarized in Table 4.

Table 4. MF1 and overall level for all components

| **Components** | | | **Di** | | |
|---|---|---|---|---|---|
| **Policy and Regulation (PR)** | 0.023 | 0.079 | 0.304 | 0.369 | 0.225 |
| **Education and Awareness (EA)** | 0.028 | 0.095 | 0.293 | 0.383 | 0.201 |
| **Business Model and Tools (BMT)** | 0.026 | 0.095 | 0.292 | 0.384 | 0.202 |
| **Market and Economic Incentives (MEI)** | 0.031 | 0.086 | 0.280 | 0.386 | 0.217 |
| **Design and Construction Practices (DCP)** | 0.030 | 0.074 | 0.298 | 0.372 | 0.227 |

### 3.3 Calculating the Total Index (TI) for each component

The FSE analysis was employed to calculate the significance indices of the main components for managing CE adoption in CMPs. BMT obtained the highest weighting, followed by PR, DCP, EA, and MEI. However, these weightings were not used to rank the components, as they are influenced by the number of CEDs within each component, which could introduce bias toward components with a larger number of CEDs.
The Total Index (TI) for each component was computed using Equation [8], For example, the TI for PR was calculated as:

$$TI_{\text{PR}} = (0.023, 0.079, 0.304, 0.369, 0.225) \otimes \begin{pmatrix} 1 \\ 2 \\ 3 \\ 4 \\ 5 \end{pmatrix} = 3.6934(1st)$$

Using the same approach, the TI values for all components of CEDs, calculated using Equation [8].
The FSE analysis revealed that the 27 CEDs collectively have a substantial impact on the successful adoption of CE practices in CMPs. Furthermore, the analysis highlighted that the five components for managing CEDs in CMPs are significance and demand the focused attention of project managers. As shown in Table 5, the results indicate that the most significant drivers for enhancing the widespread adoption of CE are PR, followed by DCP, MEI, BMT and EA, in that order.

Table 5. The total Index for the components enhancing CE Adoption in CMPs

| **Code** | **Component** | **Index** | **Ranking** |
|---|---|---|---|
| **PR** | Policy and Regulation | **3.6934** | 1 |
| **DCP** | Design and Construction Practices | **3.6925** | 2 |
| **MEI** | Market and Economic Incentives | **3.6730** | 3 |
| **BMT** | Business Model and Tools | **3.6401** | 4 |
| **EA** | Education and Awareness | **3.6320** | 5 |

## 4. DISCUSSION

The adoption of a circular economy (CE) in construction megaprojects is driven by a hierarchy of factors, with Policy and Regulation (PR), Design and Construction Practices (DCP), and Market and Economic Incentives (MEI) emerging as the most critical. PR, the top-ranked driver, serves as the cornerstone of systemic change, as governments and regulatory bodies enforce standards, mandates, and incentives that promote resource efficiency and sustainable material use. This aligns with AlJaber et al. (2024), who emphasize that clear regulatory frameworks, such as the EU's Circular Economy Action Plan, compel industries to adopt circular practices, mitigating risks and ensuring accountability. DCP, the second-ranked driver, operationalizes circularity by embedding CE principles into project lifecycles through modular design, material passports, and disassembly-friendly structures. For example, the Hong Kong–Zhuhai–Macau Bridge project demonstrates how prefabrication and early-stage design decisions minimize waste, directly supporting CE goals (Liu et al., 2022). MEI, ranked third, bridges sustainability and profitability by creating financial parity between linear and circular practices. Tax reliefs, green bonds, and procurement policies, such as Singapore's Green Building Masterplan, address economic barriers, incentivizing stakeholders to prioritize sustainability, a notion supported by John et al.(2023). This hierarchical framing underscores the systemic interdependence of drivers, with PR, DCP, and MEI acting as levers for transformative change in megaprojects.

## 5. CONCLUSIONS

This study highlights the urgent need to adopt Circular Economy (CE) principles in construction megaprojects (CMPs) to address environmental, economic, and social challenges. Through a comprehensive literature review and a survey of 379 industry experts in China, 27 critical drivers for CE adoption were identified and prioritized across five key dimensions: Policy and Regulation (PR), Design and Construction Practices (DCP), Market and Economic Incentives (MEI), Business Models and Tools (BMT), and Education and Awareness (EA). Using Fuzzy Synthetic Evaluation (FSE), the findings reveal that PR serves as a foundational driver by enforcing standards and incentives, while EA empowers stakeholders with the knowledge and skills needed for CE implementation. BMT provides practical frameworks and digital tools for material tracking, and MEI accelerates adoption through financial incentives like tax breaks and subsidies. DCP ensures feasibility through innovative design and modular construction. The study emphasizes the need for aligned regulatory frameworks, innovative practices, and market incentives, alongside enhanced education and awareness, to drive CE adoption. By uncovering the interconnectedness of these drivers, this research offers actionable insights for policymakers and industry leaders, contributing to a sustainable transformation in CMPs. Future research should address implementation challenges and explore the scalability of these findings across diverse contexts. This includes conducting sensitivity analyses to refine rankings and validate the framework's adaptability under varying parameters, ensuring robustness in real-world applications. This will include integrating factors like cross-sector collaboration and information-sharing platforms to strengthen stakeholder coordination. Additionally, validating the framework through real-world pilot projects and comparative analysis with existing methodologies will be prioritized to ensure practical relevance and adaptability. These steps aim to bridge theoretical insights with actionable strategies, fostering globally scalable solutions for sustainable megaprojects.

## REFERENCES


Ali, S., & Shirazi, F. (2023). The Paradigm of Circular Economy and an Effective Electronic Waste Management. *Sustainability*, *15*(3), 1998. https://doi.org/10.3390/su15031998

AlJaber, A., Martinez-Vazquez, P., & Baniotopoulos, C. (2024). Developing Critical Success Factors for Implementing Circular Economy in Building Construction Projects. *Buildings*, *14*(8). https://doi.org/10.3390/buildings14082319

Alotaibi, S., Martinez-Vazquez, P., & Baniotopoulos, C. (2024). Advancing Circular Economy in Construction Mega-Projects: Awareness, Key Enablers, and Benefits—Case Study of the Kingdom of Saudi Arabia. *Buildings*, *14*(7), 2215. https://doi.org/10.3390/buildings14072215

Ansar, A., Flyvbjerg, B., Budzier, A., & Lunn, D. (2017). BIG IS FRAGILE: AN ATTEMPT AT THEORIZING SCALE. *The Oxford Handbook of Megaproject Management*, *1*(March), 60–95.

Benachio, G. L. F., Freitas, M. do C. D., & Tavares, S. F. (2021). Interactions between Lean Construction Principles and Circular Economy Practices for the Construction Industry. *Journal of Construction Engineering and Management*, *147*(7). https://doi.org/10.1061/(asce)co.1943-7862.0002082

Flyvbjerg, B. (2009). What is a Megaproject. *Aalborg University*.

Flyvbjerg, B. (2014). What you should know about megaprojects and why: An overview. *Project Management Journal*, *45*(2), 6–19. https://doi.org/10.1002/pmj.21409

Gan, X., Zuo, J., Wu, P., Wang, J., Chang, R., & Wen, T. (2017). How affordable housing becomes more sustainable? A stakeholder study. *Journal of Cleaner Production*, *162*, 427–437. https://doi.org/10.1016/j.jclepro.2017.06.048

Ghufran, M., Khan, K. I. A., Ullah, F., Nasir, A. R., Al Alahmadi, A. A., Alzaed, A. N., & Alwetaishi, M. (2022). Circular Economy in the Construction Industry: A Step towards Sustainable Development. *Buildings*, *12*(7), 1004. https://doi.org/10.3390/buildings12071004

Hu, Y., Chan, A. P. C., Le, Y., & Jin, R. (2015). From Construction Megaproject Management to Complex Project Management: Bibliographic Analysis. *Journal of Management in Engineering*, *31*(4), 1–11. https://doi.org/10.1061/(asce)me.1943-5479.0000254

Ibrahim, A., Abdelkhalek, S., Zayed, T., Qureshi, A. H., & Mohammed Abdelkader, E. (2024). A Comprehensive Review of the Key Deterioration Factors of Concrete Bridge Decks. *Buildings*, *14*(11). https://doi.org/10.3390/buildings14113425

Ibrahim, A., Zayed, T., & Lafhaj, Z. (2024). Enhancing Construction Performance : A Critical Review of Performance Measurement Practices at the Project Level. *Buildings*, *14*(7).

Ibrahim, A., Zayed, T., & Lafhaj, Z. (2025). Trends and gaps in lean construction practices for construction of megaprojects : A critical review. *Alexandria Engineering Journal*, *118*(February 2024), 174–193. https://doi.org/10.1016/j.aej.2025.01.046

John, I. B., Adekunle, S. A., & Aigbavboa, C. O. (2023). Adoption of Circular Economy by Construction Industry SMEs: Organisational Growth Transition Study. *Sustainability (Switzerland)*, *15*(7). https://doi.org/10.3390/su15075929

Khadim, N., Agliata, R., Marino, A., Thaheem, M. J., & Mollo, L. (2022). Critical review of nano and micro-level building circularity indicators and frameworks. *Journal of Cleaner Production*, *357*(October 2021), 131859. https://doi.org/10.1016/j.jclepro.2022.131859

Liu, Y., Houwing, E.-J., Hertogh, M., Yuan, Z., & Liu, H. (2022). Explorative Learning in Infrastructure Development Megaprojects: The Case of the Hong Kong-Zhuhai-Macao Bridge. *Project Management Journal*, *53*(2), 113–127. https://doi.org/10.1177/87569728211065574

Locatelli, G., Mikic, M., Kovacevic, M., Brookes, N., & Ivanisevic, N. (2017). The Successful Delivery of Megaprojects: A Novel Research Method. *Project Management Journal*, *48*(5), 78–94. https://doi.org/10.1177/875697281704800506

Meshref, A. N., Abdelfattah, E., Elkasaby, A., & Ibrahim, A. (2022). *Selecting Key Drivers for a Successful Lean Construction Implementation Using Simos ' and WSM : The Case of Egypt*.

Oluleye, B. I., Chan, D. W. M., Antwi-Afari, P., & Olawumi, T. O. (2023). Modeling the principal success factors for attaining systemic circularity in the building construction industry: An international survey of circular economy experts. *Sustainable Production and Consumption*, *37*, 268–283. https://doi.org/10.1016/j.spc.2023.03.008

Saka, A. B., Chan, D. W. M., & Wuni, I. Y. (2022). Knowledge-based decision support for BIM adoption by small and medium-sized enterprises in developing economies. *Automation in Construction*, *141*(June), 104407. https://doi.org/10.1016/j.autcon.2022.104407

Shi, Q., Yao, L., & Bi, C. (2024). Dynamic incentive mechanisms in mega project-risk management considering the participation of the. *Engineering, Construction and Architectural Management*. https://doi.org/10.1108/ECAM-04-2024-0473

Wang, G., Zhou, K., Wang, D., Wu, G., & Xie, J. (2021). Tensions in governing megaprojects: How different types of ties shape project relationship quality? *International Journal of Project Management*, *39*(7), 799–814. https://doi.org/10.1016/j.ijproman.2021.08.003

Wuni, I. Y., & Shen, G. Q. (2022). Developing critical success factors for integrating circular economy into modular construction projects in Hong Kong. *Sustainable Production and Consumption*, *29*, 574–587. https://doi.org/10.1016/j.spc.2021.11.010