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The theory of complexity and construction management: An analysis of perception and impact on the construction industry in Brazil and Bolivia

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Abstract. The theory of complexity derived from systems theory emphasizes complex systems and their dynamic interactions with their environment. In this sense, in project management, this theory offers invaluable perspectives, where systems involve diverse components working towards a common objective. The construction sector is facing challenges in managing project complexity, and effective strategies are required to ensure success. While projects are often perceived as predictable, the reality of construction complexity demands a shift in perspective. Currently, the linear view of construction processes is being challenged, advocating for recognizing projects as nonlinear and dynamic phenomena. This study aims to explore the application of complexity theory in construction project management, focusing on differences in complexity perception between Cochabamba and the Metropolitan Region of Curitiba. Discriminant Analysis does not reveal a significant disparity in complexity perception between the two regions, with variables such as uncertainty about the subsoil having the most influence on complexity perception.

1 Introduction

The theory of complexity provides an integrated approach to addressing contemporary challenges by emphasizing a unified understanding of systems rather than a fragmented one. This theory explores the intricate interactions within systems, highlighting their dynamic nature. In this sense, it is crucial to distinguish between "complicated" and "complex", terms often conflated, to fully grasp the implications of this theory, especially in fields like project management, where it can offer invaluable insights, particularly in the construction industry.

In construction, systems encompass a multitude of interconnected components, ranging from materials and equipment to processes and workflows, all working towards a common

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objective. Adopting systemic thinking involves comprehending these interactions to optimize overall performance [1]. This systemic approach underscores the importance of considering the interplay between various elements within the construction context to achieve project success effectively.

Moreover, the construction industry has faced considerable hurdles in managing the increasing complexity of large-scale projects. Recognizing the concept of project complexity and mastering effective management strategies becomes imperative for achieving success in this domain [2].

In project management, the term "complexity" is often used incorrectly, implying that projects are merely complicated and attributing delays and increased costs to various variables. However, it's essential to recognize that while some infrastructure projects are complicated, true complexity involves specific characteristics like emergence, non-linearity, and pattern formation [3].

The term "complicated" refers to an object that presents challenges in analysis, understanding, or explanation [4]. A system is considered complicated when it comprises inherently interconnected parts and interrelated subsystems. These systems are characterized by their reliance on numerous elements, governed by well-defined laws, similar to simpler systems [5]. Additionally, complicated systems can be controlled through specific plans, have well-defined boundaries, and lack direct interaction with their surroundings [6].

Complex systems, unlike complicated ones, defy simple definition and comprise intricate networks of interactions [6]. These systems remain open, interacting with their surroundings, and complexity arises from these interactions. Consequently, actions on a single component affect the entire system [7]. Complex systems exhibit unpredictable behavior, generating new properties and instability, while complicated systems show emergent properties, relying on interactions among components [8].

In project management, projects are often perceived as structured and predictable, with defined stages and activities executed independently, akin to an assembly [9]. However, the construction industry faces historical challenges, particularly in cost, time, and quality metrics [10], attributed to project complexity. Hence, assessing the effectiveness of current management approaches in handling this complexity is crucial.

This study aims to explore how complexity theory can enhance project management in construction by examining differences in complexity perception among projects and identifying key factors characterizing civil construction as complex phenomena. By analyzing the sample's characteristics, insights into participating companies' profiles will be gained. Discriminant Analysis, a multivariate statistical technique, will be employed to scrutinize complexity perception differences between groups in Cochabamba and Metropolitan Region of Curitiba, focusing on variables associated with construction project complexity to discern significant disparities.

2 Methodology

The research development process, illustrated in Figure 1, consists of four stages. The first stage involves planning the data collection through a survey by defining the variables of interest based on a comprehensive literature review. This survey will be conducted digitally among construction companies in the Metropolitan Region of Curitiba, Paraná, Brazil, and Cochabamba, Bolivia, using a non-probabilistic sampling method. In the second stage, a pilot test was conducted to evaluate the feasibility of the questions and refine the questionnaire's concepts and wording.

The pilot data were analyzed, and the questionnaire was revised based on feedback from the pilot test respondents to ensure its effectiveness for the final data collection. The data collection instrument is the questionnaire. The questionnaire can be administered through personal interviews, mail, email, among others [11].

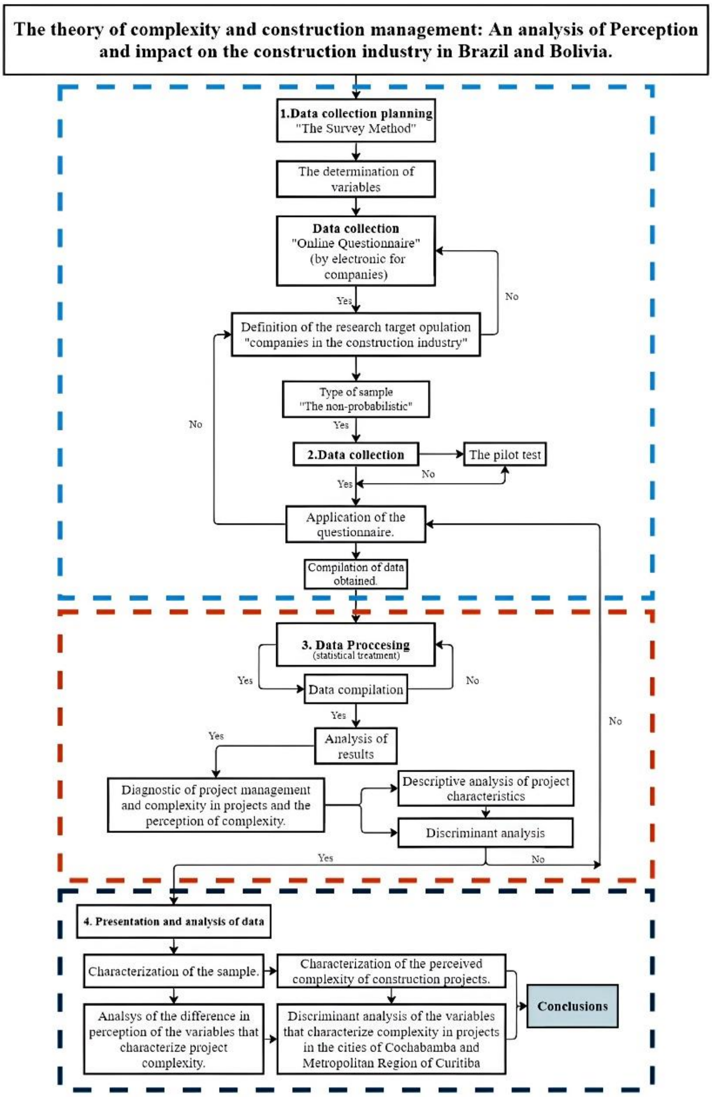

Fig. 1. Research development flowchart.

For this study, the data collection method was an online questionnaire, due to the ease of delivery provided by the electronic medium for the companies. The questionnaire proposed for the survey was divided into 4 parts.

The first section of the questionnaire focuses on the organization's profile, including questions about the number of employees, number of projects executed, and the company's field of activity. It also gathers information about the respondent's position within the company. This section consists of 13 questions, utilizing multiple-choice options or checkboxes. The second section comprises 8 questions aimed at understanding the perception of complexity. The third section addresses the diagnosis of each variable of complexity in construction projects, encompassing 36 questions to characterize each complexity-related topic. The fourth section focuses on project management and company performance, with 57 questions designed to diagnose variables related to project management. Sections two, three, and four employ a 7-point Likert scale to measure how each variable influences the complexity and management of construction projects from the respondent's perspective.

For the presentation and data analysis, statistical processing of the collected data will occur in two phases: data compilation with Microsoft Office Excel 2022 and analysis using SPSS version 24. This approach facilitates a comprehensive diagnosis of project management and complexity through descriptive and discriminant analyzes. Stage Four involves presenting and analyzing the data to characterize the perception of complexity in construction projects and to examine the differences in how variables defining project complexity are perceived, aiming to enhance understanding of complexity management in the construction industry.

3 Results

3.1 Construction as a Complex System

Complex systems, challenging to fully define, are characterized by their nonlinear and unpredictable behavior [6,12]. Comprised of numerous interconnected elements, these systems give rise to emergent behaviors that cannot be explained by analyzing the individual elements [12]. Additionally, they are open systems that interact with the environment, where any action in one component affects the entire system [13]. Consequently, studying these systems requires addressing them, as they cannot be understood by examining their components in isolation.

The product of a complex system exceeds the simple sum of its elements, with emergent properties that cannot be attributed to any individual component, while some intrinsic properties are inhibited. The systemic behavior of these elements is understood only when studied as a whole [8]. Complexity theory, derived from systems theory, explores the interdisciplinary knowledge of the structure, behavior, and dynamics of complex systems. In this sense, construction projects tend to be classified as nonlinear and non-repetitive. The construction projects exemplify nonlinear and non-repetitive processes involving numerous stakeholders [14]. They exhibit systemic characteristics, yielding outcomes disproportionate to inputs, emphasizing interoperability among participants and external collaborators. Consequently, the construction industry is regarded as a complex system.

In general, project management traditionally views projects as orderly and predictable endeavours, divisible into independent tasks and executed sequentially, akin to assembly line processes[9]. However, the success or failure of projects, commonly evaluated based on cost, schedule, and quality, often falls short within the construction sector [15]. Clients prioritize adherence to schedule, budget, and quality standards [10]. This highlights the need for a nuanced understanding of project complexity within the construction industry.

3.1.1 Complexity in construction projects

According to Ashton (2002), over 57% of companies had difficulties solely due to inadequate site investigation procedures. Similarly, it is stated that inadequate methods are often used to determine the scope and adequacy of works, and a major issue is the lack of understanding regarding the complexity and uncertainty associated with planning [16].

The key factors for measuring project success are schedule, cost, and quality. A global survey in 1992 revealed that most construction projects fail to meet time goals due to design issues and stakeholder disputes, with about 80% of projects facing high uncertainty at the start [17,18]. Statistics show that only 48% of projects meet cost targets and 46% meet schedule targets, indicating that more than half fail to meet expectations. These findings highlight the lack of significant improvement in project management over the past decade, underscoring the need for better tools, techniques, and methods [19].

Kumar Dey (2001) suggests that the primary barriers to project success are changes in the project environment, with uncertainties increasing alongside project size [20]. Large-scale construction projects face uncertain environments due to factors like planning and design complexity, numerous stakeholders, resource availability, climate, and regulations [2]. Effective management is fundamental for project success but must be timely and accurate [21]. The high failure rate of projects is often attributed to the uncertainty and complexity involved, coupled with a low level of understanding of these factors [22–24]. While uncertainty is inherent in any construction project, it is not being properly identified and managed.

Various studies underscore the complexity of the construction process, with Baccarini (1996) asserting it as the most intricate undertaking across industries. Despite this, the construction industry grapples with effectively managing the escalating complexity of large projects, as noted by Mills (2001). Baccarini emphasizes that comprehending project complexity in construction is pivotal, as specific project attributes inform critical managerial decisions. However, despite its significance, the linkage between project complexity and complexity theory in project management remains unexplored [22,23].

3.1.2 Complexity in organizational management in construction industry

Understanding complexity theory is relatively new in the scientific realm and remains an area of active investigation [25]. Drawing parallels between organizational management and construction project management is crucial. By examining how complexity science has been applied in organizational management within the construction industry, we can glean insights to inform the integration of complexity theory into construction project management practices.

As asserted by Parker and Stacey (1995), the world functions as a complex system, characterized by self-organization and emergent properties arising from interactions among its components and systems. Organizations, including those within the construction sector, exhibit adaptability as complex systems due to various factors [26]. Complex systems are synergistic wholes formed by interacting parts, surpassing the sum of individual components, and existing in perpetual interdependence with the environment. They consist of adaptive agents interacting within an environment, exchanging energy and information. These systems evolve dynamically over time, continuously adapting and learning from their environment. Nonlinearity characterizes their interactions, with positive and negative feedback leading to imbalance. Adaptability is a key feature, with agents modifying actions based on interaction events. Organizations and their environments can be viewed as adaptive complex systems, given the interplay of their characteristics [27].

3.1.3 Complexity in the construction process

In construction project discussions, "complexity" denotes intricacy, while "complex" signifies being composed of interconnected parts. Baccarini (1996) defines project complexity as encompassing diverse interrelated parts, operationalized by differentiation and interdependence. Gidado (1996) suggests that project complexity measures the difficulty in executing complex production processes, which involve intricate operational networks and workflows meeting predefined standards while avoiding conflicts among components. This highlights two perspectives on project complexity: the managerial perspective, focusing on workflow assembly, and the operational and technological perspective, addressing technical complexities and execution difficulties [21,22].

Bertelsen (2003) challenges the conventional linear view of construction processes, revealing them to be nonlinear, complex, and dynamic phenomena, often operating at the edge of chaos. Contrary to this understanding, project management tends to perceive projects as sequential linear processes, planned without considering the dynamic surrounding environment [9]. However, this overlooks the inherent complexity of projects, emphasizing the need for project management to recognize projects as complex and dynamic systems within nonlinear environments. Proposes three perspectives on complexity: projects as intricate assembly processes, the construction industry's highly fragmented nature resulting in constantly shifting patterns of cooperation, and construction sites fostering transient human systems characterized by cooperation and social interaction [9].

3.2 Diagnosis of project management and complexity in construction projects

This research work was developed focusing on companies and projects located in the Metropolitan Region of Curitiba, Brazil, consisting of 29 municipalities: Adrianópolis, Agudos do Sul, Almirante Tamandaré, Araucária, Balsa Nova, Bocaiúva do Sul, Campina Grande do Sul, Campo do Tenente, Campo Largo, Campo Magro, Cerro Azul, Colombo, Contenda, Curitiba, Doutor Ulysses, Fazenda Rio Grande, Itaperuçu, Lapa, Mandirituba, Piên, Pinhais, Piraquara, Quatro Barras, Quitandinha, Rio Branco do Sul, Rio Negro, São José dos Pinhais, Tijucas do Sul, and Tunas do Paraná, all municipalities located in Paraná, Brazil, as well as companies and projects located in the city of Cochabamba, Bolivia.

The questionnaire yielded 108 responses, with 49 from construction firms in Curitiba's Metropolitan Region and 59 from Cochabamba, Bolivia. Notably, many companies are situated in Cochabamba (55%) compared to the Metropolitan Region of Curitiba (45%). In terms of company structure, 82% of firms in both regions operate as limited liability companies with professional management (74%). Regarding respondents' roles, the majority (49%) identify as managers, while supervisors and interns represent smaller percentages (2% and 1%, respectively). This distribution underscores the predominance of individuals involved in project management within the sample (Figure 2).

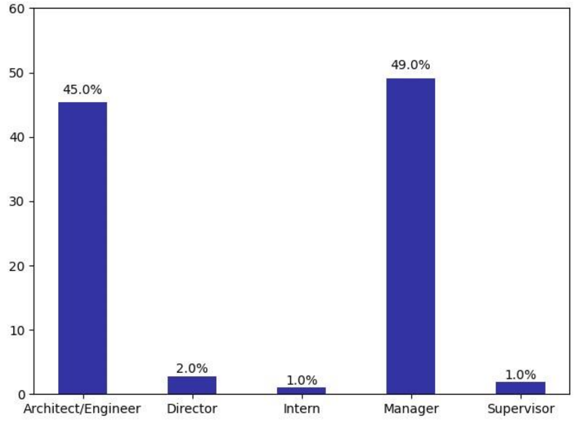

Fig. 2. Interviewer`s Characteristics.

3.2.1 Characterization of the perception of complexity in construction projects

Based on questionnaire responses pertaining to the "Defining Complexity" variable group, inquiries were made regarding the criteria for defining complexity in construction projects. Complexity poses challenges due to its multifaceted nature, with definitions ranging from intricacy to interdependence. Baccarini (1996) suggests that construction projects embody complexity, echoed by Mills (2001) and Mulholland and Christian (1999), who highlight the industry's dynamic and uncertain nature. Baccarini (1996) further defines project complexity as the presence of multiple interrelated parts exhibiting variability and interdependence. To gauge responses, a semantic differential scale was utilized, indicating the intensity of responses on a scale from 0 to 6. Analysis revealed that 47% of respondents in the Metropolitan Region of Curitiba and 44% in Cochabamba consider projects with numerous interrelated phases as complex (Figure 3) [18,22,23].

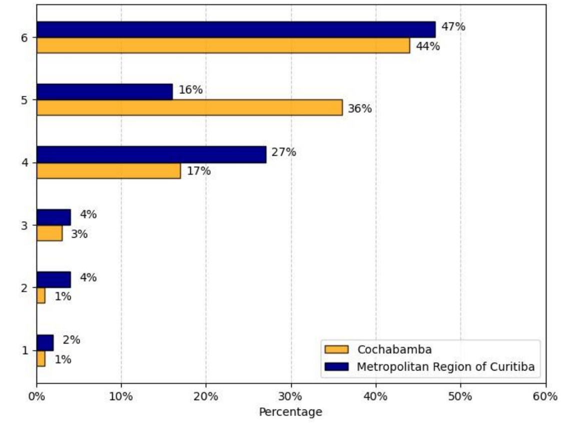

Fig. 3. Defining Complexity – Projects that have many interrelated phases.

The findings indicate that, based on the criteria provided by respondent companies, projects characterized by numerous interrelated and intricately executed phases are defined as complex. Regarding complexity related to projects with numerous specific phases, Figure 4 illustrates that 65% of companies in the Metropolitan Region of Curitiba perceive complex projects as those with a multitude of intricate phases requiring intricate execution.

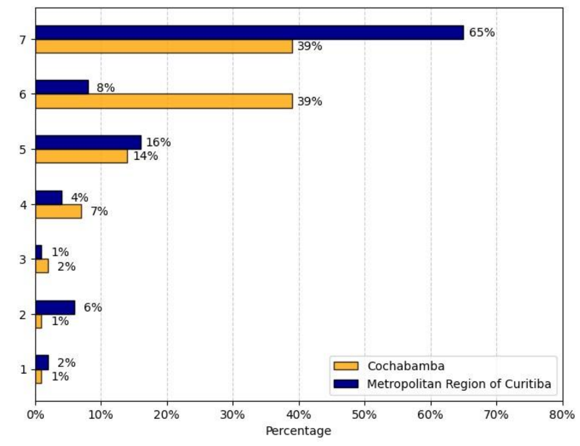

Fig. 4. Defining Complexity – Projects that involve a large number of specific phases that are challenging for realization/execution.

The research findings align closely with Woods (2010) study in the UK, revealing that 70% of respondents perceive projects with high interdependence among parts as complex, followed by those with extensive interaction with the external environment at 68%. This indicates an industry-wide consensus that projects characterized by extensive interdependence and interaction among components are deemed complex. Similarly, Gidados (1996) interviews with industry experts highlight project complexity's conceptualization, emphasizing aspects like numerous phases or processes, execution in challenging locations, and significant interaction with the external environment. These findings underscore prevailing definitions in the construction industry, emphasizing interdependence among components, interaction with the context, and reduced predictability and control. Notably, respondents perceive project complexity as closely tied to extensive interconnection among phases and significant interaction with the external environment, evident across various dimensions, including legal and economic factors. However, a significant percentage of respondents also associate project complexity with intricate stages, possibly indicating confusion between "complicated" and "complex" terms, emphasizing the need to clarify these distinctions within the construction industry.

3.3 Analysis of the difference in perception of the variables that characterize project complexity.

The perception of complexity was analyzed using Discriminant Analysis, a statistical method designed to identify significant differences between groups based on measured variables. Specifically, the aim was to distinguish differences between respondents from Cochabamba and the Metropolitan Region of Curitiba concerning various construction project complexity factors. This analysis aimed to ascertain whether notable differences exist in how complexity is perceived between these two groups.

3.3.1 Discriminant analysis of the variables that characterize complexity in projects in the cities of Cochabamba and Metropolitan Region of Curitiba

Discriminant analysis aimed to identify key factors characterizing complexity in construction projects by maximizing between-group distinction and minimizing within-group variability. The study analyzed questionnaire data focused on project complexity variables to discern pertinent factors for each city. Eigenvalues and descriptive statistics in Table 1 depicted variation within and between groups, while canonical correlation measured the relationship between discriminant variables and group membership, indicating the extent of differentiation between cities.

Table 1. Eigenvalues.

Function	Eigenvalue	% Of variance	% Cumulative	Canonical correlation
1	0.142	100	100	0.353

The eigenvalue obtained is quite close to 0, and the canonical correlation is low; hence, the discriminant variables do not allow for a clear distinction between the two groups.
Wilks' lambda statistic expresses the proportion of total variability not attributed to differences between groups; it tests the null hypothesis that the multivariate means of the

groups (the centroids) are equal. Therefore, values close to 1 indicate a great similarity between the groups, while values close to 0 indicate a significant difference between the groups [28]. In the study (Table 2), the lambda value is moderately high (0.876), which means there is a significant overlap between the groups.

Table 2. Wilks' Lambda.

Function Test	Wilks' Lambda	Chi-square	gl	Sig.
1	0.876	13.492	9	0.142

ANOVA assessed group mean equality for each independent variable, while the univariate Wilks' λ test gauged variable discrimination between groups. Table 3 indicates that p-values (Sig.) exceeding 0.05 imply a similar perception of complexity variables across both city-based groups.

Table 3. Tests of equality of group means.

Variables of Complexity in Projects	Wilks' Lambda	F	gl	gl2	Sig.
They involve a large number of execution phases	0.999	0.149	1	106	0.701
High degree of interdependencies between phases or processes	0.984	0.307	1	106	0.581
High degree of overlap between project phases	0.984	1.723	1	106	0.192
High degree of installations (hydraulic, sanitary, mechanical, and electrical)	0.975	2.690	1	106	0.104
Frequently include operations without a known procedure	0.997	0.313	1	106	0.577
High degree of technically complex functions	0.999	0.113	1	106	0.737
Taken into account in planning when the construction site is located in restricted areas	0.997	0.279	1	106	0.599
Degree of uncertainty regarding the subsurface	0.975	2.720	1	106	0.102
Lack of uniformity due to continuous changes in financial resources	1.000	0.042	1	106	0.838

The p-value (Sig.) suggests a shared perception of project complexity among respondents from Bolivia and Brazil, indicating consistency across multiple variables such as execution phases, interdependence between processes, and overlap among project phases. Bertelsen (2003) emphasizes the nonlinear and chaotic nature of construction projects, challenging traditional views of predictability. This highlights the independence and concurrent execution of project activities, disrupting conventional project management paradigms [19,29].

The structure matrix, displayed in Table 4, arranges variables based on their correlation strength with the discriminant function, aiding in identifying variables with significant discriminant power. This power is gauged by the correlation coefficient between each variable and the discriminant function. Notably, the variable "Degree of uncertainty regarding the subsoil" exhibits the highest correlation (0.425), surpassing "High degree of facilities" and others. Assessments should consider correlations in absolute terms. The matrix elucidates those stronger coefficients indicate greater disparities between cities, with "Degree of uncertainty regarding the subsoil" notably influencing the perception of complexity in construction projects.

Table 4. Structure Matrix

Variables of Complexity in Projects	Function 1
Degree of uncertainty regarding the subsurface	-0.425
High degree of installations (hydraulic, sanitary, mechanical, and electrical)	-0.422
High degree of overlap between project phases	0.338
Frequently include operations without a known procedure	-0.144
High degree of interdependencies between phases or processes	-0.143
Taken into account in planning when the construction site is located in restricted areas	0.136
Involve a large number of execution phases	-0.099
High degree of technically complex functions	-0.087
Lack of uniformity due to continuous changes in financial resources	0.053

Regarding the perception of companies, the findings reveal that a high percentage of firms in Metropolitan Region of Curitiba and Cochabamba consider projects complex if they involve numerous interrelated phases and specific stages that are challenging to execute. Additionally, a significant number of specific phases for implementation/execution are also associated with project complexity.

It is noteworthy that there are percentage differences between companies located in Greater Curitiba and Cochabamba, suggesting that the definition of complexity may vary according to the cultural perception of the firms, as mentioned by Wood (2010).

Another criterion that companies consider to define complexity in construction projects is the high degree of interdependence between parts and the interaction with the external environment, which aligns with Complexity Theory that involves systems in constant interaction with their context.

The results of the discriminant analysis indicate a similarity in the perception of complexity variables between Cochabamba and the Metropolitan Region of Curitiba, showing no significant difference. Among the variables prioritized by respondent companies, "Degree of uncertainty regarding the subsoil" emerges as the most influential, while "Lack of uniformity due to continuous change of financial resources" ranks lowest. This suggests that complexity is primarily associated with uncertainty about the project site's terrain, with soil analysis being crucial for design and construction calculations. Additionally, there's notable consideration for the potential facilities a construction project may offer, underscoring the importance of soil study in construction projects.

4 Conclusion

Construction projects are often described as complex, and the increasing complexity of modern construction projects and inadequate project management lead to low project success rates. Additionally, the construction industry is a complex system; however, the overall view of the construction process is that it is an ordered and linear phenomenon that can be easily organized, planned, and managed. Frequent failures in completing construction projects within a specific timeframe and budget suggest that the process may not be as predictable as it seems. This highlights the need for a better understanding of project complexity in the construction industry.

Based on the discriminant analysis conducted in the cities of Cochabamba, Bolivia, and Curitiba, Brazil, with the aim of understanding if the perception of complexity also varies among companies in both regions. Despite the differences between the two cities in terms of cultural, geographical, and regulatory context, the participating companies in the research have a similar view on which variables are most relevant in determining the complexity of construction projects.

The preceding conclusion suggests that certain characteristics of complexity in construction projects may be considered universal or shared among different geographical contexts. The percentage differences in responses can be attributed to cultural factors and the individual perception of companies, as pointed out by Wood (2010), highlighting the subjective nature of complexity perception.

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