Fuzzy Agent-Based Modeling of Competency and Performance Measures of Construction Organizations

by

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A thesis submitted in partial fulfillment of the requirements for the degree of

Master of Science

in

Construction Engineering and Management

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Abstract

Construction competency measures refer to a combination of the skills, knowledge, technologies, processes, and practices that a construction organization uses to improve its performance and the performance of its projects. Performance measures in construction are used to assess the effectiveness, competitiveness, and profitability of organizations based on ongoing or completed actions or processes. Previous studies have identified and developed separate measures for construction competency and performance at both the project and organization levels. However, in practice, construction organizations are project-based, and they develop competencies and performance through project execution. Project-level and organizational competencies are viewed as having a two-way relationship, where organizational competencies drive, orient, and support multiple projects and are simultaneously constantly investigated and redefined through practices brought by project-level competencies. Thus, project-level and organizational competencies appear inseparable in construction organizations. However, assessing the impact of a multilevel competency on performance is challenging because of the complex interaction between competencies and performance measures and the subjective uncertainty that exists in their measurement. Hence, an integrated framework is needed that provides a well-defined, structured model of categories of competencies that coexist in construction organizations and their projects, and the impact of these competencies on performance measures. This multilevel modeling framework should allow both competencies and performance to develop through project execution, meaning it needs to be a bottom-up modeling framework. Such a multilevel modeling framework is not found in the literature. Therefore, a significant gap exists for researchers seeking to improve competency and performance modeling in construction organizations.

To bridge this gap, this thesis aims to develop a hybrid fuzzy logic and agent-based model (FABM) that can handle the complex, dynamic, and subjectively uncertain nature of construction competency and performance measures to analyze construction competencies as inputs and predict multiple performance measures simultaneously. First, a comprehensive set of project level and organizational competency and performance measures were summarized and updated from the existing literature. Then, based on the proposed multilevel competency and performance framework, a FABM model was developed that constitutes the multi-agent environment corresponding to the hierarchical category of competency measures established. The fuzzy c-means (FCM) clustering and fuzzy inference system (FIS) were used to develop fuzzy membership functions and the initial behavioral and interaction rules of the competency agents based on the available data of project level and organizational competency measures. The parameters of the FCM clustering were further optimized, and a final set of FISs were established for the behavioral and interaction rules of the competency agents. FIS receives input competency measure variables from the multi-agent environment and delivers the predicted behavior of each agent as well as emergent performance measures. Existing construction competency and performance datasets were used to validate and verify the FABM model, with encouraging results in multilevel competency-based performance prediction in construction organizations. The contribution of this study is providing a systematic bottom-up modeling approach to measure and assess competencies at the project and organization levels and mapping these multilevel competencies to construction performance measures. Furthermore, the outcomes of this study are expected to support construction practitioners by providing a set of comprehensive hierarchical competency and performance metrics at the project and organization levels for managerial actions taken to identify, construct, and develop competency models to assess performance at both levels.

Preface

This thesis is an original work by Yisshak Tadesse Gebretekle. Chapter 3 has been published as Gebretekle, Y. T., & Fayek, A. R., 2022, "Identifying multilevel metrics for construction competency and performance measures," in *Proceedings of the 2022 Construction Research Congress*. Chapter 4 has been submitted for publication as Gebretekle, Y. T., & Fayek, A. R. (n.d.) "Fuzzy agent-based modeling of competency and performance measures in construction," in review, submitted to *Journal of Construction Engineering and Management* (ASCE). For these publications, I was the main person responsible for data analysis and composition of the manuscripts. Dr. Aminah Robinson Fayek was the supervisory author and was involved with concept formation and manuscript composition and editing.

Dedication

I dedicate my thesis work to my family. A particular feeling of gratitude to my loving parents, Tadesse Gebretekle and Shina Sied, whose words of encouragement and push for tenacity ring in my ears. And to my late sister Hana, you will always be with me.

I also dedicate this work and give special thanks to my wife and best friend Kokeb – without your love, support, and patience, I would not be able to complete this journey.

Acknowledgments

First and foremost, I would like to express my sincere gratitude to the almighty God for blessing me with the strength, determination, and perseverance to complete this study. I am deeply grateful for the divine guidance and protection that I received throughout the course of my research, which helped me to overcome challenges and obstacles along the way. I would also like to extend my heartfelt appreciation to my professor, Dr. Aminah Robinson Fayek, for her unwavering support, valuable directions, and generous allocation of time and energy towards guiding me through the research process. Her expert knowledge, insightful feedback, and constructive criticism have been instrumental in shaping the direction and scope of this study, and I am truly grateful for her mentorship and encouragement.

I would like to acknowledge the postdoctoral fellows of our research group Dr. Phuong Nguyen, Dr. Nima Gerami Seresht, Dr. Mohammad Raoufi, and Dr. Nebiyu Kedir for their valuable input which helped me refine my work at various stages of the research. In addition, I want to mention fellow researchers at the Hole School of Construction Engineering at the University of Alberta: Dr. Getaneh Tiruneh, Dr. Nasir Siraj, Kassa Tarekegn, Dr. Hamed Fateminia, Sahand Somi, Sara Ebrahimi, Matin Kazerooni, and Daniel Kamau or their help during my studies. I would also like to thank my colleagues Renata Brunner Jass and Sarah Miller for their critical work in editing my research papers.

I would like to express my deepest gratitude to my father, Tadesse Gebretekle, my mother, Shina Sied, and my sister, Hana, for their love, motivation, and encouragement during my research. Finally, I must express my very profound gratitude to my wife, Kokeb, who has stood by with unfailing support and continuous encouragement throughout my years of study and through the process of researching and writing this thesis. She gave me support and help, discussed ideas, and prevented several wrong turns not only during this research work but also in the journey of life.

Content

List of Tables

List of Figures

Chapter 1. Introduction

1.1. Background

The construction industry in general is often criticized for its underperformance compared to other industries, due to the increasing uncertainties in technology, budgets, complex processes, and the environment under which construction organizations operate (Liang et al. 2019). The productivity of the world's construction industry averaged only 1% growth per year from 1997 to 2017, compared to a rate of 2.8 percent growth in the total economy and 3.6 percent in manufacturing (Barbosa et al. 2017). Recent studies by Hanna et al. (2016), Loufrani-Fedida and Saglietto (2016), Omar and Fayek (2016), and Tiruneh and Fayek (2022) all strongly emphasize the importance of construction organizations adopting effective strategies in competency and performance measurement methods to improve the competitiveness of the industry. Furthermore, successful identification, understanding, and management of construction competencies and their effects on performance are critical for construction organizations to forecast their performance, recognize those competencies that require improvement, and develop performance enhancement strategies. Since McClelland (1973) first proposed the concept of "competency," researchers have proposed several definitions of construction competency. Having clearly defined competencies allows organizations and their employees to know exactly what is expected of them and how they should accomplish their tasks. In this thesis, the working definition of a construction competency as "an integrated combination of resources, particular sets of skills, necessary information, technologies, and the right corporate culture that enable construction organization to achieve its corporate goals, competitive advantage, and superior performance in its project execution" is used, based definitions provided by Succar et al. (2013), Loufrani-Fedida and Missonier (2015), Loufrani-Fedida and Saglietto (2016), Omar and Fayek (2016), and Tiruneh and Fayek (2020). The term *performance* has been of particular interest in the construction industry, although its interpretation can vary among construction practitioners (Georgy et al. 2005). Georgy et al. (2005) claim that performance may imply several dimensions including effectiveness, efficiency, quality, productivity, quality of work life, innovation, and profitability. Rambe and Makhalemele (2015) agree that the performance of an organization relates to the efficiency and effectiveness with which it carries out its tasks in the process of providing products and services. One major challenge is to be able to estimate or predict such performance in measurable terms that can be used for budgeting and control activities (Georgy et al. 2005; Lin & Shen 2007).

However, performance measurement is a complex process that no single factor can be used to predict or evaluate it. The literature reveals three specific types of performance measures used in the construction industry (Tiruneh & Fayek 2020): key performance indicators (KPIs); key performance outcomes (KPOs); and perception measures (PerMs). KPIs indicate assigned processes and can predict future trends, which aids in identifying problems at the early stages of a project. KPIs are considered leading measures in that they provide information on opportunities for change. In contrast, KPOs are the results of completed actions or processes, so they are lagging measures and do not enable change. PerMs can be either lagging or leading, depending on when surveys and interviews are conducted relative to completed actions or processes, and they are dependent on the management's focus.

According to Campion et al. (2011), competency models can help organizations align their initiatives to their overall business strategy. Previous studies have developed models to capture competency and performance from individual/personal (trade foreman, architects, engineers, managers, etc.) at the organization level. Competency-based multidimensional conceptual models have been proposed to predict the performance of project managers (Dainty et al. 2005, 2004). For instance, conceptual models include the project manager competency development framework (PMCDF) model (PMI 2017), international competence baseline (ICB) model (IPMA 2015, 2006), and global standard for project management competences (GSPMC) model (Vukomanović et al. 2016). These conceptual models are generic; hence, they do not capture industry and organization contexts. Some studies employed regression models that correlate project managers' behavior with the final project outcomes (Cheng et al. 2007; Ling 2004). Similarly, Elwakil et al. (2009) developed a regression model to predict construction organizations' performance. Neuro-fuzzy models have also been developed to predict the performance of engineers and design professionals (Georgy et al. 2005; Georgy & Chang 2005). However, models presented in these studies lack the capability to fully capture the subjective uncertainty and complex interaction that exists between construction competency and performance. More recently, Omar (2015) and Omar and Fayek (2016) developed a fuzzy neural network (FNN) to model project competency and performance, and Tiruneh and Fayek (2020) developed an adaptive-network-based fuzzy inference system (ANFIS) to model organizational competency and predict organizational performance.

In practice, construction is a complex system with numerous interactions between competencies at different levels influencing overall construction performance. Several authors have pointed out the need for simultaneous development of multiple levels of competencies (Frame 1999; Loufrani-Fedida & Saglietto 2016). In particular, Frame (1999) states that if an organization focuses on only one level, it will be unable to achieve its desired results. Similarly, Loufrani-Fedida & Saglietto (2016) revealed that competencies in construction projects must be seen as an integrated quality of individuals, teams, and organizations. According to Hobday (2000), construction organizations can be classified as project-based organizations (PBOs) where "the project is the primary business mechanism for co-ordinating and integrating all the main business functions of the organizations." In PBOs, competencies are built up through the execution of major projects, and it is important to have a holistic insight of both project level and organizational competencies (Loufrani-Fedida & Missonier 2015). Hence, competency and performance models in construction organizations should be modeled on multiple levels (e.g., project, organization).

1.2. Problem Statement

A key perspective in past studies on competence and performance modeling was the understanding the level of competence to investigate (Frame 1999). In construction organizations, projects are the primary business mechanism for co-ordinating and integrating all the organization's main business functions, particularly interrelated projects that fulfill the construction organization's overall business and strategy (Loufrani-Fedida & Missonier 2015). Within the organization studies literature, organization-level competencies represent the company's strengths or capabilities, described as aggregated learning in an organization, including the co-ordination and integration of various project and task execution skills and numerous types of processes (Prahalad & Hamel 1990). Brady and Davies (2004) define project competency as the internal ability of a PBO to create lasting performance based on multiple short-term projects. Project level and organizational competencies can be viewed as being in a two-way relationship where organizational competencies drive, orient, and support multiple projects and are simultaneously constantly investigated and redefined through practices brought by project-level competencies. Thus, project-level and organizational competencies appear to be inseparable in construction organizations

(Loufrani-Fedida & Saglietto 2016). However, a literature review on multilevel competency and performance modeling indicates that although the importance of a simultaneous approach for modeling is important in future work, there are currently no published multilevel competency frameworks or models for the construction domain. Therefore, although the existing body of knowledge provides a foundation for construction competencies measure identification, the **first gap** related to multilevel competency and performance modeling is a lack of defined hierarchies for measuring construction competencies at both the project and organizational levels. The **second gap** is that much of the current studies develop frameworks dealing with competency and performance separately, but they do not establish the link between competency and performance measures, and those that do formulate a relationship are conceptual and limited to a single level (i.e., individual, project, or organization). The **third gap** is that most previous studies do not consider the complex relationship between multilevel competency and performance measures accounting for subjective uncertainties that are inherent in their measures. Variables that define construction competencies and performance measures are both quantitative and qualitative, requiring modeling techniques that can capture both, which adds complexity to modeling efforts. Given the dynamic and complex nature of construction environments, these uncertainties pose significant challenges to developing models of construction competencies and performance.

Hence, an integrated framework is needed that provides a well-defined, structured model of categories of competencies that coexist in construction organizations and their projects and their impact on performance measures. This multilevel modeling framework should allow both competencies and performance measures to develop through project execution, meaning it needs to be a bottom-up modeling framework. Such a multilevel modeling framework is not found in the literature, which is a significant gap for researchers seeking to improve competency and performance modeling in construction organizations. To address these gaps, this study presents a fuzzy hybrid agent-based model for bottom-up modeling of the complex and dynamic nature of and subjective uncertainties involved in construction competency and performance measures of a construction organization at the project and organization levels.

1.3. Research Objectives

The main objective of this research is to develop a hybrid fuzzy logic and agent-based model (FABM) that can handle the complex, dynamic, and subjectively uncertain nature of construction competency and performance measures to analyze construction competencies as inputs and predict multiple performance measures simultaneously. To achieve this overall objective, this thesis had the following detailed modelling objectives:

1. To develop a comprehensive list and a hierarchical categorization of construction competency and performance measures at the project and organization levels.
2. To develop a multilevel construction competency and performance framework that establishes the relationship between competency and performance measures accounting for the characteristics of PBOs.
3. To develop a FABM model capable of assessing multiple construction competencies and predict multiple construction performance measures simultaneously.
4. To develop a systematic fuzzy c-means (FCM) clustering based, data-driven approach to establishing multiple fuzzy inference system (FIS) and decision rules in the FABM model to assess competencies and predict performance measures.

1.4. Expected Contributions

This thesis aims to provide contributions that will improve modeling and management of the competency and performance measures of construction organizations and their projects. Results of the thesis are expected to make contributions to the body of knowledge (Academic Contributions) and practitioners (Industrial Contributions).

1.4.1. Academic Contributions

The expected academic contributions of this research are:

- Development of a multilevel construction competency and performance conceptual framework linking competency measures at the project and organization levels and providing a useful reference on a comprehensive hierarchical list of competencies and performance measures for future multilevel analysis and modeling purposes.

- Development of an FABM approach that can handle the complex and dynamic construction environment while accounting for the subjective uncertainty that is inherent in construction processes and practices.
- Providing a methodology for developing multilevel construction competency and performance FABM models with multiple FISs for interaction and behavioral rules that can handle multiple competency measures as model inputs and performance measures as outputs simultaneously.

1.4.2. Industrial Contributions

The expected industrial contributions of this research are:

- Providing a useful reference of a comprehensive hierarchical list of competency and performance metrics at the project and organization levels in construction, for future competency and performance identification, analysis, and management purposes.
- Providing a conceptual framework that presents multilevel construction competency and performance measures while identifying the relationship between hierarchical categories of competency and performance measures at the project and organization levels.
- Providing a hybrid FABM modeling approach that enables construction industry practitioners to assess competencies and predict performance at multiple levels while accounting for the subjective uncertainties in measuring competencies by experts, and furthermore to assist in identifying competencies that need improvement and so help to improve performance.

1.5. Research Methodology

The proposed research methodology to fulfil research objectives stated is presented in Figure 1.1 and is briefly described below.

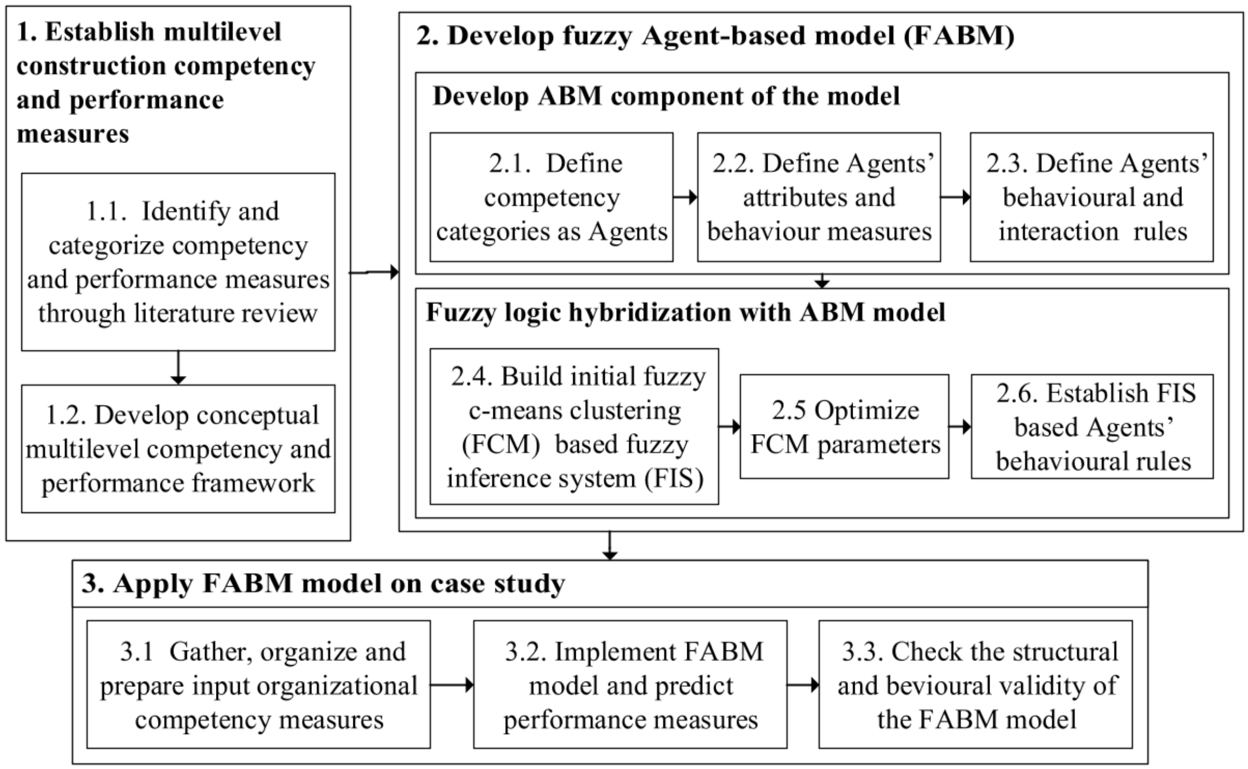

Figure 1.1. Research methodology to develop fuzzy hybrid agent-based model (FABM) of multilevel construction competency and performance.

1.5.1. First stage: Establish Multilevel Construction Competency and Performance Measures

In the first stage, a comprehensive set of project-level and organizational competency and performance measures are summarized and updated from the existing literature. Both competency and performance measures are further divided into sets of evaluation criteria that can be captured through different data collection methods involving construction experts and construction organizations and their projects, either quantitatively or qualitatively. Furthermore, a framework that captures the two-way relationship in PBOs, where organizational competencies drive, orient, and support multiple projects and are simultaneously constantly investigated and redefined through the execution of projects level competencies is proposed. The proposed integrated framework provides a hierarchical link between competencies at the project and organization levels of assessment, developed specifically for the construction context, and maps the multilevel competencies to the hierarchy of project- and organization-level performance measures. Both competency and performance categories were further divided into sets of evaluation criteria that can be captured through different construction experts and collected from construction organizations and their projects either quantitatively or qualitatively. Finally, a data collection approach for measuring construction competencies and performance measures that account for quantitative and qualitative evaluation criteria is presented.

1.5.2. Second stage: Develop a Fuzzy Agent-Based Construction Competency and Performance Model

Based on the proposed multilevel competency and performance framework in the first stage, a construction competency-based performance model was developed using the FABM approach. There are two major functional components in the FABM competency and performance model development: the fuzzy logic component and the agent-based model (ABM) component. The ABM component constitutes the multi-agent environment where each agent represents competency measure category. An agent is an identifiable, discrete, and flexible conceptual modeling element with a set of attributes and rules governing its behaviors and decision-making capability (Macal & North 2015). The attribute of an agent represents the competency measures under each category and the overall competency measure of each category/agent is represented by the behavior of the agent. The FCM clustering and a FIS make up the fuzzy logic component. FCM clustering is used to develop fuzzy membership functions and initial rules for the behavioral and interaction rules of the competency agents based on the available data of project-level and organizational competency measures. Parameters of the FCM clustering are further optimized and a final set of FISs is established for the behavioral and interaction rules of the competency agents. The FIS receives input competency measure variables from the ABM environment and delivers the predicted behavior of each agent and emergent performance measures.

1.5.3. Third stage: Implement FABM Model on Case Study

The construction competency and performance dataset used to validate and verify the FABM model proposed in this thesis was provided from a previous study conducted by Tiruneh and Fayek (2022). First, the collected competency and performance data were subjected the preprocessing steps of normalization, ignoring incomplete data instances, and eliminating outliers that transform the dataset into a format that is more easily and effectively processed in FABM analysis. Then, the

FABM model is verified to confirm that both the ABM and fuzzy logic components of the model work as expected. To verify the FABM model, all mathematical equations and methods of the model, such as MATLAB codes, are checked for correctness. Further, the model is run multiple times to check for replicability of results, with tracing graphs used to track changes in model results. Finally, the FABM model validation determines how well the model reflects a real-world system (Sargent 2013), which was accomplished in two steps. First, conceptual validity was performed by basing the model on validated competency and performance concepts from the literature (Sargent 2013). Construction organizational and project-level competency and performance measures were defined based on past literature in the construction and related domains. The identified list of measures is then validated by industry experts (e.g., Omar & Fayek 2016; Tiruneh & Fayek 2020). Furthermore, as suggested by Macal and North (2015), the problem to be modeled should fully be described, including all model components such as agents, rules, and data preparation. Second, operational validity should be performed using both subjective and objective approaches (Sargent 2013). A subjective approach to operational validity was performed using graphical displays such as prediction versus target values. Hence, all performance measure results were plotted in the FABM model to observe their behavior for both the testing and training datasets. The objective approach to operational validity was performed by comparing the statistical test results (e.g., root-mean-square error) obtained from the FABM model with those obtained by the genetic algorithm–adaptive neuro-fuzzy inference system (GA-ANFIS) model developed by Tiruneh and Fayek (2022), which provided the modeling dataset used in this study.

1.6. Thesis Organization

Chapter 1 provides background information on construction competency and performance research and identifies the gaps in the construction context regarding multilevel modeling and management of competency and performance management in construction organizations. This chapter also presents the research objectives, expected academic and industrial contributions, and research methodology of the thesis.

Chapter 2 presents an extensive literature review on the relevant topics, including identification of construction competency and performance measures, competency-based performance modeling in construction, and applications of fuzzy hybrid modeling in the construction competency and performance research domain. Furthermore, some limitations and research gaps in existing works are also discussed.

Chapter 3 presents a multilevel competency framework to identify the link between project-level and organizational competency and performance measures. In addition, comprehensive set of project-level and organizational competency and performance measures that are summarized and updated from existing literature.

Chapter 4 presents the overall methodology and the detailed steps for developing the hybrid FABM model with multiple FISs that can handle multiple inputs (i.e., competency measures) and multiple outputs (i.e., performance measures) with multiple FIS rule sets. Finally, the applied model verification and validation methods are also described.

Chapter 5 describes the conclusions, contributions, and limitations of the study as well as recommendations for future research.

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Chapter 2. Literature Review

This section presents an overall review of past studies on competency and performance measurement and modeling in the construction domain, followed by a review of fuzzy hybrid modeling approaches in construction competency-based performance studies. Construction competency and performance studies are investigated in general, with emphasis given to studies related to multilevel modeling in the construction domain.

2.1. Construction Competency and Performance Measures

2.1.1. Competency in Construction

Much of the literature cites *competency* as a concept first proposed and developed in McClelland (1973), which argues that traditional intelligence tests do not predict future life success. However, McClelland (1973) failed to provide an explicit definition for what a competency is, instead giving examples, such as traditional cognitive skills (reading, writing, calculating) and personal variables, of what he considered to be competencies. The next major milestone often cited in many studies in advancing the concept of *competency* is attributed to the Boyatzis's (1982) study, where he coined the definition of competency: "an underlying characteristic of a person which results in effective and/or superior performance in a job." Boyatzis further suggested an underlying characteristic of a person could include a motive, trait, skill, an aspect of one's self-image or social role, or a body of knowledge, which is causally related to the achievement of effective, or better, work performances. Camuffo and Gerli (2005) argued that Boyatzis's definition is "general enough to reflect either individual or specific organizational concern." Escrig-Tena and Bou-Llusar (2005) added that in existing literature, competencies are frequently identified as individual employee skills and capabilities rather than a team, a process, or overall organizational core competencies that drive business execution. Escrig-Tena and Bou-Llusar (2005) affirm that the concept of competencies consists of individual/personal competency (e.g., experience, technical knowledge, skills, abilities) and corporate competencies (i.e., a combination of skills and knowledge that belong to the organization itself). They argue that the competencies of organizations are a combination of skills and knowledge not only possessed by individual members, but also embedded in company processes and systems. Thus, these skills and knowledge remain in the organization even when individuals leave it. Hence, studies by Succar et al. (2013), Loufrani-Fedida and Missonier (2015), and Loufrani-Fedida and Saglietto (2016) attempt to capture competency using a multilevel approach at the individual, team/collective, and organizational levels.

For instance, Succar et al. (2013) viewed the competency of an organization as multilevel, consisting of competency (i.e., an individual's ability) and capability (i.e., a team or organization's ability) to perform a specific task, as well as maturity (i.e., a team or organization's excellence) in performing a task. Their study argued that total organizational competency is an aggregation of individual and/or team/group competencies. According to Crawford (2015), the concept of maturity is used to describe the state of an organization's effectiveness at performing certain tasks. The competency versus maturity approach perceives organizational competency (i.e., capability and/or maturity) as an aggregation of individual and/or team capability/maturity. This approach enables performance assessment and improvement that teams and/or organizations aspire to achieve (Succar et al. 2013). However, the competency versus maturity approach fails to capture the overall aspect of an organization that goes beyond simply aggregating individual competency and/or team capability or maturity. Loufrani-Fedida and Missonier (2015) viewed competency in a broad sense as "the ability of an individual, a team, or a company to mobilize and combine resources in order to implement an activity." Furthermore, Loufrani-Fedida and Saglietto (2016) defined project management competence (PMC) mechanisms as those used to identify and develop competencies of individuals, collectives, and organizations that can aid in the performance of project tasks. However, the multidimensional and multicultural construct of competency faces a challenge in establishing the precise definition of construction competence. Accordingly, many organizations should define required competencies based on the goals that are identified within the context of their strategic plan (Loufrani-Fedida & Saglietto 2016). For this study, Gebretekle and Fayek's (2022) working definition of construction competency is used: "an integrated combination of resources, particular sets of skills, necessary information, technologies, and the right corporate culture that enable construction organization to achieve its corporate goals, competitive advantage, and superior performance in its project execution."

2.1.2. Performance Measurement in Construction

The term *performance* has been of particular interest in the construction industry, although its interpretation can vary among construction practitioners (Georgy et al. 2005). Georgy et al. (2005) claimed that performance may imply several dimensions including effectiveness, efficiency, quality, productivity, quality of work life, innovation, and profitability. Rambe and Makhalemele (2015) agreed that the performance of an organization relates to the efficiency and effectiveness with which it carries out its tasks in the process of providing products and services. One major challenge is to be able to estimate or predict such performance in measurable terms such that they can be used for budgeting and control activities (Georgy et al. 2005; Lin & Shen 2007).

A review of the literature indicated that research studies have focused on establishing the performance measurement frameworks for construction companies (Kagioglou et al. 2001; Bassioni et al. 2004; Yu et al. 2007). Kagioglou et al. (2001) adapted the Balanced Scorecard approach to the construction industry, wherein company goals are linked with performance measures in terms of financial, customer, internal business, innovation and learning, project, and suppliers. Bassioni et al. (2004) developed a conceptual framework based on the Balanced Scorecard for measuring the business performance of construction organizations; however, they did not implement the framework nor develop evaluation methods for the performance factors. Yu et al. (2007) developed a model to measure and compare performance of construction companies based on company-level key performance indicators (KPIs). Therefore, research in the construction domain has largely been focused on establishing performance measurement frameworks for construction companies. Furthermore, performance measurement frameworks, such as KPIs and the Balanced Scorecard, consider performance measurement from a different perspective, while they either overlap or complement one another in terms of giving focus on the financial aspect (Omar & Fayek 2016).

2.2. Categorization of Construction Competency and Performance Measures

According to Campion et al. (2011), competencies can be hierarchically arranged, meaning they can be divided into categories and subcategories. The existing body of knowledge provides a foundation for construction competencies identification and categorization. For instance, IPMA (2015) identified 46 project management competencies and classified them into three major categories: technical, behavioral, and contextual. Omar and Fayek (2016) categorized 41 construction project competencies into two groups: functional and behavioral. IPMA (2015) developed 28 competencies, categorized as practice, people, and perspective competencies, which are analogous to the technical, behavioral, and contextual competencies of IPMA (2006). Janjua et al. (2012) derived five competency classes: functional, generic management, social skills, cognitive skills, and personal characteristics. Salajeghe et al. (2014) developed a framework for competency assessment with five categories of knowledge, performance, personal, industry, and organizational competencies. Takey and Carvalho (2015) classified project management competencies into the four categories of project management processes, personal, technical, and context and business. Loufrani-Fedida and Missonier (2015) grouped competencies into three categories: functional, integrative, and collective. The variety of approaches to competency categorization indicate that organizations define their competencies and categorize them on the basis of their needs and strategic goals. Based on the literature, this study categorizes construction competency measures at both the organizational and project-levels in two sets: functional and behavioral competencies. Functional competencies are related to how an organization or project operates and functions, and behavioral competencies refer to attributes of individuals working at the project or organizational level.

Performance is such a complex process that no single factor can be used to predict or evaluate it (Poveda & Fayek 2009). The literature (Radujković et al. 2010; Deng & Smyth 2014; Omar & Fayek 2016; Tiruneh & Fayek 2022) reveals three specific types of performance measures used in the construction industry: KPIs, key performance outcomes (KPOs), and perception measures (PerMs). KPIs are indicative of assigned processes and can predict future trends, which aids in identifying problems at the early stages of a project. The use of KPIs dominates the practice of performance measurement in construction (Deng & Smyth 2014). KPIs are considered leading measures in that they provide opportunities for change. In contrast, KPOs are the results of completed actions or processes, so they are lagging measures and do not enable change. Managers in construction sometimes utilize KPOs such as profit, return on equity, and time, as though they were KPIs, although they may be unaware of it (Beatham et al. 2004). PerMs can be either lagging or leading, depending on when surveys and interviews are conducted relative to completed actions or processes, and they are dependent on the management's focus. PerMs are subjective in nature and are often measured through surveys and interviews (Radujković et al. 2010).

Previous studies do not capture overall multilevel construction competency and performance or the dynamic and complex nature of construction organizations and their projects. Such studies consider either individual (IPMA 2015; Janjua et al. 2012), project-level competencies (IPMA 2015; Omar & Fayek 2016) or organizational level (Tiruneh & Fayek 2022) but fail to frame them as multilevel phenomena. To address these gaps, this study develops a more comprehensive categorization of construction competencies that can be applied at the project and organization levels. This project also proposes a framework for relating multilevel construction competencies to performance measures. The proposed categorization of construction competency and performance measures, identified through a thorough literature review and analysis, helps to capture construction processes and practices as a whole for organizations.

2.3. Competency-Based Performance Modeling in Construction

A construction organization and its projects' performance depends greatly on its competencies, and measuring and improving performance has always been an important endeavor for construction practitioners (Georgy et al. 2005). Competency models are a realization of a specific combination of knowledge, skills, and other personal characteristics necessary for the efficient execution of tasks (i.e., that are needed for effective performance) in the organization (Campion et al. 2011). In construction projects, individuals work on team activities, which are part of a network of multiple, interrelated projects that fulfill the construction organization's overall business strategy (Loufrani-Fedida & Missonier 2015). Thus, the four levels of competencies – individual, activity, project and organization – appear inseparable in construction organizations (Loufrani-Fedida & Saglietto 2016). However, past studies have developed mechanisms to identify and develop competency and performance measurement at the individual, activity, project, and organizational levels separately.

Most of the research focusing on individual competencies deals mainly with the competencies of project managers who have been described using different attributes (Cheng et al. 2005; Crawford 2005; Starkweather & Stevenson 2011). According to (Crawford 2005), as organizations tend to define their activities more as projects, the demand for project managers grows, and there is an increasing interest in project management competency (PMC) as well as in standards for assessment, development, and certification of PMC. Conceptual PMC frameworks have been developed, such as the project manager competency development framework (PMCDF) model (PMI 2017), the international competence baseline (ICB) model (IPMA 2015), and global standard for project management competencies (GSPMC) model (Vukomanović et al. 2016). Cheng et al. (2005) proposed classifying the critical competencies of project managers in two categories: generic competencies applied to all types of projects, and job-task competencies specific to the sector in which project managers operate. Starkweather and Stevenson (2011) identified six critical competencies for project managers: leadership, ability to communicate at multiple levels, verbal skills, written skills, attitude, and ability to deal with ambiguity and change. These were considered indicative of characteristics important to successful project management. In addition, Poveda and Fayek (2009) developed a fuzzy expert system performance evaluation model that has a capacity to predict and evaluate construction trade foremen performance.

However, as Midler (1995) showed, the diversity and complexity of the competencies involved in the course of a project mean it is insufficient to adopt an approach that focuses solely on team members taken individually or on the project manager alone. The fundamental characteristic of a project is precisely its collective dimension. The notion of activity competence can be defined as "a group's ability to perform together towards a common goal, which results in the creation of a collective outcome, an outcome that could not be accomplished by one member due to its complexity" (Ruuska & Teigland 2009). Therefore, at the activity level, studies have reported the effects of activity competence on projects' performance (Maznevski 1994; Ruuska & Teigland 2009; Ruuska & Vartiainen 2003). Maznevski (1994) revealed that to reach desired project performance, it was necessary to go beyond individual competencies and combine them in a common effort. Also, studies in the project management field found that successful projects are those able to achieve collective competence (Ruuska & Teigland 2009; Ruuska & Vartiainen 2003).

Studies by Cheng et al. (2007) by Omar and Fayek (2016) suggested that construction organizations must develop project-level competency and performance models. They defined project competence as an organization's ability to generate/select and implement/execute projects skillfully, and identified performance measurements for final project outcomes. Omar and Fayek (2016) developed a fuzzy neural network (FNN) to model project competency and performance. However, if individuals' and activities' competencies have to be expressed in projects, Frame (1999) underlined that in project-based organizations (PBOs), development of project-level competencies need the support of their organization. Within the literature on organizational level studies, the organization-level competencies represent a company's strengths or capabilities. Thus, they have been described as the aggregated learning of an organization, including the co-ordination and integration of various production skills and numerous types of technology (Tiruneh & Fayek

2020). Tiruneh and Fayek (2022) developed an adaptive neural fuzzy inference system (ANFIS) to model organizational competency and predict organizational performance.

Both project-level and organizational competencies are essential to conducting projects in PBOs (e.g., construction organization) and should not be considered separate competency and performance systems that are isolated from each other. Some studies (Loufrani-Fedida & Missonier 2015; Loufrani-Fedida & Saglietto 2016; Melkonian & Picq 2011; Muffatto 1998; Ruuska & Vartiainen 2003) have highlighted that a simultaneous approach of addressing multilevel competencies appears fundamental to a relevant analysis of competence management in PBOs. However, the literature review on multilevel competency and performance modeling indicates that there are currently no multilevel competency models in the construction domain.

2.4. Fuzzy Agent-Based Modeling (FABM) in Construction Competency-Based Performance Modeling

The diversity, dynamism, complexity, and inherent subjective uncertainty that exist in construction organizations and projects make construction management–related model development challenging (Rezk et al. 2019). To address these shortcomings, fuzzy hybrid models have been implemented in construction management studies. Fuzzy logic is a powerful modeling technique designed to handle natural language and approximate reasoning. Moreover, it can process linguistic inputs with subjective uncertainty to provide outputs or decisions (Pedrycz & Gomide 2007). Fuzzy hybrid techniques combine fuzzy logic with other techniques, such as FNN, fuzzy reasoning, fuzzy expert systems (FES), fuzzy c-means (FCM) clustering, and fuzzy simulation techniques. Such fuzzy hybrid modeling approaches have been gaining popularity in construction competency and performance studies. At the individual level, Rezk et al. (2019) developed an FES competency evaluation model for trade workers in transportation projects for a state highway agency. Omar and Fayek (2016) and Tiruneh and Fayek (2022) presented an FNN-based model for evaluating competency and predicting performance at the project and organization levels, respectively. However, a well-defined, structured modeling framework of categories of competencies that coexist in construction organizations and their projects and their impact on performance measures is needed. This multilevel modeling framework is a significant gap for researchers and managers seeking to improve competency and performance management in construction organizations (Loufrani-Fedida & Saglietto 2016).

The agent-based modeling (ABM) approach is well suited to modeling competency-based performance models in PBOs, such as construction organizations, due to several modeling advantages it offers. First, ABM allows for the representation of individual agents within an organization, such as project managers, workers, and stakeholders, each possessing their own competencies and behaviors. This individual-level modeling enables a granular understanding of how competencies influence the performance of agents and how their interactions shape overall organizational performance. Second, ABM captures the dynamic nature of PBOs by simulating the iterative and adaptive decision-making processes that occur during project execution. It considers the complex interdependencies and feedback loops that exist among agents, competencies, and performance, allowing for the exploration of various scenarios and the identification of emergent behaviors. Third, ABM provides a platform for experimentation and testing of different strategies and interventions aimed at improving competency utilization and performance outcomes. It enables the evaluation of alternative scenarios and the assessment of their impact on an organization's performance, facilitating evidence-based decision-making (Macal & North 2008). Despite the advantages of ABM, its application in construction management is in early stages (Stieler et al. 2022) because of the lack of a valid approach to incorporating subjective uncertainties in construction system models.

Fuzzy ABM (FABM) is a fuzzy hybrid modeling technique that integrates fuzzy logic with ABM and has the advantage of being able to capture subjective uncertainty and model the complex and dynamic nature of construction systems (Bokor et al. 2019). Notable works in FABM application in construction management are very rare, and the most relevant ones have focused on construction crew motivation and performance. Raoufi and Fayek (2018) developed a predictive FABM model for construction crew performance–based crew motivation. They used fuzzy inference system (FIS) rules to address the subjective uncertainty that exists in decision-making variables and their interaction. FIS is a powerful tool for dealing with uncertainty in decision-making processes. FIS operates by converting input variables into linguistic terms, which are then processed through a set of rules to generate an output. The linguistic terms and rules are usually defined by experts in the domain of interest, and the system can be fine-tuned using real-world data. Similarly, Kedir et al. (2020) presented a methodology for integrating multicriteria decision-making (MCDM) with FABM to develop a decision support model that simulates the complex relationships and social interactions between crews and crew members. The contribution of such novel works validates the value of FABM in modeling the complex and dynamic nature of and the subjective uncertainties involved in construction systems. This chapter presents the application of FABM in modeling the competency and performance measures of a construction organization at multiple levels, namely the project and organization levels.

2.5. Summary

Competency management is the set of managerial actions taken by an organization to identify, construct, and develop competency models for assessing the organization's performance using one of the two modes of learning referred to as exploitation and exploration (Loufrani-Fedida & Saglietto 2016). Competency models refer to a specific combination of knowledge, skills, abilities, and other characteristics that are needed for effective performance in the execution of tasks (Campion et al. 2011). These competency models can be developed for specific jobs, job groups, organizations, occupations, or even industries. Modeling approaches and techniques for competency and performance are identified after a review of past studies, as summarized in Table 2.1, which capture competency and performance from individual/personal (trade foreman, architects, engineers, managers, etc.) level and an organization level. However, because of the diversity, dynamism, and complexity of construction organizations and their projects, the current success of different competency and performance modeling approaches is difficult to measure. Furthermore, the relationships between project and organizational competencies and performance have not been well established.

Table 2.1. Summary of past competency and performance models in construction.

Model type and reference(s)	Limitation
Conceptual models IPMA (2015), PMI (2017), Cheng et al. (2007)	• Models are limited to specific aspects that do not capture project and organizational aspects. • Many models lack evidence-based relation; hence, need validation.
Correlation and/or regression models Dainty et al. (2004, 2005)	• Models are developed at individual level for project managers. • Self-report measures used in and lacks to account subjective uncertainties in measures.
Artificial neural network (ANN) models Elwakil et al. (2009)	• The model does not consider competency aspects as the inputs and outputs in the model are performance measures in terms of CSFs. • It lacks capturing uncertainty which is common in construction.

Fuzzy expert systems (fuzzy logic) models Poveda & Fayek (2009)	• Factors considered in the model affecting performance capture only behavioral aspect of competency since it considers individual perspective of trade foremen.
Hybrid fuzzy models (FNN, ANFIS) Georgy et al. (2005), Georgy & Chang (2005), Omar & Fayek (2016), Tiruneh & Fayek (2022)	• Some models do not present a distinction between competency and performance. • Are limited to a single level (project or organizational)

Variables that define construction competencies and performance are both quantitative and qualitative, requiring modeling techniques that can capture both, which adds complexity to modeling efforts. Quantitative variables (e.g., "high" competency measures) can be best expressed in linguistic terms rather than crisp values. Fuzzy logic is a powerful modeling technique designed to handle natural language and approximate reasoning; moreover, it is able to process linguistic inputs to provide outputs or decisions (Pedrycz 2013). Hence, the application of fuzzy logic hybrid techniques has been gaining popularity in construction management research in the last two decades (Sadeghi et al. 2016). However, the application of these fuzzy hybrid modeling techniques for competency and performance research is limited, as Table 2.1 shows. In particular, agent-based simulation techniques such as FABM are not implemented in construction competency and performance models, despite their advantage of providing a bottom-up modeling approach suitable to PBOs.

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Chapter 3. Multilevel Construction Competency and Performance Measures Framework[1]

3.1. Introduction

Successful identification, understanding, and management of construction competencies and their effects on performance is critical for construction organizations to forecast their performance, recognize competencies that require improvement, and develop performance enhancement strategies. Recent studies strongly emphasized the importance of construction organizations adopting effective strategies and performance measurement methods to improve the competitiveness of the construction industry (Eken et al. 2020; Hanna et al. 2016; Loufrani-Fedida & Saglietto 2016; Omar & Fayek 2016; Tiruneh & Fayek 2020). Researchers have developed mechanisms to identify and develop construction competencies separately at both the project (Omar & Fayek 2016) and organization (Eken et al. 2020; Tiruneh & Fayek 2020) levels. However, previous studies have not linked these competencies to each other and performance measures at multiple levels. Several authors have noted the need for simultaneous development of multiple levels of competencies (Frame 1999; Loufrani-Fedida & Saglietto 2016), stating that if an organization focuses on only one level, it will be unable to achieve the expected performance results in project execution.

According to Hobday (2000, p. 874), construction organizations can be classified as project-based organizations (PBOs) in which "the project is the primary business mechanism for co-ordinating and integrating all the main business functions of the organizations." In PBOs, the competencies are built up through the execution of major projects, and it is important to establish a holistic view of both project- and organization-level competencies (Loufrani-Fedida & Missonier 2015). The main challenges associated with multilevel construction competencies and performance measures are 1) identifying the interrelationship between competencies at the project and organization levels and 2) relating these multilevel competencies to construction performance measures at the project and organization levels. In this study, a comprehensive set of the project-level and organizational competency and performance measures are summarized and updated from existing literature. In

1 The contents of this chapter have been published on Gebretekle, Y. T., & Fayek, A. R. (2022). Identifying multilevel metrics for construction competency and performance measures. *Proceedings of the 2022 Construction Research Congress* (pp. 744–753). https://doi.org/10.1061/9780784483978.076.

addition, a multilevel competency framework is proposed that can enable researchers in identifying the link between project-level and organizational competency and performance measures, that can also provide construction organizations with an improved means of predicting performance.

3.2. Multilevel Construction Competency and Performance Framework

In PBOs, project execution is the major business endeavor, and the effectiveness of competency and performance management in project execution affects the development of new opportunities (Loufrani-Fedida & Saglietto 2016). The fundamental characteristic of a construction project is precisely its collective dimension. The notion of collective competence can be defined as "a group's ability to perform together towards a common goal, which results in the creation of a collective outcome, an outcome that could not be accomplished by one member due to its complexity" (Ruuska & Teigland 2009, p. 324). Hence, although each level of competencies is essential to performing projects in PBOs, the project and organization levels should not be considered separate competency-based performance systems, isolated from each other.

As a PBO, a construction organization is recognized as a learning organization, because it requires comparisons and co-ordination between project competencies and allows competency development through the execution of tasks and major projects (Hobday 2000). More recently, the literature also suggests PBOs must develop project competencies, which describe the internal ability of a PBO to create a lasting performance based on multiple short-term projects. Söderlund (2005) defines project competence as an organization's ability to generate/select and implement/execute projects skillfully and considers organization-level competencies to include the procedures, skills, and co-ordination processes of projects. In addition, organizational competencies are essential for effectiveness in project completion. In accordance with PBO characteristics, this study proposes a framework that allows both competencies and performance to develop through project execution. The proposed integrated framework, illustrated in Figure 3.1, provides a hierarchical link between competencies at the project and organization levels of assessment, is developed specifically for the construction context, and maps the multilevel competencies to the hierarchy of project- and organization-level performance measures.

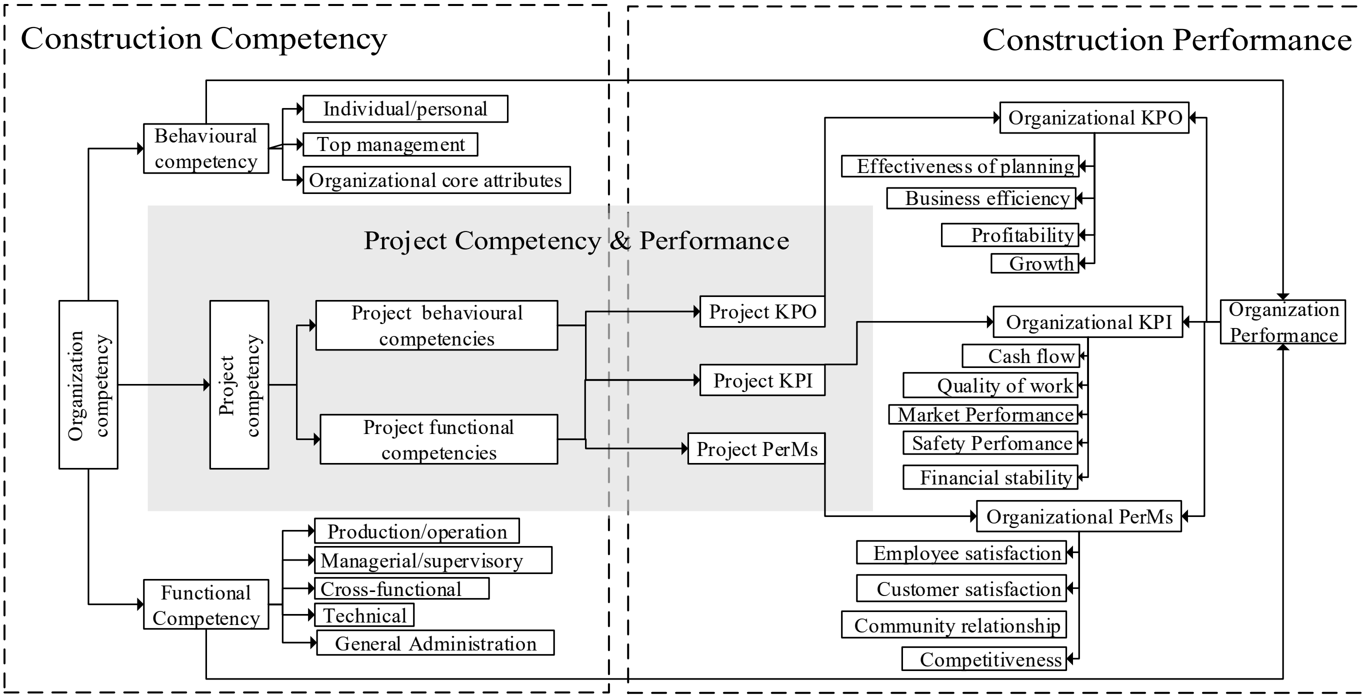

Figure 3.1. Proposed multilevel construction competency and performance framework.

The proposed framework addresses the major challenge associated with developing a multilevel construction competency and performance measure, by: defining hierarchies of construction competencies and performance measures at the project and organization levels; identifying how competencies at each level will be integrated into a multilevel competency model; and relating the multilevel model of competencies to performance at each level of assessment. Hence, the proposed framework permits holistic competency measurement as well as performance evaluation and prediction.

3.3. Multilevel Construction Competency Measure

Competency measures are better managed when hierarchically arranged, meaning they can be divided into categories and subcategories (PMI 2017). Based on the literature, competency measures necessary for determining construction competencies at both the organization and project-levels were identified and categorized into either functional or behavioral competencies (Gebretekle & Fayek 2022). Functional competencies refer to how an organization or project operates and functions. Behavioral competencies refer to attributes of individuals working at both levels. At the organization level, functional and behavioral competency measures were further divided into five and two subcategories, respectively. The multilevel construction behavioral and functional competency measures used in this study are summarized, categorized, and presented in Table 3.1 and Table 3.2, respectively.

Table 3.1. Construction behavioral competency measures.

Category	Organizational behavioral competency measures
Organizational core attributes	Ability to build trust; competitiveness; adaptability/flexibility. achievement drive; innovation; organizational awareness and culture
Top management	Leadership; strategic thinking; judgment; analytical ability, values, and ethics
Individual/personal	Reliability/Dependability; commitment; teamwork; ethics; effectiveness; resourcefulness; perseverance; attention to detail
Category	**Project behavioral competency measures**
Middle management	Interpersonal skills; decision-making; reasoning; conflict and crisis resolution/issue management; assertiveness
First-line management	Problem solving; results orientation; responsiveness; influence; communications

Table 3.2. Construction functional competency measures.

Category	Organizational functional competency measures
General administration	Staff development/training; goal orientation; human resources/personnel; management and support of diversity; interdisciplinary alignment
Cross-functional	Co-operation and co-ordination (collaboration); customer/stakeholder focus; interface management; communications management
Technical	Quality of work; technical/job knowledge; commitment to safety, planning and organizing of tasks/activities; technical innovation
Production/ operational	Construction technology and integration management; construction, production, and manufacturing; material management; operations and maintenance; process engineering management; resource management;
Managerial/ supervisory	Engagement; management excellence, resource management; delegation

Category	Project functional competency measures
Project management	Safety management; quality management; schedule (time) management; scope management; commissioning and startup management; change management; managing performance; cost management; risk management; procurement management; integration management; communication management; contract administration;

3.4. Multilevel Construction Performance Measure

Performance measures can be either leading indicators (KPIs), lagging indicators (KPOs), or both (PerMs) (Radujković et al. 2010). KPIs comprise five categories at both the organization and project-levels. Performance measures within the KPI categories are leading indicators that enable prediction of future trends and identify problems in the early stages of organizational operations and/or projects, which provides the opportunity for intervention to improve performance. KPOs comprise four and three categories at the organization and project levels, respectively. Performance measures within the KPO categories are lagging indicators, which are measured as a result of an outcome and do not enable change. PerMs are categorized as *Employee/internal customer satisfaction*, *Customer/external satisfaction*, *Competitiveness*, or *Community relationship* at both levels, depending on the manager/individual's perception and/or focus. PerMs can be either leading or lagging indicators, depending on when they are measured. The list of KPOs, KPIs, and PerMs measures were identified from existing literature and are presented in Table 3.3. The selection of KPOs, KPIs, and PerMs was based on the review of their application in past research in the construction domain (Campion et al. 2011; Gebretekle & Fayek 2022; Omar & Fayek 2016; Tiruneh & Fayek 2020; Rezk et al. 2019; Loufrani-Fedida & Saglietto 2016).

Table 3.3. Construction performance measures.

Category	Organization-level performance measures	Project-level performance measures
KPIs	Quality of work/service Market performance Safety performance Financial stability Cash flow	Project cost Project schedule Project changes Project safety Project quality
KPOs	Profitability Growth Business efficiency Effectiveness of planning	Project engineering/construction productivity Project absenteeism Project employee turnover

PerMs	Employee/internal satisfaction	Project employee satisfaction
	Customer satisfaction	Project subcontractor satisfaction
	Competitiveness	Project team competitiveness
	Community relationship	Project spending on charitable institutions and local community

3.5. Methods of Measuring Multilevel Construction Competencies and Performance

The proposed framework includes both competency and performance measures, which are further divided into sets of evaluation criteria that can be assessed by different construction experts. The evaluation criteria were collected from construction organizations and their projects either quantitatively or qualitatively Qualitative measures used to characterize competencies and performance are measured using linguistic terms, and quantitative measures are measured numerically. Two types of scales are identified for qualitative measures of functional competencies at project and organizational level. The first scale is a five-point maturity scale (levels 1–5) that measures project and organizational maturity and focuses on practices and processes to assess the presence of different evaluation criteria (Omar & Fayek 2016). The second scale is a seven-point importance rating scale (levels 1–7) to identify the importance and relative weight of each evaluation criterion.

Table 3.4 presents sample functional competency criteria for the organization-level cross-functional category. The maturity levels are scaled as follows:

1. Informal – Use of the practice is ad hoc or inconsistent for each project and organizational unit.
2. Documented – Disciplined processes exist for each individual project and the organization.
3. Integrated – Defined processes exist across each individual project and the organization.
4. Strategic – Quantitatively managed process control exists across each individual project and the organization.
5. Optimized – Continuous process improvement exists across each individual project and the organization.

The importance rating scale is ordered as follows: 1 = Extremely Unimportant, 2 = Unimportant, 3 = Slightly Unimportant, 4 = Neither Important nor Unimportant, 5 = Slightly Important, 6 = Important, and 7 = Extremely Important.

Table 3.4. Sample cross-functional (functional) competencies measurement scale.

Competency evaluation criteria	Description	Maturity Scale (1–5)					Importance Scale (1–7)						
Co-operation and co-ordination (collaboration)	Establish and maintain effective both internal (among teams, departments, and projects) and external (partners, stakeholders) co-operation, co-ordination, and collaboration	1	2	3	4	5	1	2	3	4	5	6	7

Similarly, Omar and Fayek (2016) and Tiruneh and Fayek (2020) used two sets of seven-point bipolar measurement scales for behavioral competencies, measuring agreement and importance. The agreement rating scale is ordered as follows: 1 = Strongly Disagree, 2 = Disagree, 3 = Somewhat Disagree, 4 = Neither Agree nor Disagree, 5 = Somewhat Agree, 6 = Agree, and 7 = Strongly Agree. This scale is used to measure the extent to which respondents agree that the different evaluation criteria for behavioral competencies exist within an organization (Omar 2015). Table 3.5 gives sample behavioral competency criteria for the *Middle management* category at the project level.

Table 3.5. Sample middle management (behavioral) competencies measurement scale.

Competency evaluation criteria	Description	Agreement Scale (1–7)						
Interpersonal skills	Ability to with employees/teams from diverse backgrounds by managing their needs and feelings through maintaining open-line communication	1	2	3	4	5	6	7

Furthermore, numerical scales are assigned to measure quantitative performance measures. For example, profitability and growth can be assigned percentage points on a numerical scale. Qualitative performance measures, such as company image/reputation under competitiveness, can be measured using predetermined rating scales. In general, qualitative performance measures include subjective PerMs (e.g., satisfaction, competitiveness) and some measures under KPIs (e.g., quality of service, market returns). Satisfaction rating scales are ordered as follows: 1 = Very Dissatisfied, 2 = Dissatisfied, 3 = Neither Satisfied nor Dissatisfied, 4 = Satisfied, and 5 = Very Satisfied. Table 3.6 shows measurement scales for construction competencies and performance.

Table 3.6. Measurement scales for construction performance measures.

Category	Example(s) of measures	Data type	Scale of measure
KPI	Cash flow, Rework factor, Market share	Quantitative	Number, Percentage
	Quality of service, Market returns	Qualitative	Satisfaction (1–5) rating scale (perception metrics)
KPO	Profitability, Growth rate	Quantitative	Number, Percentage
PerMs	Company image/reputation, Satisfaction, Competitiveness	Qualitative	Satisfaction (1–5) rating scale (perception metrics)

3.6. Summary

This chapter presents the development of a multilevel construction competency and performance framework to address a significant gap in the literature, linking competencies at the project and organization levels and mapping these multilevel competencies to construction performance measures at both levels. Based on the study and analysis of the literature and characteristics of PBOs, hierarchical categorization of competency and performance measures is developed. A comprehensive list of functional and behavioral competency measures as well as performance measures (i.e., KPIs, KPOs, PerMs) are developed for use in the proposed multilevel framework. Finally, this chapter proposes a data collection approach for measuring construction competencies and performance measures accounting for quantitative and qualitative data.

This chapter contributes to the state of the art in construction competency-based performance modeling by developing a multilevel novel framework that enables researchers to identify the link between the project level and organizational competency and performance measures, which in turn can provide construction organizations with an improved means of predicting construction performance. Second, this chapter identifies, categorizes, and ranks a comprehensive list of construction competency and performance measures for both researchers and the industry. The next chapter presents how this framework is used to develop a novel methodology for a hybrid fuzzy agent-based model (FABM) of construction organization competency and performance is presented that captures a set of organizational and project-level competencies as decision-making entities (i.e., agents) of the model and predicts multiple performance measures simultaneously.

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Chapter 4. Fuzzy Agent-Based Modeling (FABM) of Competency and Performance of Construction Organizations[2]

4.1. Introduction

The proposed fuzzy agent-based modeling (FABM) model for capturing construction competency measures at organizational and project levels to predict the performance measures of construction organizations is presented in Figure 4.1. The proposed model comprises three phases, namely: 1) establishing multilevel competency and performance measures, 2) developing the FABM model, and 3) application of the developed FABM in a case study.

In the first phase, discussed in chapter 3, multilevel construction competency and performance measures are identified through a comprehensive background review of the literature and categorized in a framework based on the work by Gebretekle and Fayek (2022). In the second phase, the FABM component of the model is developed, which involves two steps. First, the agent-based modeling (ABM) component is developed, which involves defining a set of agents representing competency measure categories, defining agents' attributes and behaviors, and establishing the agents' behavioral and interaction rules. Second, the fuzzy machine learning technique of fuzzy c-means (FCM) is integrated with the ABM component to generate fuzzy inference system (FIS)-based agents' behavioral and interaction rules. The third phase entails the application of the developed model in a case study, where the FABM model is empirically implemented and validated by comparing the structure and behavior of the model with data from a real-world system.

[2] The contents of this chapter have been submitted for publication on Gebretekle, Y. T., and Fayek, A. R(n.d.). "Fuzzy agent-based modeling of competency and performance measures in construction." Journal of Construction Engineering and Management, ASCE, (under review).

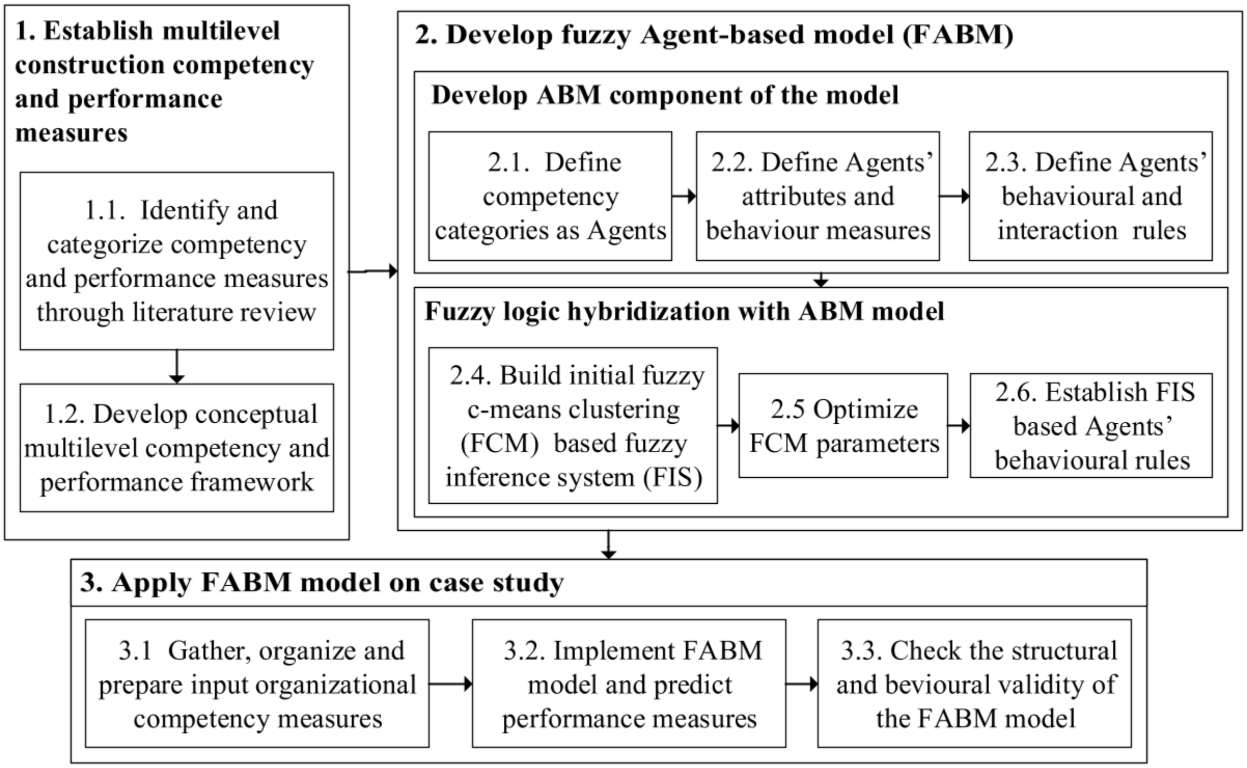


Figure 4.1. FABM model development methodology for construction competency and performance.

4.2. FABM Development Methodology

4.2.1. Fuzzy Logic and Agent-Based Model Integration Architecture

The FABM competency and performance model architecture has two major functional components: the fuzzy logic component and the ABM component (Djennas 2012). As presented in Figure 4.2, FCM clustering and FIS make up the fuzzy logic component. FCM clustering is used to develop fuzzy membership functions and initial rules based on the available data of project and organizational competency measures. The parameters of the FCM clustering are further optimized, and a final set of FIS is established for the agents' behavioral and interaction rules.

The ABM component constitutes the multi-agent environment in which each agent represents a competency measure category presented in Tables 3.1 and 3.2. An agent's attribute represents the competency measures under each category, and the overall competency measure of each category/agent is represented by the agent's behavior. The FIS receives input competency measure

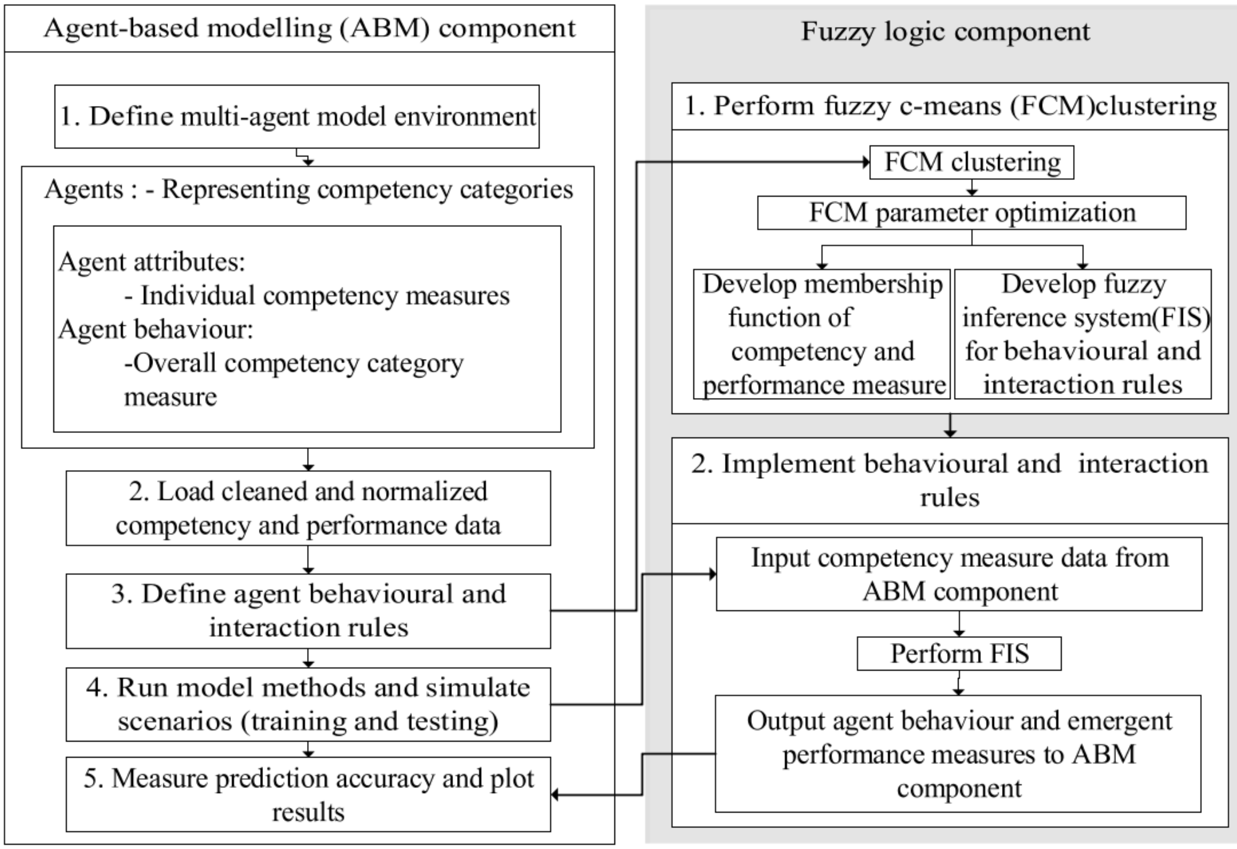


Figure 4.2. Fuzzy logic and ABM integration for competency and performance.

variables from the ABM environment and delivers the predicted behavior of each agent and of emergent performance measures.

4.2.2. Define the Basic Structure of Competency Agents: Agent Attributes and Behaviors

The multi-agent environment represents the multilevel competency and performance conceptual framework established, where both the behavioural and functional categories of competency measures affect the performance measures. Figure 4.3 shows the proposed model of the relationship between competency and performance measures at the project and organization levels. Competency agents are the decision-makers in the FABM model; hence, correctly specifying their attributes and behaviors and appropriately representing agent interactions is the first step. Based on the information shown in Tables 3.1 and 3.2, 11 competency agents (eight organization-level and three project-level) were established, as shown in Figure 4.3.

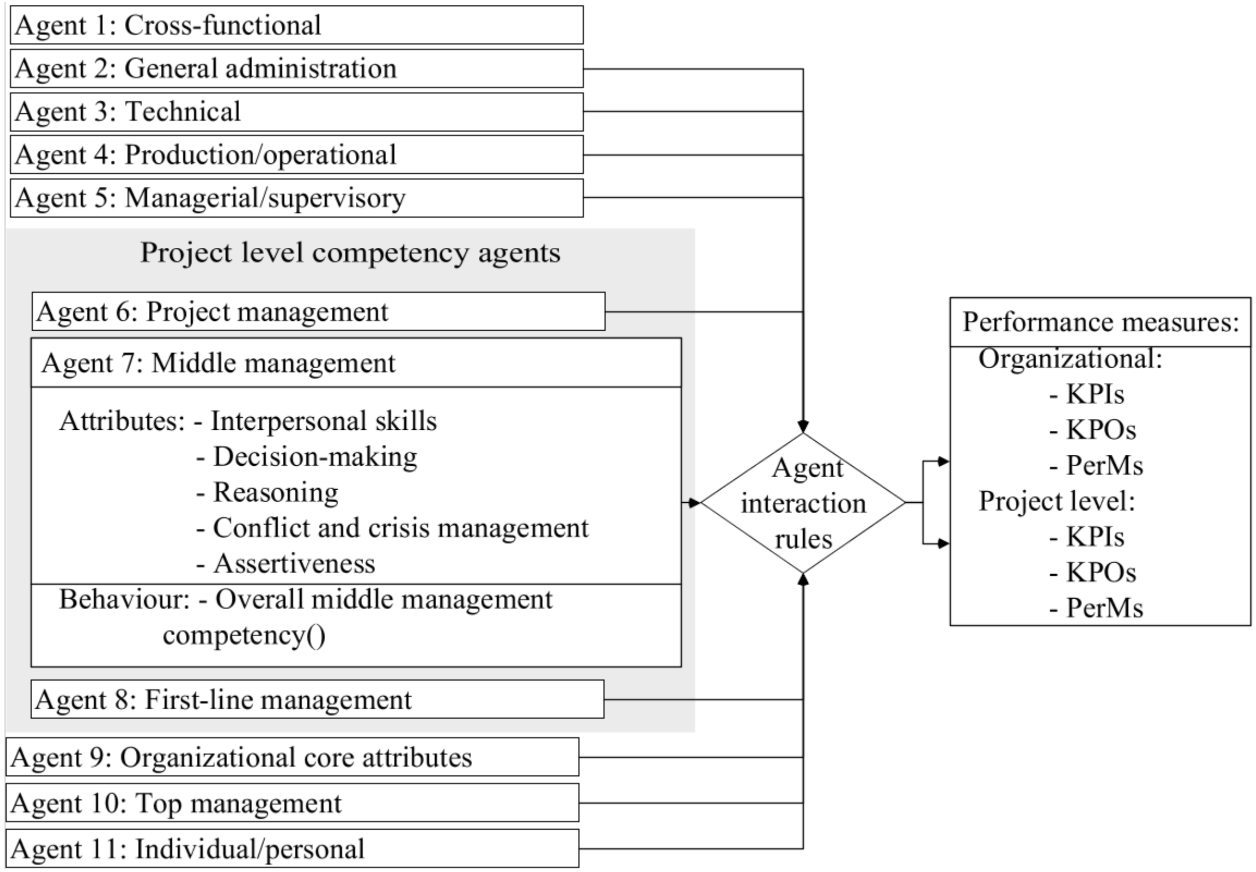


Figure 4.3. Sample representation of the basic structure of behavioral competency agent at project level, for *Middle management* agent class.

All competency agent classes represent competency categories, with the individual competency measures in each category representing the attributes of a given agent and the overall category measure as the behavior of the agent, as shown in Figure 4.3. The overall competency measure of a category (i.e., behavior of each agent) aggregates into the emergent behavior of the model, which constitutes the measures for project and organization performance. Figure 4.3 also shows a sample of the basic structure of the *Middle management* agent using agent-unified modeling language to represent a behavioral competency project-level category. Qualitative and quantitative measures are used to capture competency and performance in construction organizations and their projects within the proposed multilevel framework, with qualitative measures employing linguistic terms due to uncertainties arising from subjective linguistic expression, while quantitative measures are expressed numerically. Hence, to model behavioral rules in FABM, fuzzy rules need to be defined, which can be accomplished using either an expert-driven approach (i.e., using domain expert judgments) or data-driven approaches (e.g., fuzzy machine learning techniques) where sufficient data regarding the agents' attributes and behaviors are available. Pedrycz and Gomide (2007) showed how to define fuzzy rules from data using fuzzy machine learning techniques, such as FCM clustering.

4.2.3. Define Competency Agent Behavioral and Interaction Rules

The proposed model utilizes multiple FISs that are defined for each agent's behavior (i.e., agent's attributes as inputs and agent's behavior as output) and agents' interaction rules for emergent behavior of the FABM model (i.e., agent's behavior as input and performance measures as output). Therefore, the proposed model is not limited to a single FIS, but rather consists of multiple FISs that represent agent behavior and interaction rules. In this study, FCM clustering was used to develop the FIS rules of agent behavior and interaction rules. FCM clustering is a fuzzy machine-learning technique that groups a dataset into clusters, assigning each data instance a membership degree ranging from 0 to 1. It achieves this by iteratively adjusting the membership degrees based on the distance of each data point from the cluster center. The initial estimates for cluster centers and membership grades are randomly assigned, and through iterative optimization, the cluster centers and membership grades are updated to minimize an objective function representing the distance from each data point to the cluster center (Pedrycz and Gomide 2007). Equations (1) and (2) outline the iterative update process for the partition matrix ($U=[u_{ik}]$) and cluster centers ($V=[v_j]$), respectively, where the fuzzification coefficient m is a parameter influencing the shape of the fuzzy clusters.

$$u_{ik} = \frac{1}{\sum_{j=1}^{c} \left(x_k - v_i / x_k - v_j\right)^{2/(m-1)}}, i = 1, \ldots, c, k = 1, \ldots, N \quad (1)$$

$$v_j = \frac{\sum_{k=1}^{N} u_{ik}^{m} x_k}{\sum_{k=1}^{N} u_{ik}^{m}}, i = 1, \ldots, c, k = 1, \ldots, N \quad (2)$$

Hence, FCM clustering results in the development of c number of fuzzy rules in the form of "If input variable is Ai, then output variable is Bi." Two types of FIS are commonly implemented in construction management research: Mamdani and Takagi-Sugeno. Mamdani FIS is intuitive and has better interpretability, namely explicit knowledge representation. Takagi-Sugeno FIS has a greater capability for numeric processing, namely accuracy of prediction. In this research, both Mamdani and Takagi-Sugeno FIS types were applied, depending on their prediction accuracy.

4.2.4. Implementation and Validation of FABM Model

The FABM model underwent verification and validation processes to ensure the proper functioning of its ABM and fuzzy logic components. Verification included four steps: checking mathematical equations for errors, conducting a structured walk-through of the model components (e.g., MATLAB codes), running the model multiple times for result replicability, and utilizing tracing and run-time graphs to track variable changes during training and testing predictions (Sargent 2013).

Validation of the FABM involved three steps. First, conceptual validity was achieved by basing the model on validated competency and performance concepts from the literature, with input from industry experts (e.g., as in Tiruneh and Fayek 2020). Per Ormerod and Rosewell (2009), the problem to be modeled was fully described, including all model components such as agents, rules, and data preparation. Second, data validity was ensured through a structured data collection methodology. Finally, operational validity was assessed through subjective approaches, using graphical displays to compare predictions and targets, and objective approaches, comparing results with the genetic-algorithm–adaptive neuro-fuzzy inference system (GA-ANFIS) model developed by Tiruneh and Fayek (2022) using the same dataset. The conformity of predicted values to actual observations was evaluated using root-mean-square error (RMSE) as the fitness function.

4.3. Case Study and Competency and Performance Dataset Overview

In this case study, a FABM model of construction organization competency and performance was developed based on the proposed multilevel framework and methodology. The FABM model was implemented on a competency and performance dataset that describes the relationship between the organization's project management competency and its overall organizational performance. The goal is to develop a FABM model that can predict performance in a way that reflects the variations in each competency category agent's attributes and behaviors, and the interactions with other agents.

The construction competency and performance dataset used in this research was provided from a previous study conducted by Tiruneh and Fayek (2022), who collected data regarding competencies influencing organizational performance from two surveys—a senior management survey and a staff survey. The senior management survey addressed everything in the staff survey plus additional organizational competencies and performance metrics that can only be evaluated by senior management and were not known to the other respondent group. All other participants, including project managers, field supervisors, and foremen, completed the staff survey. In all, 34 functional and 29 behavioral competencies (total = 63) were collected.

For measuring attributes of functional competency levels, participants used a five-point maturity scale (levels 1–5) to assess the presence of each functional competency in the organization. Similarly, for behavioral competencies, participants used a seven-point (1–7) bipolar measurement scale to measure the extent to which they agreed each behavioral competency existed within the organization. Furthermore, numerical scales were assigned to measure quantitative performance measures. For example, profitability and growth can be assigned percentage points on a numerical scale. Qualitative performance measures, such as *Company image/reputation under competitiveness*, can be measured using predetermined rating scales. In general, qualitative performance measures include subjective PerMs (e.g., satisfaction, competitiveness) and some measures under KPIs (e.g., quality of service, market returns). Satisfaction rating scales were as follows: 1 = Very Dissatisfied, 2 = Dissatisfied, 3 = Neither Satisfied nor Dissatisfied, 4 = Satisfied, and 5 = Very Satisfied. In summary, 62 data instances were obtained with 63 competency measures (34 functional and 29 behavioral) to be used as attributes for 11 competency agents (five behavioral and six functional) and six organizational performance measures. The six organizational performance metrics that had sufficient data variability were: *Employee satisfaction*, *Customer satisfaction*, *Competitiveness*, *Quality of work*, *Safety performance*, and *Effectiveness of planning*. The dataset was then checked for missing values, outliers, and inconsistencies. Next, data were normalized using Equation (3), which transforms the dataset to the range of [0 1] to simplify and enhance training performance and improve prediction accuracy of the model. Normalizing the input-output data helps avoid domination of attributes in greater numeric ranges over smaller numeric ranges and avoid numerical difficulties (Cheng & Roy 2010).

$$x_N = \frac{x_i - x_{max}}{x_{min} - x_{max}} \qquad (3)$$

where x_i and x_N are the original and normalized values of x, respectively, and x_{min} and x_{max} are the minimum and maximum values of x, respectively.

4.3.1. Agent Behavior and Interaction Rules

After data cleaning and normalization, agent behavior rules were established. The behavioral rules of the agents are functions of competency measures that correspond to competency categories presented in Tables 3.1 and 3.2. Using an FIS is proposed in the FABM methodology section to address the subjective uncertainty in the measure of competency and performance. According to the proposed methodology, FCM clustering was applied on the collected field data to develop fuzzy rules to represent the 11 competency agent behavioral rules; in other words, these are rules regarding how the six functional and five behavioral competency agents perform based on their attribute values, which are individual competency measures. Next, the behavioral outputs of the 11 agents were used as inputs to establish the six organizational performance measures using separate fuzzy rules. The identified fuzzy rules were then used to construct a corresponding FIS. The accuracy of the FIS was checked using RMSE between predicted output values and the actual output values of the testing data, as expressed in Equation (4). A combination of different values for the number of clusters and the fuzzification coefficient for the FCM clustering were investigated to optimize the FCM and subsequently develop the FIS.

$$RMSE = \sqrt{\sum_{i=1}^{N}(x_i - \hat{x}_i)^2/N} \qquad (4)$$

where x_i and $\hat{x}_i$ are target and predicted values, respectively, and N is the number of data instances.

4.3.2. Fuzzy c-Means Parameter Optimization

The development of the code for determining the optimal number of clusters, denoted as *c*, and the fuzzification coefficient, represented as *m*, for both Mamdani and Takagi-Sugeno FIS types was conducted using the MATLAB programming language. The dataset utilized for this process underwent cleaning and normalization prior to application of the FCM clustering algorithm. To optimize the FCM parameters, an extensive investigation was conducted with varying values of *c* ranging from 3 to 7 and values of m ranging from 1.25 to 3.75, utilizing a step size of 0.25. The objective was to identify the combination of *c* and *m* that yielded the minimum RMSE when running the MATLAB code for a total of 100 iterations. The corresponding FCM parameters associated with the minimum RMSE were recorded as the optimum values.

To provide insights into the process, Figure 4.4 illustrates a sample plot depicting the outcome of the parameter optimization for FCM clustering for the *Middle management* agent class behavioral rule with Takagi-Sugeno FIS type. This plot shows the relationship between the selected FCM parameters and the achieved optimization result, which is subsequently utilized to formulate the behavioral rule for the *Middle management* agent. A similar procedure was repeated for each of the 11 agents within the model to determine their respective behavioral rules. Additionally, the optimization process was extended to encompass the six performance measures, which encompass the interaction rules between the agents. Tables 4.1 and 4.2 present a comprehensive summary of the FCM parameters associated with the minimum RMSE for agent behavior rules and agent interaction rules, respectively. These tables consolidate the essential information regarding the FCM parameter optimization, aiding in the understanding of the chosen parameter configurations for the agents' behavioral rules and the performance measures.

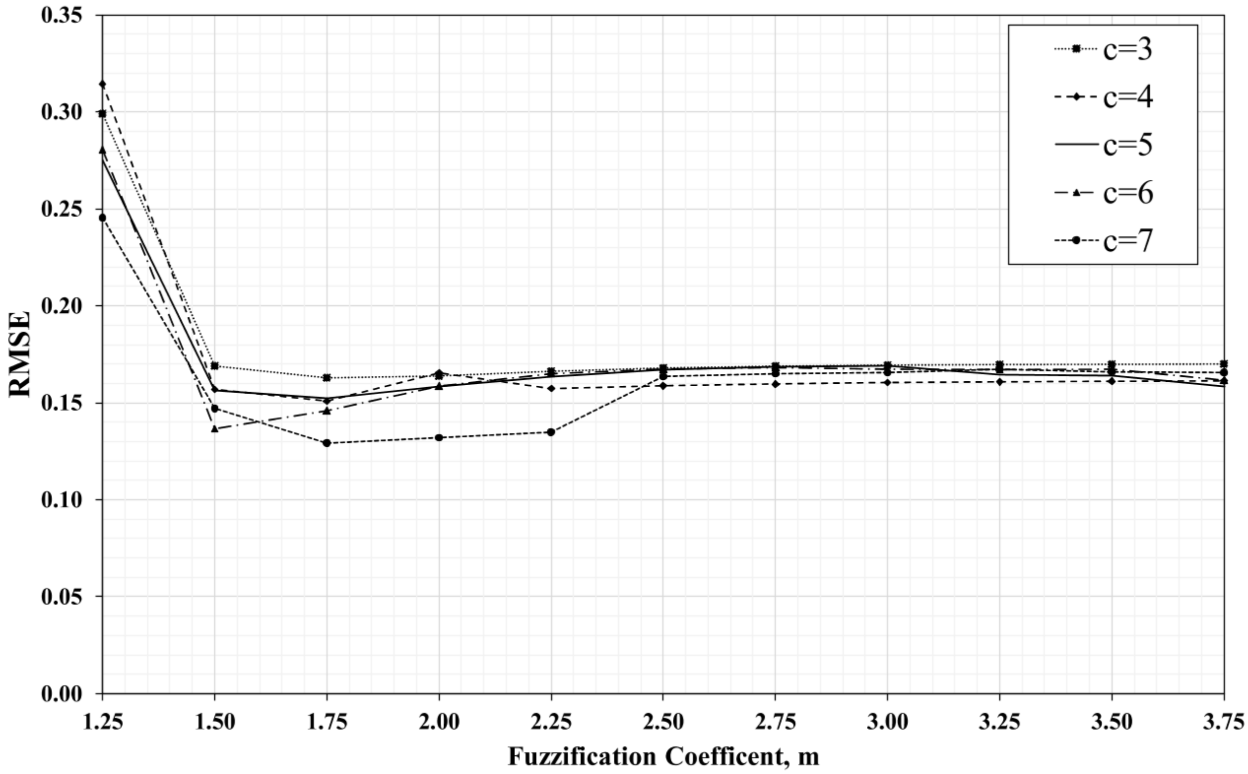


Figure 4.4. Parameter optimization result for *Middle management* agent class behavioral rule with Takagi-Sugeno FIS.

Table 4.1. FCM parameter optimization results for agent behavior rules.

Agent	FIS type	Number of clusters (*c*)	Fuzzification coefficient (*m*)	Minimum RMSE
General administration	Sugeno	4	1.50	0.151357
Technical	Mamdani	7	2.00	0.120261
Cross-functional	Sugeno	4	2.00	0.198843
Production/operational	Mamdani	7	1.50	0.120984
Project Management	Sugeno	3	2.00	0.077400
Managerial/supervisory	Sugeno	6	2.00	0.122091
Organizational attributes	Sugeno	7	1.75	0.059894
Top management competencies	Mamdani	5	1.50	0.096479
Middle management competencies	Mamdani	7	1.50	0.110201
Technical innovation competencies	Sugeno	5	1.75	0.152784
Individual/personal competencies	Mamdani	6	1.50	0.096723

Table 4.2. FCM parameter optimization results for agent interaction (performance measure prediction) rules.

Performance measure	FIS type	*c*	*m*	Minimum RMSE
Employee satisfaction	Sugeno	3	1.75	0.179601
Customer satisfaction	Sugeno	6	1.50	0.242416
Competitiveness	Mamdani	7	1.50	0.091035
Quality of work	Mamdani	4	2.00	0.224325
Safety performance	Sugeno	4	2.00	0.167002
Effectiveness of planning	Sugeno	5	1.50	0.154864

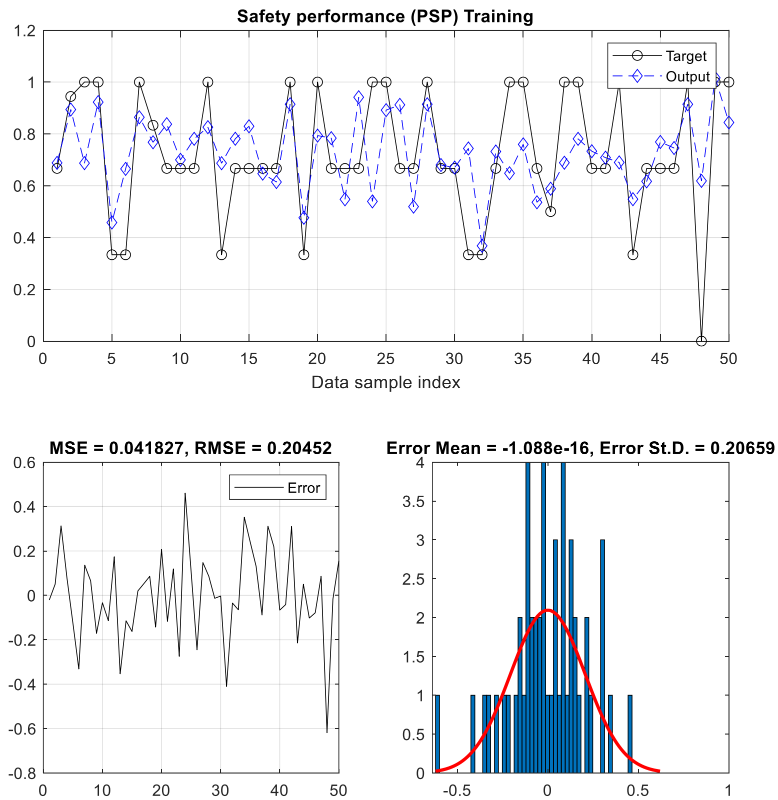
4.3.3. FABM Model Implementation and Results

Once the FABM was developed, the next step was to implement the model on the 62 data instances. The dataset obtained from the data preprocessing stage was used for training and testing the FABM model. All data were shuffled in rows before selecting training and testing data to ensure the training and/or testing datasets were chosen randomly. Thus, 80% (50 data instances) of the dataset was used for training the FABM model, and the remaining 20% (12 data instances) was used for validating the model. Based on the optimized parameters in Table 4.1 and Table 4.2, FCM-based FIS was used to develop each competency agent's behavior and the organizational performance measures. The behavior of each agent was then trained with the training dataset to predict its behavior. Then these behaviors of the 11 agents are used as inputs to predict the six performance measures (*Employee satisfaction*, *Customer satisfaction*, *Competitiveness*, *Quality of work*, *Safety performance*, and *Effectiveness of planning*.) The predicted performance measures were then observed for both the testing and training datasets, and the measurements regarding the prediction accuracy were calculated. Figure 4.5 and Figure 4.6 present sample model predictions for performance measure plots for *Safety performance* and *employee satisfaction* respectively, and Table 4.3 summarizes the results for all performance measures.

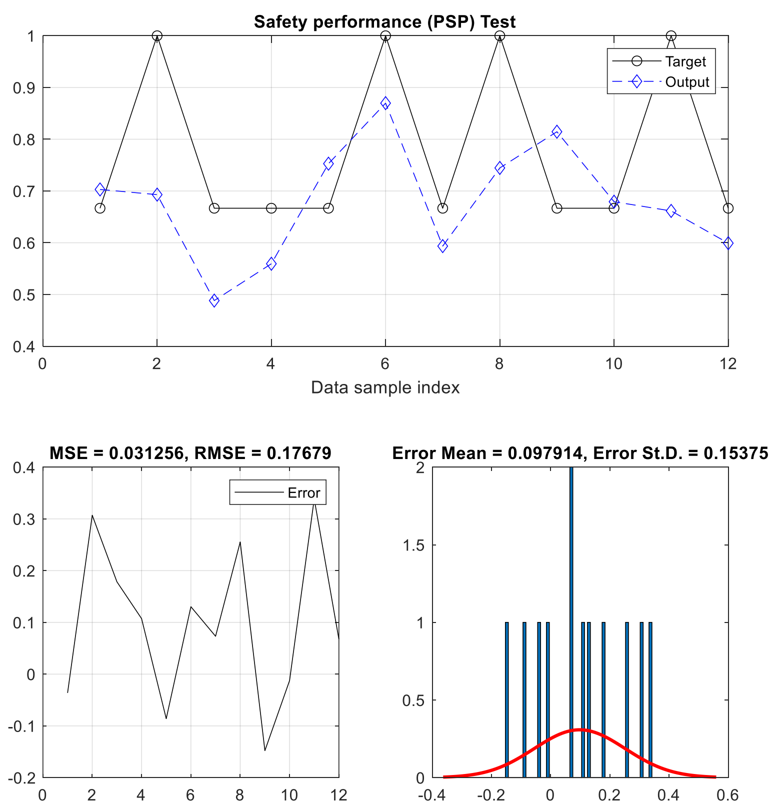
Table 4.3. Summary of FABM model outputs.

	Training			Testing		
Performance measure	**RMSE**	**Error mean**	**Error SD**	**RMSE**	**Error mean**	**Error SD**
Employee satisfaction	0.2140	0.0181	0.2154	0.2054	-0.0086	0.2143
Customer satisfaction	0.2247	0.0452	0.2223	0.2782	-0.0214	0.2897
Competitiveness	0.2191	0.0185	0.2205	0.1818	0.0369	0.1860
Quality of work	0.3350	-0.0996	0.3231	0.3189	-0.1362	0.3011
Safety performance	0.2045	$-1.09e^{-16}$	0.2066	0.1768	0.0979	0.1538
Effectiveness of planning	0.2030	$-1.78e^{-17}$	0.2051	0.2237	-0.1487	0.1746

The plots of results showed a good fit for both the training and testing datasets. Graphical methods such as residual analysis are advantageous for illustrating the relationship between model output and actual data, and between numerical or statistical methods (e.g., sum of square error, mean squared error, or RMSE) for model validation. As such, predictions with mean squared error (MSE) or RMSE value closer to 0 (zero) indicate a good fit that is useful for prediction. For example, Figure 4.5 (a) indicates that the model output values for s*afety performance* with RMSE =0.2045, error mean = -1.088e-16 and standard deviation = 0.2066 for training dataset. The prediction for testing data provided in Figure 4.5 (b) indicates RMSE = 0.1768, error mean = 0.0979, and standard deviation = 0.1538. And closer look at Figure 4.5 (b) further indicates that the model output value for the *safety performance* follows the behavior of the target or actual values of the testing data. The highest prediction accuracy for the testing data with a minimum RMSE = 0.1768 was obtained for *Safety performance*, and the prediction performance of the model for *Quality of work* was the lowest with RMSE = 0.3189.

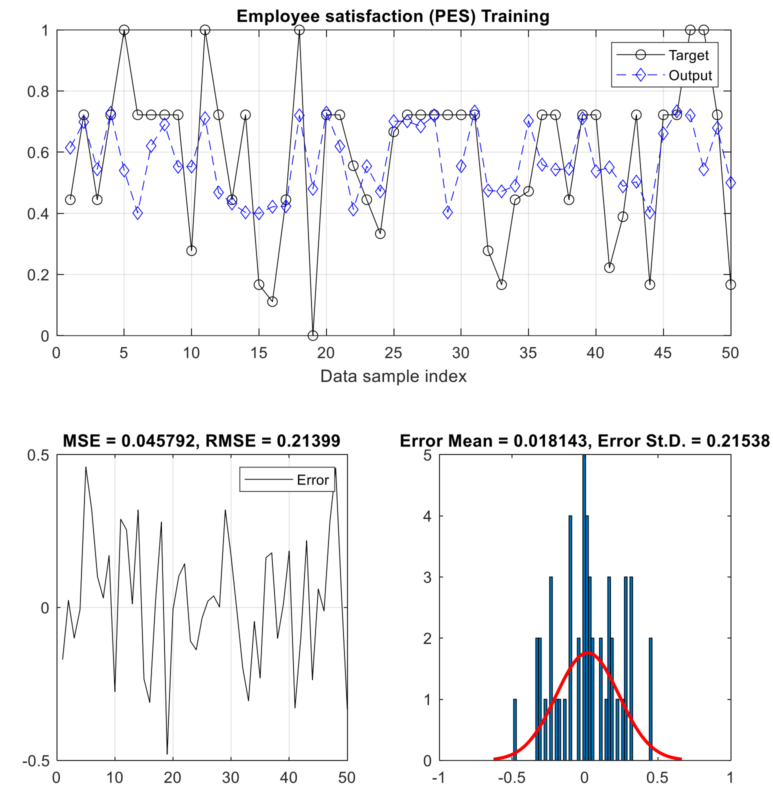


(a)

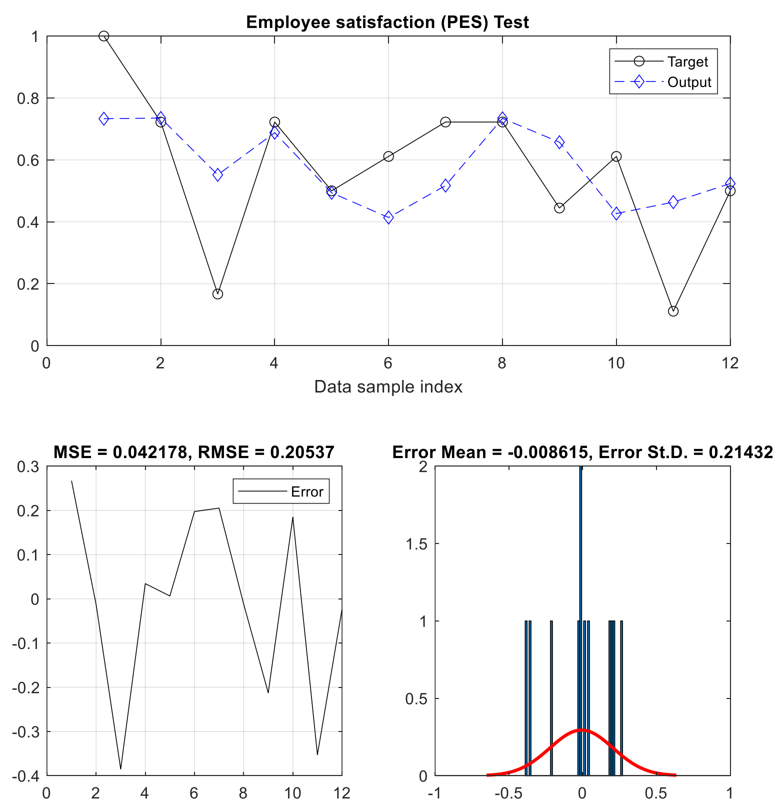


(b)

Figure 4.5. Model prediction for *Safety performance* for (a) training and (b) testing dataset.



(a)



(b)

Figure 4.6. Model prediction for *Employee satisfaction* for (a) training and (b) testing dataset.

In summary, the accuracy of the proposed FABM model prediction was found to be in agreement with the target value. The performance curves, or graphical plots, for training and testing datasets are similar, which indicates that the model output shows a good fit that follows the patterns of the target results (i.e., actual values). Furthermore, the FABM model showed good performance in predicting four of the six organizational performance metrics: *Employee satisfaction*, *Competitiveness*, *Safety performance*, and *Effectiveness of planning*, with an RMSE < 0.20. The relatively poor fit for *Quality of work* and *Customer satisfaction*, with RMSE values of 0.3189 and 0.2782, respectively, resulted from the lack of adequate variability in the testing dataset.

4.3.4. Model Verification and Validation

The GA-ANFIS model developed by Tiruneh and Fayek (2022) predicted the six performance measures in this study. In the GA-ANFIS model, only 19 of the 63 competency measures were used as an input after feature selection was performed. To calculate the accuracy error term for both, RMSE was used. RMSE expresses errors as a fraction of actual data, thus providing a way to judge the differences in the extent of the errors in one model compared to other models developed by different modeling methods. Table 4.4 presents the RMSE values for the six performance measures predicted for both the training and testing datasets (i.e., 20% of data for testing and 80% for training) using the GA-ANFIS model (Tiruneh & Fayek 2022). Comparison with the FABM model proposed in this chapter indicates that both models have consistent performance in accuracy, with the FABM model averaging a higher accuracy for both the training and testing datasets, as shown in Table 4.4. Furthermore, the FABM model performed better in predicting *Customer satisfaction*, *Safety performance*, and *Quality of work* performance measures for the testing dataset. The FABM model also has the capability to analyze all inputs (63 competency measures) and predict multiple organizational performances simultaneously.

Table 4.4. Summary of GA-ANFIS and FABM model performance.

Performance measure	RMSE for training		RMSE for testing	
	GA-ANFIS	FABM	GA-ANFIS	FABM
Employee satisfaction	0.2004	0.2140	0.1890	0.2054
Customer satisfaction	0.2538	0.2247	0.1808	0.2782
Competitiveness	0.2128	0.2191	0.2451	0.1818
Quality of work	0.4166	0.3350	0.3225	0.3189
Safety performance	0.2941	0.2045	0.2760	0.1768
Effectiveness of planning	0.2314	0.2030	0.1933	0.2237
Average	**0.2682**	**0.2334**	**0.2345**	**0.2308**

4.4. Summary

This chapter presents a novel methodology for developing a FABM model of organizational competency and performance that is capable of predicting the performance measures of construction organizations using the input of behavioral and functional competency measures. The developed FABM can account for all 63 organizational competency measures that were categorized and modeled as the attributes of 11 competency agents, whose behaviors predicted organizational performance. The developed FABM model was then verified and validated based on data collected from a company active in various industrial projects in Canada. The results indicate that the proposed methodology can enable researchers to identify the links between project level and organizational competency and performance measures, which in turn can provide construction organizations with an improved means of predicting construction performance. Moreover, the developed FABM model can predict the performance of construction organizations by considering not only the complexities related to agent interactions, but also the subjective uncertainty involved in construction experts' measuring of competency and performance levels. The results also showed that the optimal model for predicting organizational performance metrics with minimum RMSE consists of multiple FISs, one for each of the 11 competency agents and their interaction. The proposed FABM model was implemented on a case study accounting for all 63 competency measures as input variables, showed a good performance in accuracy in predicting multiple organizational performance measures simultaneously with a minimum RMSE value of 0.1768 for *Safety performance* and a maximum RMSE value of 0.3189 for *Quality of work*.

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Chapter 5. Conclusions and Recommendations

5.1. Introduction

This chapter presents the research summary and the academic and industrial contributions of this research. It also discusses the limitations of the presented research and provides recommendations for future research and development.

5.2. Research Summary

This thesis aimed to fill the gaps in construction research regarding modeling multilevel construction competency measures and their relationship to performance measures. A literature review of competency-based performance modeling in construction revealed several gaps: The majority of previous studies on competency and performance modeling have developed mechanisms to identify and develop construction competency and performance measures at the project and organization levels, separately. However, construction organizations are project-based organizations in which competencies are built up through the execution of major projects, and it is important to have a holistic insight into both project- and organization-level competencies (Loufrani-Fedida & Missonier 2015). Therefore, the **first gap** related to multilevel competency and performance modeling is the lack of well-defined hierarchies of construction competencies measures at both the project and organization levels, despite the existing body of knowledge providing a foundation for construction competencies measure identification. The **second gap** is the lack of studies addressing the link between multilevel competency and performance measures. Most current studies develop frameworks dealing with competency and performance separately, and those that manage to formulate a relationship are conceptual and limited to a single level (i.e., project or organization). The **third gap** is that most past studies do not consider the complex relationship between multilevel competency and performance measures accounting for subjective uncertainties that are inherent in their measures. Variables that define construction competencies and performance measures are both quantitative and qualitative, requiring modeling techniques that can capture both types of data, which increases complexity in modeling efforts. Given the dynamic and complex nature of construction environments, these uncertainties pose significant challenges to developing models of construction competencies and performance. To address the mentioned gaps, the objectives of this research were achieved in three stages as follows.

5.2.1. Stage 1: Establish Multilevel Construction Competency and Performance Measures

In the first stage, multilevel construction competency and performance framework was developed linking competencies at the project and organizational levels and mapping these multilevel competencies to construction performance measures at both levels. Furthermore, a comprehensive set of the project level and organizational competency and performance measures were summarized and updated from the existing literature. Based on the study and analysis of the literature and characteristics of PBOs, hierarchical categorization of competency and performance measures were developed. Both competency and performance categories were further divided into sets of evaluation criteria that can be captured through different construction experts and collected from construction organizations and their projects either quantitatively or qualitatively. Finally, a data collection approach for measuring construction competencies and performance measures that account for quantitative and qualitative evaluation criteria was proposed.

5.2.2. Stage 2: Develop a Fuzzy Agent-Based Construction Competency and Performance Model

In this stage, based on the proposed multilevel competency and performance framework developed in the first stage, a construction competency-based performance model was developed using fuzzy agent-based modeling (FABM) approach. The FABM competency and performance model has two major functional components: the fuzzy logic component and the agent-based model (ABM) component. The ABM component constitutes the multi-agent environment in which each agent represents the category of competency measure. Fuzzy c-means (FCM) clustering and a fuzzy inference system (FIS) make up the fuzzy logic component. Hence, the FABM competency and performance model development involves two phases. First, the ABM component of the model is developed, which involves defining a set of agents representing competency measure categories, defining agents' attributes and behaviors, and establishing the agents' behavioral and interaction rules. Second, the fuzzy machine learning technique of FCM is integrated with the ABM component to generate FIS-based agents' behavioral and interaction rules. The FIS receives input attributes (i.e., competency evaluation criteria) of a competency agent (i.e., category of competency measure) from the ABM environment and delivers the predicted behavior of each agent and multiple emergent performance measures simultaneously.

5.2.3. Stage 3: Implement the FABM Model on the Case Study

The construction competency and performance dataset, provided from a previous study conducted by Tiruneh and Fayek (2022), was used to validate and verify the FABM model developed in the second stage. Verification of the FABM model was carried out to confirm that both ABM and fuzzy logic components of the model work as expected. To verify the FABM model, all mathematical equations, and methods of the model, such as MATLAB codes, were checked for correctness. Further, the model was run multiple times to check for replicability of results, with tracing graphs used to track changes in model results. Validation of the FABM model involved two steps. First, conceptual validity was performed by basing the model on validated competency and performance concepts from the literature (Sargent 2013). Construction organization- and project-level competency and performance measures were defined based on past literature in the construction and related domains. The identified list of measures was then validated by industry experts (e.g., Omar & Fayek 2016; Tiruneh & Fayek 2020). As suggested by Macal and North (2015), the problem to be modeled was fully described, including all model components such as agents, rules, and data preparation. Second, operational validity as performed by both subjective and objective approaches (Sargent 2013). A subjective approach to operational validity involves graphical displays, such as prediction versus target values. All performance measure results were plotted in the model to observe their behavior for both the testing and training datasets. The objective approach to operational validity was performed by comparing the statistical RMSE test results obtained from this model with those obtained by the genetic algorithm–adaptive neuro-fuzzy inference system (GA-ANFIS) model developed by Tiruneh and Fayek (2022), which provided the modeling dataset used in this study.

5.3. Research Limitations and Recommendations for Future Research

The following limitations were encountered in the research study, and some recommendations are suggested for future work:

1. The proposed hierarchical multilevel competency and performance measures are general in the construction context. Future research should focus on the identification of common construction competencies and performance metrics and their respective categorization methods for specific contexts based on the type of organization (e.g., owner, consultant, construction management, general contractor, specialty/subcontractor); ownership type of

organization (e.g., public/government-owned, privately owned, employee-owned, publicly traded); the size of organization and/or projects; and construction industry subsector type (e.g., building, commercial, industrial).

2. The data used in the FABM competency-based performance model was collected from a single construction company. Therefore, the result cannot be generalized to the wider construction industry. Future research should focus on collecting data from multiple organizations from various construction industry subsectors for a different specific context.
3. The FABM model developed in this study considered only competency and performance measures at the project and organization levels. Future research can explore the integration of competency–performance models at different levels, such as team/crew, task, and individual.
4. Future research should focus on exploring other hybrid fuzzy systems, such as fuzzy cognitive mapping, to model agents' behavioral and interaction rules in the FABM model. Optimization algorithms such as genetic and evolutionary algorithms can also be investigated to train and optimize the FABM model to help improve the model's prediction accuracy.
5. Future research should focus on exploring and developing an approach to integrate feature selection and data instance selection for more accurate modeling efforts. Dimensionality reduction techniques such as feature selection, feature extraction, principal component analysis, factor analysis, and/or subjective judgment should be explored to obtain fewer critical input (competencies)–output (performance measures) for practical applications by different industry stakeholders, such as owners, consultants, and contractors, based on the context of the company for which the model is developed.
6. Due to the limited amount of data available for modeling, a ratio of 80/20 of testing to training data was used for validation. Thus, future research should consider *k*-fold cross-validation to compare the prediction performance of different models, particularly those developed using small data sets.

5.4. Research Contributions

Results of the thesis are expected to make several contributions to the body of knowledge (Academic contributions) and practitioners (Industrial contributions), as follows.

5.4.1. Academic Contributions

The expected academic contributions of this research are:

- Development of a multilevel construction competency conceptual framework linking competency measures at the project and organization levels and relating multilevel competencies to construction performance measures.
- Development of a comprehensive hierarchical and categorical list of project level and organizational construction competencies and performance measures that can serve as useful references for future multilevel analysis and modeling purposes.
- Development of a multilevel construction competency and performance FABM methodology that can handle the complex and dynamic construction environment while accounting for the subjective uncertainty inherent in construction processes and practices.
- Providing a methodology for developing multilevel construction competency and performance FABM models with multiple FISs for interaction and behavioral rules that can handle multiple competency measures as model inputs and performance measures as outputs simultaneously.

5.4.2. Industrial Contributions

The expected industrial contributions of this research are:

- Providing a conceptual framework that presents a holistic view of project- and organization-level construction competency and performance measures identifying the relationship between hierarchical categories of competency and performance measures at both levels.
- Providing construction industry practitioners with a set of comprehensive hierarchical arrangement of construction competency evaluation criteria for managerial actions taken to identify, construct, and develop competency models to assess the performance at project and organization levels.
- Providing a hybrid FABM modeling and analysis approach that allows construction industry practitioners to assess multiple construction competencies and the impact they have on performance measures, which can aid in identifying competencies that need improvement and so help to improve performance.

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Appendix A. Competency Measures for Case Study

Table A.1. Functional competency measures for case study.

No.	Cat. Id.	Category	Comp Id.	Competencies Measures
1	1.1	General administration	1.1.1	Staff development/training
2			1.1.2	Goal orientation
3			1.1.3	Human resource (personnel) management
4			1.1.4	Management and support of diversity
5			1.1.5	Interdisciplinary alignment
6	1.2	Technical	1.2.1	Quality of work
7			1.2.2	Technical/job knowledge
8			1.2.3	Commitment to safety
9			1.2.4	Planning and organizing of tasks/activities
10			1.2.5	Technical innovation
11	1.3	Cross-functional	1.3.1	Co-operation and co-ordination (collaboration)
12			1.3.2	Customer/stakeholder focus
13			1.3.3	Communications management
14			1.3.4	Interface management
15	1.4	Production/ operational	1.4.1	Construction technology and integration management
16			1.4.2	Operations and maintenance
17			1.4.3	Process engineering management
18			1.4.4	Construction, production and manufacturing
19			1.4.5	Product engineering
20			1.4.6	Materials management
21	1.5	Project Management	1.5.1	Project quality management
22			1.5.2	Project safety management
23			1.5.3	Project schedule (time) management
24			1.5.4	Project scope management
25			1.5.5	Project change management
26			1.5.6	Project cost management
27			1.5.7	Project risk management
28			1.5.8	Project integration management
29			1.5.9	Project procurement management
30			1.5.10	Project finance management
31	1.6	Managerial/ supervisory	1.6.1	Engagement
32			1.6.2	Management excellence
33			1.6.3	Delegation
34			1.6.4	Resource management

Table A.2. Behavioral competency measures for case study.

No.	Cat. Id.	Category	Comp Id.	Competencies Measures
1	2.1	Organizational core attributes	2.1.1	Ability to build trust
2			2.1.2	Competitiveness
3			2.1.3	Adaptability/flexibility
4			2.1.4	Achievement drive
5			2.1.5	Innovation
6			2.1.6	Organizational awareness and culture
7	2.2	Top management competencies	2.2.1	Leadership
8			2.2.2	Strategic thinking
9			2.2.3	Judgement
10			2.2.4	Analytical ability/thinking
11			2.2.5	Values and ethics
12	2.3	Middle management competencies	2.3.1	Interpersonal skills
13			2.3.2	Decision-making
14			2.3.3	Reasoning
15			2.3.4	Conflict and crisis resolution/ Issue management
16			2.3.5	Assertiveness
17	2.4	First-line management competencies	2.4.1	Problem solving
18			2.4.2	Results orientation
19			2.4.3	Responsiveness
20			2.4.4	Influence
21			2.4.5	Communications
22	2.5	Individual / personal competencies	2.5.1	Reliability/Dependability
23			2.5.2	Teamwork
24			2.5.3	Ethics/Professionalism
25			2.5.4	Commitment/Motivation
26			2.5.5	Effectiveness
27			2.5.6	Resourcefulness/Initiative
28			2.5.7	Perseverance/Self-regulation and control
29			2.5.8	Attention to detail

Appendix B. FABM Model Results for Case Study

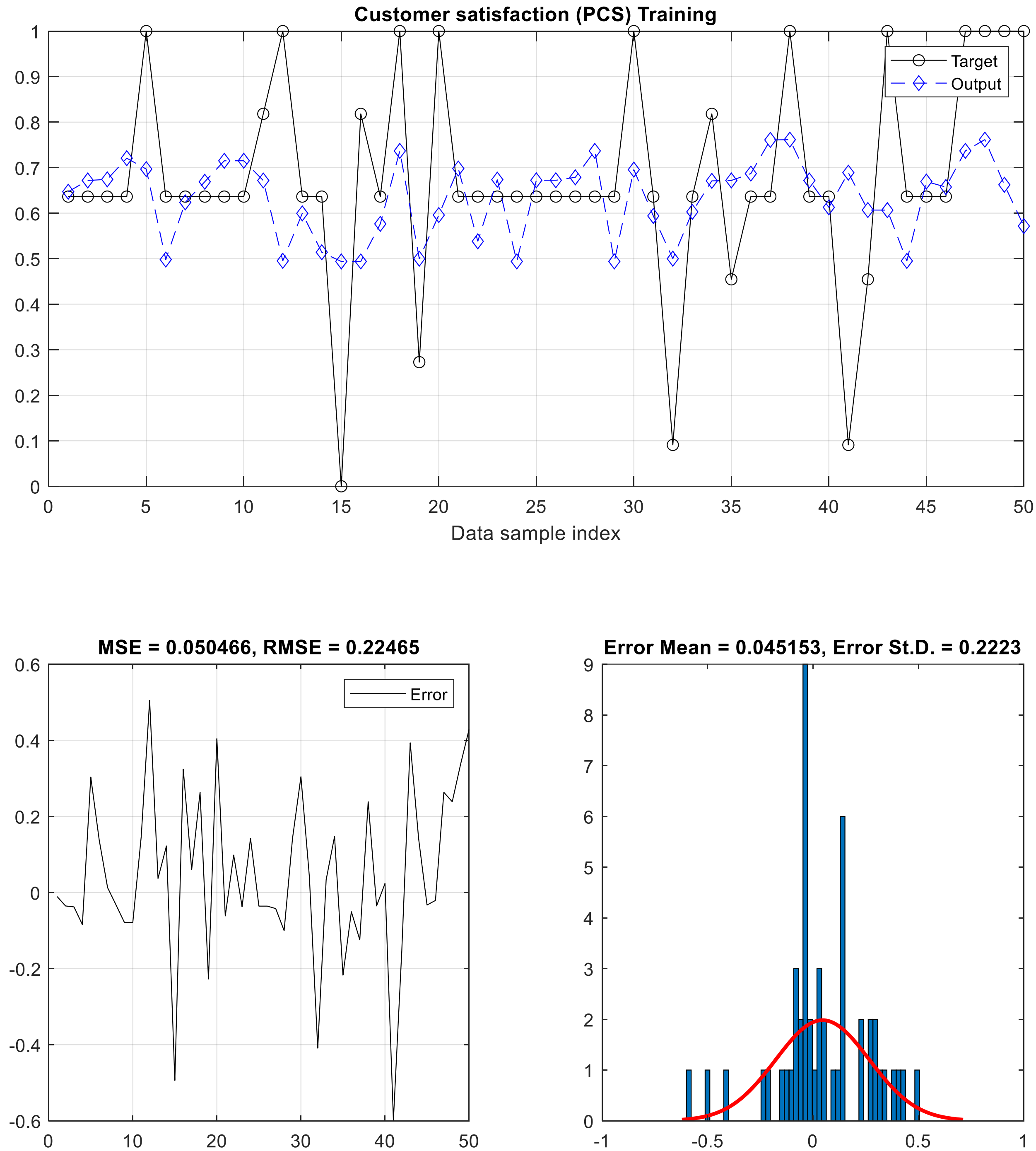

Figure B.1. FABM model prediction for *Customer satisfaction* measure with training dataset.

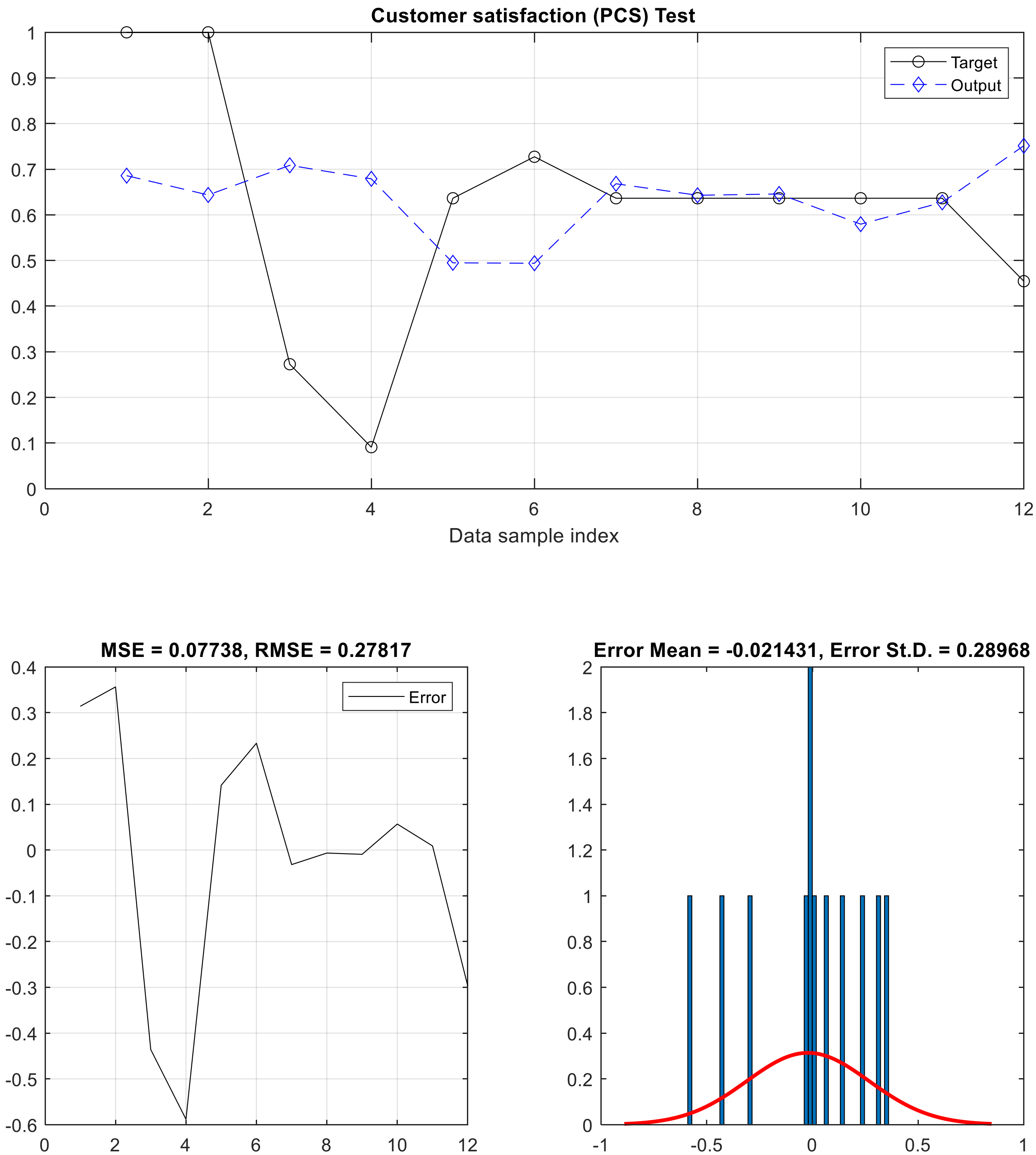

Figure B.2. FABM model prediction for *Customer satisfaction* measure with testing dataset.

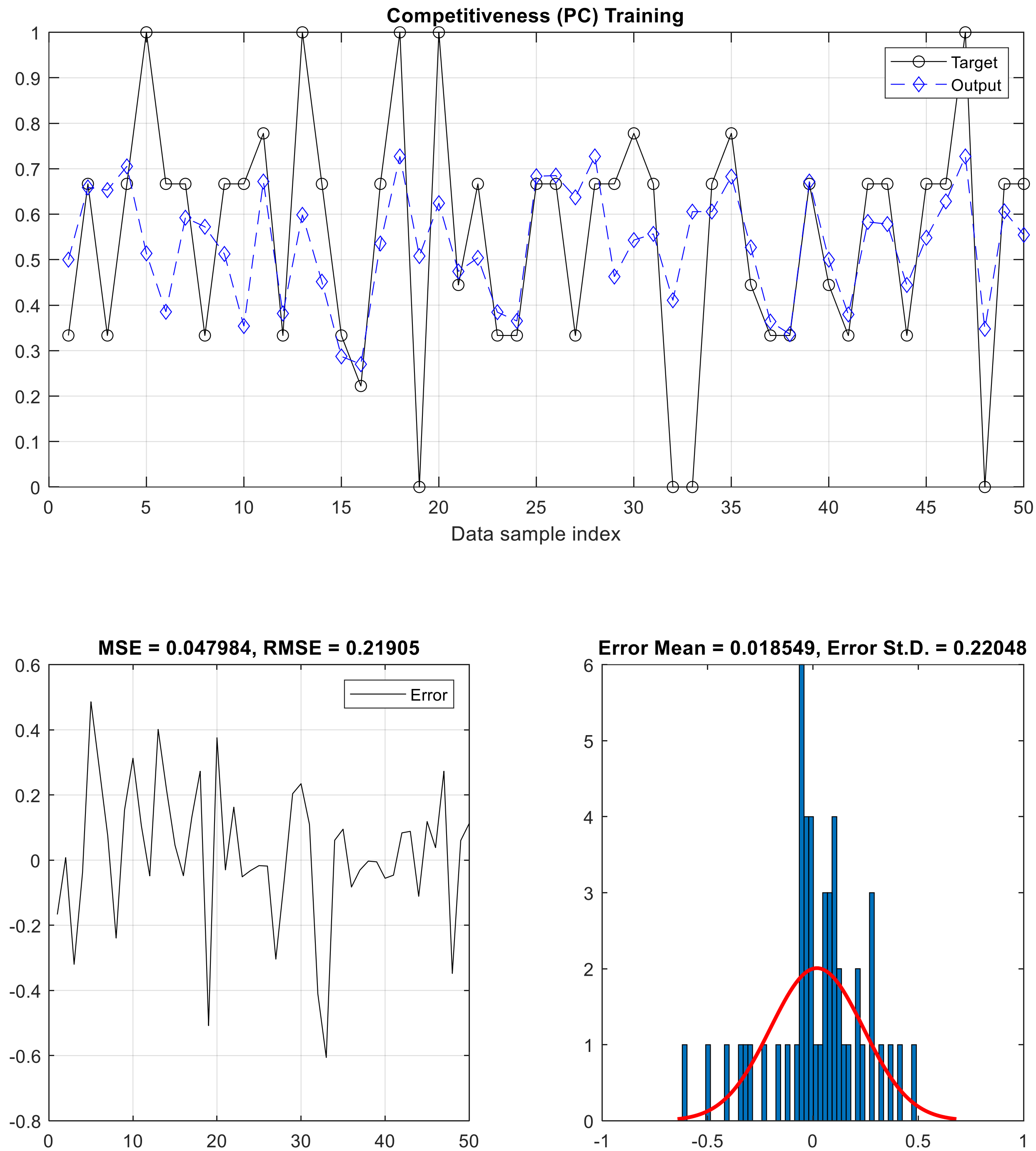

Figure B.3. FABM model prediction for *Competitiveness* measure with training dataset.

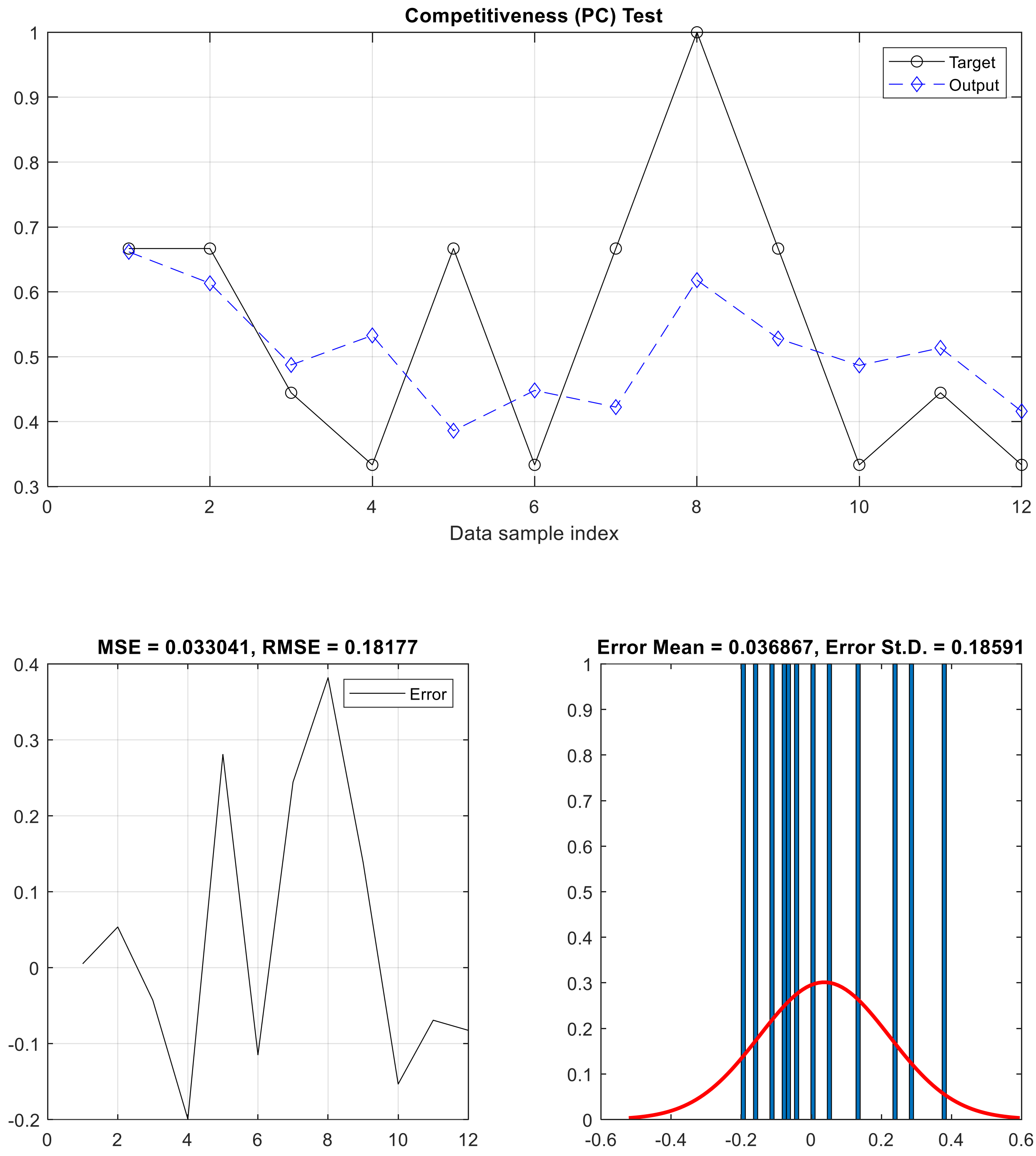

Figure B.4. FABM model prediction for *Competitiveness* measure with testing dataset.

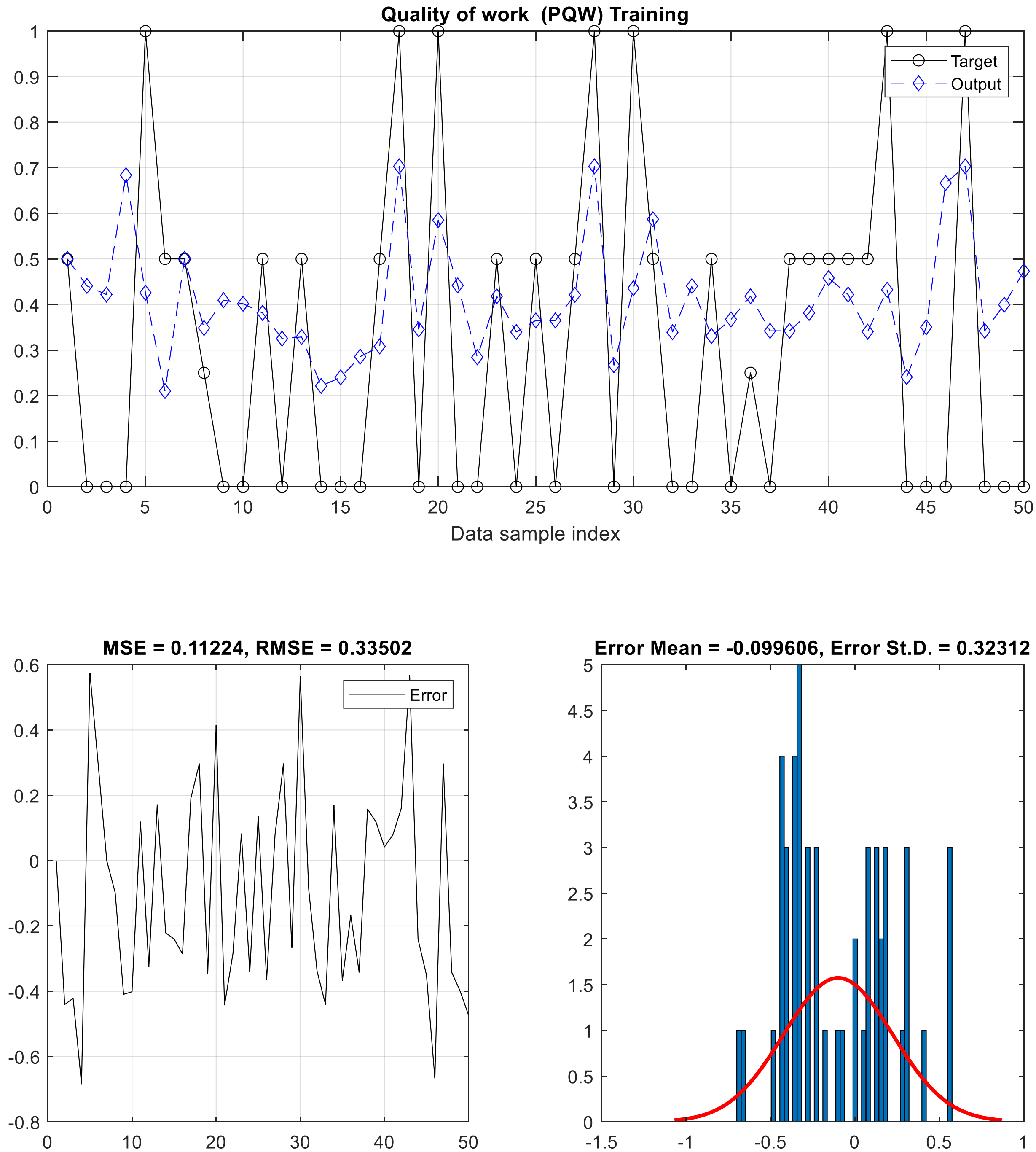

Figure B.5. FABM model prediction for *Quality of work* measure with training dataset.

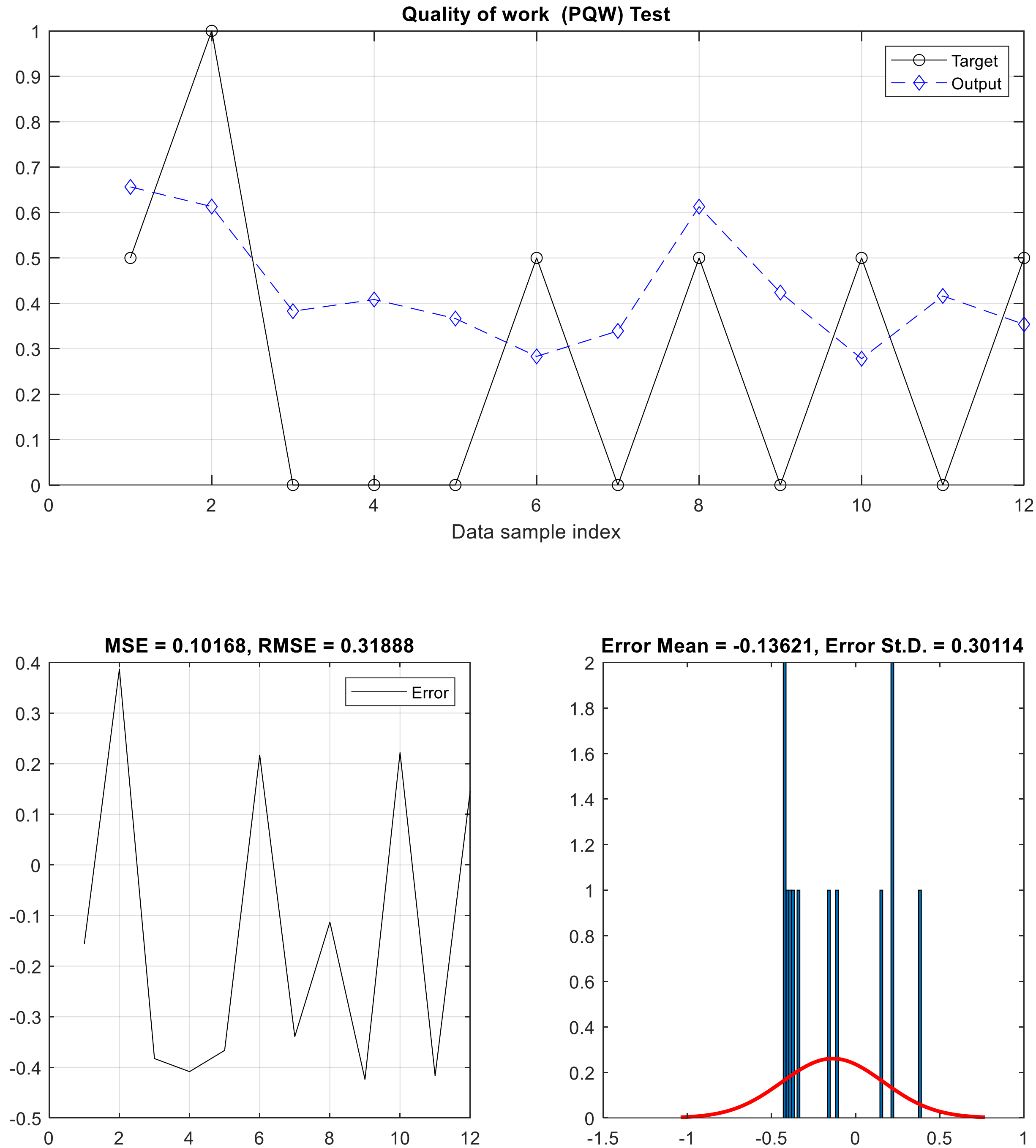

Figure B.6. FABM model prediction for *Quality of work* measure with testing dataset.

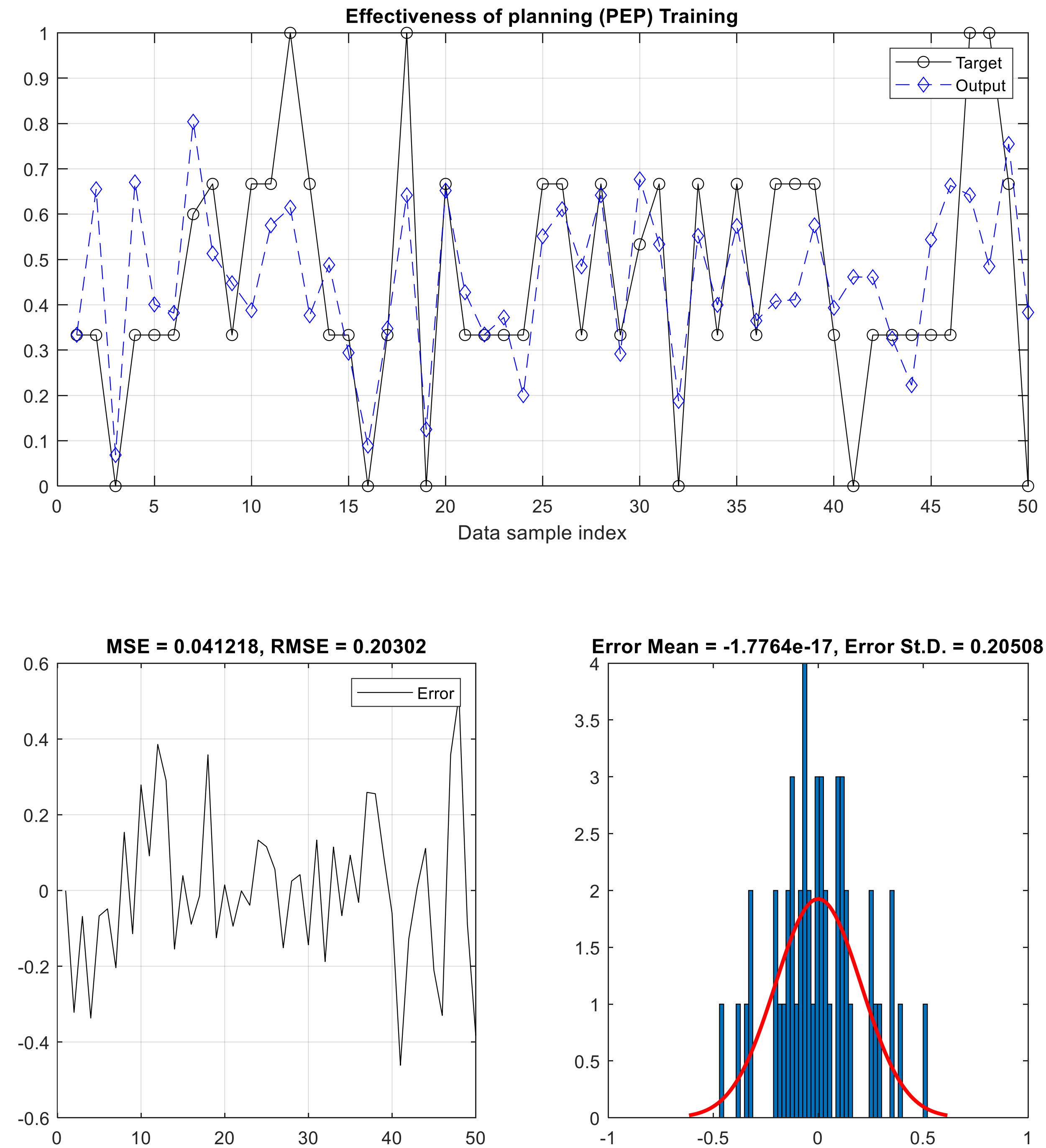

Figure B.7. FABM model prediction for *Effectiveness of planning* measure with training dataset.

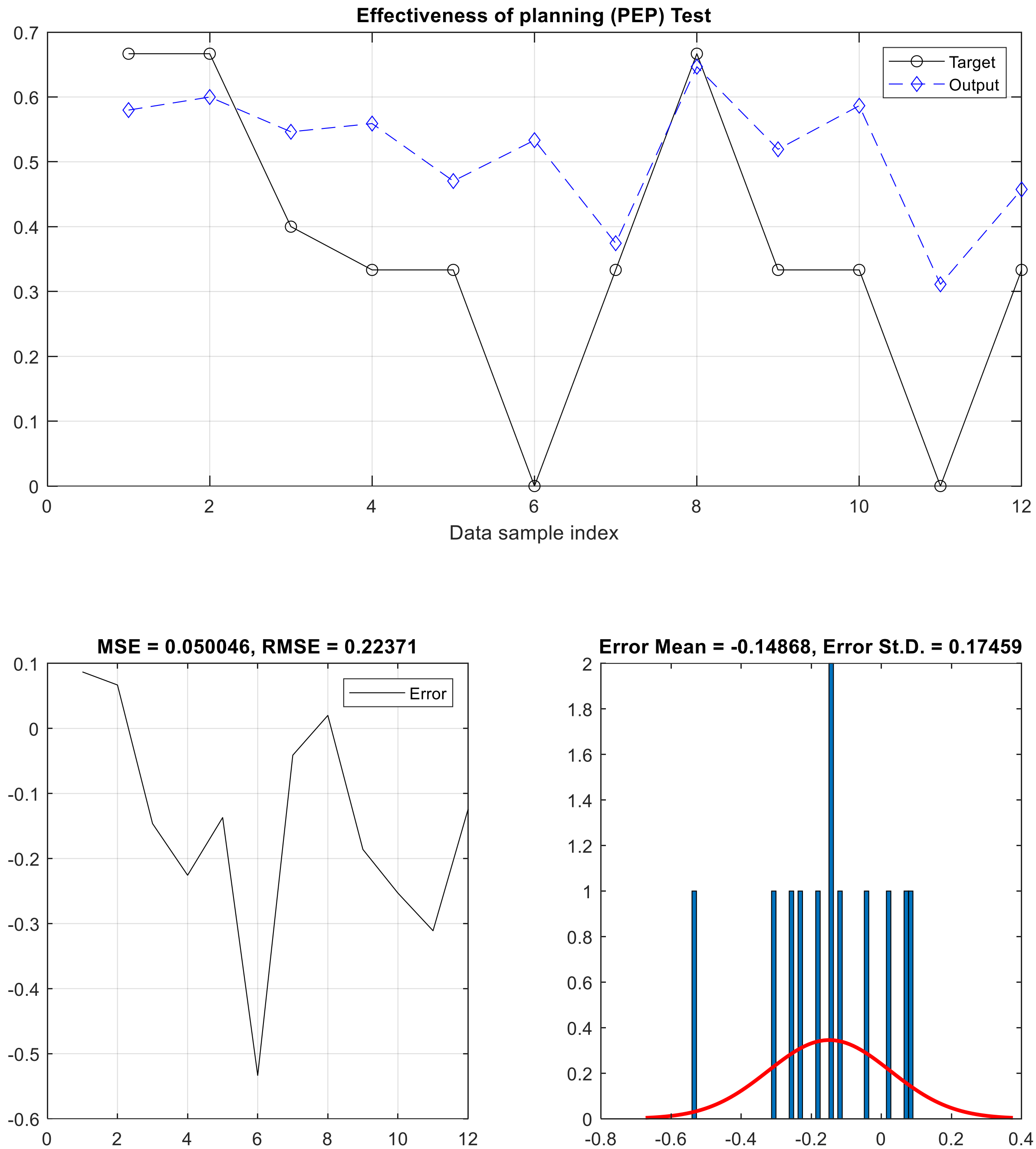

Figure B.8. FABM model prediction for *Effectiveness of planning* measure with testing dataset.