Supplier Performance Evaluation in Construction Projects: Challenges and Possible Solutions

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Abstract: Supplier performance analysis can enlighten a construction company about improvement possibilities for better project outcomes. However, for systematic evaluation of a supplier across projects, changing the operating environment between projects should be addressed. Therefore, we first elaborate how supplier evaluation is challenged due to differences between projects in three characteristic groups: project product and location characteristics, project organization characteristics, and buyer–supplier transaction characteristics. We next discuss the possibility of applying data envelopment analysis (DEA) for supplier evaluation in construction, and argue how changing the operating environment can lead to nonhomogenous decision-making units in DEA. Building on these, we propose the process for supplier evaluation in the presence of a changing operating environment and different input–output profiles. Characteristics of 12 projects and supplier evaluations in 44 projects are used to illustrate evaluation challenges. The research extends current knowledge on supplier evaluation in construction by underlining how changing the operating environment across projects challenges systematic performance evaluation and by suggesting the process which further research could develop toward practical applications. **DOI: 10.1061/(ASCE)CO.1943-7862.0001616.** © *2019 American Society of Civil Engineers.*

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Introduction

Effective construction supply chain management (SCM) is one of the major driving forces for productivity and performance improvement in the construction industry (Egan 1998; Vrijhoef and Koskela 2000; Segerstedt and Olofsson 2010). To accomplish this objective, identifying the high-value creation processes and parts in the supply chain spectrum is essential. To do so, a contractor can highlight material and service suppliers with significant contributions, up to 75%–80% of costs (Vrijhoef and Koskela 2000) and 90% of operations (Karim et al. 2006) for construction projects. Considering suppliers' prominent role in projects, supplier performance and efficiency evaluation is an important task in identifying high-value creators in the supply chain. Strengthening the relationship and widening the transactions with high-performance suppliers can help a contractor to move toward high-performance construction.

Although suppliers (i.e., service and material providers) are the main contributors of project cost, quality, and delivery time (Vrijhoef and Koskela 2000; Eom et al. 2008; Aretoulis et al. 2010), little is known about efficiency evaluation of suppliers in construction projects. The central importance of supplier efficiency evaluation is highlighted in other industries, such as food (Weber 1996), telecommunications (Narasimhan et al. 2001), automobiles (Kumar et al. 2014), steel (Mahdiloo et al. 2015), and semiconductors (Hatami-Marbini et al. 2017). Therefore, applying efficiency analysis methods at the construction project level can result in improvement possibilities with suppliers. However, understanding the operating environment is necessary for a fair evaluation of a supplier's performance in the construction context.

Regarding operating environment, while homogeneity of units under evaluation is one of the main assumptions in the performance and efficiency evaluation literature, construction projects are relatively unique in nature (Akinsola et al. 1997; Sun and Meng 2009). In the words of Eccles (1981, p. 338) "the unique combination of input factors is required to complete the project." The importance of changes in the operating environment has been discussed and highlighted in the efficiency analysis literature (e.g., Fried et al. 2002; Coelli et al. 2005; Avkiran 2009; Johnson and Kuosmanen 2011). However, in the context of construction projects, reviewing the limited literature (e.g., Tsolas 2013; Iyer and Banerjee 2016) shows that environmental variations have not received particular attention in performance measurement. In line with this argument, past studies have placed almost no emphasis on variation between construction projects regarding suppliers when applying data envelopment analysis (DEA), which is one of the most popular efficiency analysis approaches.

In the construction industry, the effectiveness of the DEA technique has been exemplified in different studies. For example, DEA was used for safety performance analysis of construction companies (El-Mashaleh et al. 2010), performance estimation and change in efficiency frontier over time for construction companies operating in Europe, Asia, and North America (Horta et al. 2013), performance measurement of 265 largest construction companies in the United Kingdom (Deng and Smyth 2013), productivity change in Spanish and Portuguese construction companies (Kapelko et al. 2015), and to evaluate the performance of the construction industry in Australia (Hu and Liu 2016). However, despite the recent applications of DEA for analyzing construction companies' performance, very limited studies have investigated using DEA for

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supplier evaluation in the construction SCM. Therefore, we find it valuable to discuss the possibility of using the DEA method and its challenges in the construction supply chain.

This study aims to shed light on the dilemma about supplier performance evaluation in the changing operating environment of projects. We describe how the heterogeneity of the operating environment, affecting supplier performance and efficiency evaluation, can stem from different origins. For the sake of demonstration, we empirically study some of the discussed characteristics by analyzing 12 real-world construction projects undertaken between 2010 and 2016 in Finland. We further highlight that change in operating environment between projects can result in nonhomogenous decision-making units (DMUs), where a supplier may have different inputs and/or outputs data profile. In DEA terminology, DMU refers to a unit that is able to transform multiple inputs (resources) to multiple outputs (products or services). DMUs with better performance, having inputs with a smaller value and outputs with a larger value relative to other DMUs, build an efficiency (best practice) frontier (Cook et al. 2014). Performance of other DMUs is compared against the efficiency frontier. In this study, DMU is synonymous with a supplier in a specific project, and DMUs represent this one supplier in different construction projects.

The rest of this paper is organized as follows. First, we present construction projects' attributes that can affect a supplier operating environment. Second, we discuss the changing operating environment and nonhomogenous DMUs concepts in DEA. Third, some of the discussed characteristics from the earlier part are illustrated in practice, utilizing suppliers' data in various real construction projects. Finally, we summarize our contributions and recommendations for future studies.

Characteristics of Operating Environment Affecting Supplier Performance in Construction Projects

Past studies have suggested using DEA for supplier evaluation and selection (e.g., Mahdiloo et al. 2015; Liu et al. 2000), green supplier selection (Kumar et al. 2014), supply chain risk analysis (Talluri et al. 2013), reverse logistics provider analysis (Min and Joo 2006), container selection (Shabani et al. 2011), and supplier development (Noorizadeh et al. 2018), among others. However, it seems that the construction supply chain performed poorly in adopting and adapting efficiency evaluation methodologies compared with manufacturing SCM [see Lampe and Hilgers (2015) for a more detailed review on distribution of applied efficiency analysis methods in different fields]. We elaborate on major challenges that might help to realize the potential reasons for this poor adoption. In this study, we categorize these challenges in three main groups of project product and location characteristics, project organization characteristics, and buyer–supplier transaction characteristics. This classification is based on our observations and earlier studies describing construction supply chain and projects specifications (e.g., Baiden et al. 2006; O'Brien et al. 2009; Sun and Meng 2009; Gadde and Dubois 2010; Eriksson 2010). Table 1 presents the three main categories of the changing operating environment with their subsections that we discuss throughout this section.

Project Product and Location Characteristics

Project Product Type

Depending on the adopted business strategy, contractors decide to operate in construction of one specific or multiple different types of project products. With a diverse product portfolio, access to different machinery, technical capabilities, and proper suppliers can be more challenging than in routine production with focused products. Furthermore, the circumstances and requirements vary from project to project, even in projects that only focus on construction of buildings. In such cases, a supplier performance can be affected only due to variation in building types considering differences, for example, in the way residential, office, educational, healthcare, sport, retail, and warehouse buildings are constructed.

Moreover, priorities regarding quality and cost of supplied items may change based on product type. In other words, lack of standardization and higher variability in product types (Azambuja and O'Brien 2009, pp. 2–9) may result in different levels of expectations from a supplier regarding, for example, quality, cost, and time. Therefore, by change in the product type, it can be claimed that the base of a supplier comparison changes. This issue regarding change in base of analysis and its influence on deriving accurate comparison has been argued by Kahneman (2011, p. 282).

In order to exemplify how product type can affect supplier performance, we can consider the critical role of suppliers' safety in construction operations. The comprehensive study by Hu et al. (2011) shows that fall injuries are the main common and costly occupational hazards in construction projects. They identified and sorted various factors that contribute to the risk of falls, including height of workplace and working surfaces and platforms. It is clear that these factors vary according to the product type.

Project Product Size

Buildings' specifications such as size can vary a lot between projects. Following the size variation, constructability level also can differ (Kärnä and Junnonen 2017). The project size has a direct effect on the complexity of operations because for large and small projects different sorts of expertise, facilities, and experience are required (Pheng and Chuan 2006).

Furthermore, usually project size determines the number of project participants and duration. It is almost certain that a higher number of stakeholders increases the coordination tasks and project time (Pheng and Chuan 2006; Xia and Chan 2012). For example, large hospital projects often last for several years, and during this time different changes in design and specifications are imposed on the project by a client or regulators.

Moreover, time pressure in large projects is higher than in smaller ones (Eriksson and Westerberg 2011). This can result in a vast number of activities that should be undertaken simultaneously. However, concurrent operations by a large number of suppliers on a construction site can considerably increase rework (Love 2002). Consequently, while project size is considered among the factors that affect the success and failure rate of projects (Belassi and Tukel 1996; Chan et al. 2004), we can suggest that supplier performance might also be affected via differences in project size.

Table 1. Characteristics of the changing operating environment in construction projects

Project product and location characteristics	Project organization characteristics	Buyer–supplier transaction characteristics
Project product type	Client type	Number and mix of suppliers
Project product size	Number of orders and inventory management	Position of supplier in project operations spectrum
Project location	Project delivery method	Continuity of transactions and relationship

Project Location

Location as another contributing factor to projects' overall performance (Xia and Chan 2012) can impact the delivery performance of the contractor. For instance, weather conditions, state of preservation, and authorized construction regulations can be different from one project location to another, and these may affect the predefined project budget and time (e.g., Kaming et al. 1997; Sun and Meng 2009). Moreover, Zhu and Mostafavi (2017) highlighted the role of location affecting the complexity of projects. They identified project location in the third position contributing to project complexity, after quality of information and project type. For example, they mention the problems that arise from limited space in urban districts for installing construction machinery and equipment and storing the materials. In a more detailed view, we can also outline the role of project location in a supplier's safety performance. For instance, construction site location and weather conditions are listed among the variables that influence risk of fall injuries (Hu et al. 2011). This suggests that, despite taking general construction safety regulations into account, a supplier's workers in some projects are more prone to risk of injuries than others.

Project Organization Characteristics

Underlining the difficulty of performance management in project-based organizations (Kwak et al. 2015), we elaborate on the project organization characteristics in the following. In this section, client type, number and mix of suppliers, and project delivery methods are covered as factors that can influence a supplier's operating environment in a project.

Client Type

The client, as an owner, is the main initiator of a construction project. The client finances the project and looks for a designer and a contractor to start the construction process. From the contractor perspective, clients can differ from one project to another. Therefore, the way of acquiring the projects (e.g., competitive bidding, negotiations), the client knowledge and expertise, definition of quality and expectation, financing conditions of a project, the level of necessity and possibility to follow the predefined schedule, and incentives to deliver the project ahead of time can be varied by changing the type of clients.

Regarding the client types, usually they are divided into public and private sector. However, to provide greater details concerning project ownership, in this study we further break down public projects into two groups: owned by states (municipalities) and third parties (foundations and social organizations). On the other hand, private projects refer to business to business (for corporate use) and business to customer (for residential use). Based on clients' attitudes toward the projects, it can be argued that the contractor has to deal with different challenges in its operations, which may be transferred to its suppliers in the next level. For example, competitive bidding with the aim of winning the project with the lowest price is a common practice for public projects. However, the private project can have more flexibility and freedom concerning contractor selection (Tadelis 2012). In the case of a competitive bidding, for a contractor to keep the costs under control and protect its profit margin, it has to transfer most of the cost pressure to suppliers. In this cycle, they also try to provide services and materials at a lowest possible price only in order to satisfy basic requirements.

Number and Mix of Suppliers

The number, mix, and involvement stage of suppliers can also be quite different within projects with different size and type. Considering building projects, for example, the number of suppliers that are usually involved in residential construction can be higher than warehouse buildings. In this structure, the dependency of supplier operations together can be increased by having a high number of suppliers working on site. A problem with one supplier can affect the performance of another supplier. While construction processes are mostly interrelated and an output of one earlier supplier can be considered as an input of a later one (Eccles 1981; Fearne and Fowler 2006; Sun and Meng 2009), a delay in completing a task by a supplier can result in a domino or cascading effect in other suppliers' operations. In such cases, either meeting the initial project time and cost plan will be infeasible or the later suppliers should allocate more time and resources than what was predicted in the initial plan.

In addition, in construction projects, suppliers with different backgrounds come together and establish a temporary operation team. While a diverse set of suppliers may participate in each project, the successful delivery of the project is the ultimate goal. Regarding the diversity of suppliers, their effective integration into project teams is one of the contributing factors to improving the project performance (e.g., Baiden et al. 2006; Lahdenperä 2012; Lavikka et al. 2015).

Project Delivery Methods: Contract Type with Client

Besides the uniqueness of the construction operations in each project, there are different contracting mechanisms for executing and delivering projects. Project delivery methods refer to different strategies of formal agreements between or among the main project parties considering their predefined tasks and obligations, which may start before a project is designed to even after a project is constructed (Hanna 2016). Baiden et al. (2006) stressed that selecting the project delivery method can influence the integration of project team members and as a result the project performance. The traditional most commonly practiced project delivery methods are design-build, design-bid-build, and construction management at risk (Mesa et al. 2016). Recently, alliancing contracts such as integrated project delivery as new collaborative contracting formats have also been applied in construction projects (Mesa et al. 2016). Table 2 briefly describes the important characteristics of the four most popular delivery methods, in which each one can influence a supplier's working environment differently.

Buyer–Supplier Transaction Characteristics

We next discuss supplier contract features that can affect supplier performance evaluation via a contractor. This part is associated with a buyer–supplier relationship, such as variation in purchasing items' volume, value, and frequency of orders. Although one may consider the following section more as attributes of the buyer–supplier relationship, we believe it is within the project operating environment that can influence supplier performance in one way or another.

Number of Orders and Inventory Management

Following we outline how changes in the purchase frequency from suppliers and limited storage capacity on sites can be reflected in the contractor evaluation of supplier performance. For one thing, whiles inventory is considered as a source of cost (Azambuja and O'Brien 2009, p. 8), optimizing purchase volume for the contractor can result in huge cost savings. For example, consider aggregating orders for transportation cost reduction and bulk purchases to obtain the volume discount.

Furthermore, while the frequency of orders from suppliers can vary based on the availability of projects, a contractor should understand that supplier availability may change due to participation in multiple other projects executed by other contractors (Azambuja and O'Brien 2009, p. 16). Put differently, future purchasing from

Table 2. Characteristic of main project delivery methods

Project delivery method	Important characteristics and their implications for supplier performance
Design-bid-build (Ibbs et al. 2003; Hale et al. 2009; Pabor and Pennington 2012; Walewski et al. 2001)	• Contracts between owner-designer and owner-contractor • Owner is responsible for design, which may cause a constructability problem in suppliers' operations • Project parties are responsible for risk handling only for their own tasks, shifting risks down to suppliers • High competition to win the project by contractor, and therefore contractor requests more competent suppliers • Lack of effective coordination among the parties, resulting in long construction time and increased costs by suppliers • Contractor's desire to finish the project as early as possible to protect its profit results in time pressure to suppliers • Contractor tries to employ suppliers with minimum material and/or service standards • Contractor inflexibility in implementing the changes by owner-designer, and therefore fewer changes in suppliers' operations or completed tasks
Design-build (El-Sayegh 2009; Friedlander 2015; Dell'Isola 2002; Pabor and Pennington 2012; Walewski et al. 2001)	• Contracts between owner-contractor and contractor-designer • Contractor, as the main decision maker regarding time, cost, and quality control, has more freedom with supplier employment or replacement • Contractor as the designer-builder should be responsible for the entire project's success, which forces the contractor to be more careful with supplier performance • Early access of a contractor to right and relevant suppliers is important because contractor selection is based on proposed design feature, schedule, qualifications, capabilities, and cost • Fewer change orders by owner and reduced design errors that decrease rework time and cost in suppliers' operations • Early start of construction operations and involving suppliers by contractor
Construction management at risk (Mesa et al. 2016; El-Sayegh 2009; Uher and Davenport 2010; Walewski et al. 2001)	• Contracts between owner-designer and owner-contractor • Contractor mostly involved in complex projects with responsibility to control cost and design quality that lead to strict cost and performance control of suppliers • Improved communication and coordination due to preconstruction involvement of the different parties and suppliers • Greater flexibility of contractor with possible changes during the construction process that can help to promote a no-blame culture and supplier willingness to work on requested changes • Contractor has a good overview of the project, resulting in higher quality of contractor's relationship with suppliers
Alliancing and integrated project delivery (Cohen 2010; Lahdenperä 2012; AIA 2014)	• A contract between the owner, designer, and contractor • Contractor selection based on its potential capabilities, qualifications, and teamwork attitudes, in which contractor has similar requirements for its suppliers • Supplier has lower risk due to sharing gain and pain concept among all involved parties • Supplier has early stage involvement, direct communication, and active collaboration with other parties • Supplier gains financial benefit or loss on project outcome the same as other parties • Supplier multilateral relationship and peer appraisal environment (i.e., feedback from a client and other surrounding suppliers) that helps joint goal achievement • Supplier has an opportunity to learn from other integrated members • Enhanced transparency in supplier's financial and technical documentation

a supplier in the manufacturing supply chain mostly is assured for a specific time frame with predefined quality, cost, and lead times. However, in the construction supply chain, because of the unpredictability in having future projects by the existing contractor, suppliers try to be involved in as many emerging projects as possible.

In addition, even the frequency of orders from a supplier may change based on project type and size. While there is no possibility of storing some materials (e.g., concrete), a frequent number of orders is required. On the other hand, materials are almost always customized for the particular project and rarely could be transferred and used in other projects. This means the ordered materials should be consumed, otherwise they will be wasted or impose handling and transportation costs on the contractor. Therefore, to achieve optimal cost and delivery performance of the supplier and avoid extra costs associated with materials leftover on site, the right number of orders in sufficient quantities is required based on project type and size. However, it is thought that costs with materials and their transportation may vary between projects based on frequency and quantity of orders.

Position of Supplier in Project Operations Spectrum

The diversity and change in purchased items, from project to project, by the contractor is an important component of purchasing in the construction supply chain. Realizing this purchasing behavior, the contractor–supplier relationship can be shaped based on close and loose interaction in different levels (Bildsten 2014). These differences in purchased services and materials and strength of relationships can lead to diverse understanding of suppliers' performance. Following this line of reasoning, suppliers' performance may have different definitions for the contractor in a project's success. For instance, consider suppliers that need to complete their tasks, which have fallen into the critical path. These suppliers' performance in associated activities can be very important and sensible for the project time and cost. This highlights the concern regarding performance measurement of suppliers based on their position in project operations spectrum.

Additionally, regarding the stage of supplier involvement, the early stage of the construction process usually starts with a few suppliers working with operations related to preparing the building foundation such as pouring concrete. In this stage, normally a limited number of suppliers start to work and a contractor is more in control of supplier activities. To keep cost, quality, time, and other predefined project specifications under control from the very early stages of a project (Chapman and Ward 2003, p. 7), a contractor tries to be too cautious concerning its suppliers' performance from earlier phases to avoid or reduce possible problems in the later stages of the project (Peltokorpi et al. 2016).

Continuity of Transactions and Relationship

As projects' specifications mostly differ from one to another, purchased materials and services can vary based on the clients' needs and requirements. This corresponds to the one-of-a-kind nature of each project. Thus, a contractor should adjust its procurement process based on the acquisition of each new project. It is thought that this may prevent forming long-term supplier–contractor business relationships due to switching suppliers by changing projects (Brown et al. 2001). In simple terms, discontinuous purchase coupled with uncertainty about the availability of future projects can lead to suboptimal allocation of a supplier's resources because a supplier devotes its limited resources to various upcoming projects obtained from different contractors. In such a working atmosphere, most of the suppliers would not be able to demonstrate their full capacities in the performance evaluation process. In the same vein, Gadde and Dubois (2010, p. 256) mentioned that "the more important the buyer is perceived to be for the future, the more resources and efforts the supplier is willing to direct to the current episode." In a similar spirit, a supplier bills the contractor with the same price list if they had collaborated in the past, otherwise it may ask for 5%–10% extra cost for similar product or service from a contractor without or with limited collaboration experience (Shash 1998). Therefore, discontinuing purchase can be another aspect of changes in the operating environment of suppliers that can affect measuring and understanding of supplier performance by the contractor.

In addition to the benefits of a long-term business relationship, it is worth discussing briefly some pitfalls of close supplier–buyer relationships. For one thing, understanding that it takes a long time and considerable effort from the buyer to define strategic suppliers and build close relationships with them (Carr and Pearson 1999) can influence a buyer's objectivity, for example, by reducing rigidness in supplier performance monitoring (Villena et al. 2011). In turn, the high level of trust may result in a supplier's opportunistic behavior in its transactions and performance with a buyer (Grandinetti 2017). Deep familiarity of a supplier with the strengths and weaknesses of a buyer's audit system may tempt a supplier to cut corners in a calculating manner (Anderson and Jap 2005). Also, supplier motivation for continuous performance improvement may begin to deteriorate because it takes the continuity of purchasing for granted (Villena et al. 2011). Furthermore, long-term collaboration with some specific suppliers can result in losing the chance to discover more capable emerging suppliers in the market (Bendoly et al. 2010). This also may affect a buyer's responsiveness to supply chain disruption where the buyer has a time restriction while it is not aware of an alternative suitable supplier. In summary, continuity of transactions and relationship between buyer and supplier can have bright and dark sides. The strengths of those mechanisms define how this dynamism affects supplier performance development and its evaluation across projects. This section highlighted the challenges of supplier evaluation in construction projects. Next we discuss the changing operating environment and nonhomogeneous decision-making units from DEA literature for tackling such issues.

the changing operating environment Causing Nonhomogeneous Decision-Making Units

In the current section, we provide a brief explanation about the DEA technique and the concept of the changing operating environment within this context. The supporting reason for limiting our attention to DEA comes from reviewing the supply chain management and efficiency analysis literature that reveals DEA as a most common method of supplier efficiency evaluation (Ho et al. 2010; Lampe and Hilgers 2015). We then discuss the idea of nonhomogenous DMUs as a result of the changing operating environment in efficiency evaluation. Next, to deal with such settings, some of the proposed and applied solutions are presented from the DEA literature. Finally, we suggest the process that can be used for a supplier evaluation in construction projects.

DEA (Farrell 1957; Charnes et al. 1978) is one of the most popular approaches to derive performance analysis. DEA is a mathematical programming methodology for measuring relative efficiency of DMUs. In DEA, the efficiency score is measured by comparing DMUs' inputs and outputs and allocating the most optimal weights for each DMU's inputs and outputs (Charnes et al. 1978). Having obtained the optimal weights, an efficiency score of unity for efficient and a score less than unity for inefficient DMUs are provided [see, e.g., Ramanathan (2003) and Ray and Chen (2015) for more studies about DEA].

The conventional DEA approach assumes that all the DMUs operate in a similar environment and, at the same time, they are homogenous regarding applied inputs and outputs criteria (Haas and Murphy 2003). However, those conditions are not always met in real-world applications. In the previous section, we discussed consequences of the dissimilar operating environment on supplier evaluation. Equipped with this knowledge, yet the latter case of nonhomogeneity, in which not only the values of inputs and outputs are different but also some input and/or output variables are not consumed or produced by all DMUs, leads to even more severe challenges in supplier evaluation. Here the main challenge is to find a proper solution that can enhance comparability among DMUs despite having different input and output profiles. With these in mind, the following briefly discusses the main ideas behind these two categories.

First, the changing operating environment refers to a situation that is not under the DMUs' control, but it can affect their performance. This considers conditions in which normal inputs and outputs of DMUs are influenced by an external factor(s). These are mostly known as environmental factors in the extant DEA literature. In the words of Coelli et al. (2005, p. 190), environmental variables refer to "factors that could influence the efficiency of a firm, where such factors are not traditional inputs and are assumed not under the control of the manager." Different approaches are proposed to deal with environmental factors and their advantages and disadvantages are discussed by others [see Coelli et al. (2005, p. 190), Thanassoulis et al. (2008, p. 340), Yang and Pollitt (2009), and Huguenin (2015) for more detailed discussions]. This group of studies aims to purge the influence of environmental factors in efficiency evaluation. In this process, the objective is to remove the impact of operating environment that may work in favor of some DMUs and be unfavorable for others in one way or another (Avkiran 2009). For example, a bank's branches located in the center of the city surrounded by commercial communities experiencing a different environment than a branch in the rural area with the residential neighborhood as argued by Aggelopoulos and Georgopoulos (2017).

Second, nonhomogeneity among DMUs is caused by differences in the inputs and outputs bundle. That is, some DMUs may not consume all the defined inputs for producing similar outputs or may consume similar inputs but do not produce all the outputs as other DMUs. There were earlier studies that considered having no data for some DMUs in their inputs or outputs as a missing value that should be estimated (e.g., Saen et al. 2005). One may also suggest dividing DMUs into smaller groups for making them homogeneous, regarding common inputs that produce common outputs, in case a large number of DMUs are available. However, the recent research highlights that the lack of data in input and/or output variables should not be treated as missing values if a DMU does not consume or produce some specific inputs or outputs due to the nature of its activities (Cook et al. 2013). Also, in most of the applications, separating a set of DMUs into multiple homogenous groups is not practical due to the small sample size and decreasing discrimination power in obtained efficiency results (Cook et al. 2013). Therefore, the efficiency of DMUs should be compared based on their actual existing inputs and outputs. For example, in performance analysis of cities, Li et al. (2016) investigated the absence of natural resources in some cities compared to others. In this scenario, all the cities produced the same outputs such as gross domestic product and nitrogen dioxide, while some had no access to natural resources as inputs such as coal, natural gas, and petroleum.

To elaborate more on the concept of nonhomogeneous DMUs, Table 3 presents six hypothetical construction projects in which a unique supplier has participated. This table provides a supplier's input and output data structures that vary across different project types. That is, due to the nature of the projects, some input and/or output values are not available or are not among the priorities of a site manager in supplier evaluation. For example, consider distance (input) and personnel training (output) for the retail project, and performance history in the same project type and warranty (outputs) for the warehouse project, which are not applicable for evaluating a supplier. Put differently, despite having a list of standard evaluation criteria, feedback data have not been assigned for some evaluation measures. In the present study, we associated this problem with the changing operating environment of a supplier moving from one project to another.

Reviewing the previous literature, although much attention has been focused on understanding the changing operating environment and nonhomogeneity among DMUs for performance evaluation in different manufacturing and service sectors, little is known about these concerns in the construction projects. More specifically, joint discussion of the changing operating environment and nonhomogeneity among DMUs has been neglected in the extant literature. Building on these, we believe that the changing operating environment and nonhomogeneity among DMUs should be considered in supplier evaluation in construction projects. Although a supplier operating environment is changing by moving between the projects, usually a contractor uses the same efficiency evaluation criteria across all projects. In this case, it is supposed that supplier tasks and roles are identical in each project. Nonetheless, as characteristics of projects can vary from each other, the same set of supplier evaluation variables may not be exactly as relevant in all the projects.

Table 3. Hypothetical supplier evaluation data bundle

	Inputs			Outputs		
Project	Distance	Price	Delivery	Personnel training	Performance history in the same project type	Warranty
Housing	x	x	x	x	—	x
Retail	—	x	x	—	x	x
Warehouse	x	x	x	x	—	—
Educational	x	x	x	x	x	x
Sports hall	x	x	x	—	x	x
Shopping center	—	x	x	x	x	—

Realizing the importance of the changing operating environment and nonhomogeneity of units in a supplier performance evaluation using DEA, we present some of the relevant studies in each category in Tables 4 and 5. In these studies, information regarding environmental variables or causes of nonhomogeneity, suggested solutions, application areas, and number of DMUs were considered. The aim of these tables is not to compare the methods and outline their superiority and inferiority relative to each other, and thus we did not cover all the existing models because such comparisons have already been conducted by others (e.g., Yang and Pollitt 2009; Huguenin 2015). However, highlighting some information regarding prior studies in these domains can be valuable for the better understanding of the current research. In so doing, some of the studies covering topics of the changing operating environment and nonhomogeneity among DMUs in the DEA literature are provided.

In this study, we contend that the changing operating environment may cause nonhomogeneity among DMUs. Therefore, in such settings, first we suggest dealing with differences in a supplier's inputs and outputs bundle in an applied model (Table 5). Second, we recommend taking into account the effect of changing the project environment in the next level (Table 4). In simple terms, having data for input and output variables is a prerequisite of conducting performance comparison among DMUs. As such, if some DMUs are missing data in evaluation measures due to the nature of their activities that do not consume or produce some specific inputs and/or outputs, we argue that this concern should be tackled first because a comparability situation for evaluating all DMUs should be provided before investigating the role of the changing operating environment. In such a scenario, in most of the proposed methods such as the four-stage approach (Fried et al. 1999) in the literature, analysis of the obtained performance results is the primary condition for realizing the effect of the changing operating environment on performance differences among DMUs. For instance, to understand the favorable or unfavorable impact of the environment on nursing home performance, Fried et al. (1999) attained initial performance, adjusted input and outputs value, and then recalculated the efficiencies to purge uncontrollable factors influencing the obtained efficiency results. Therefore, we argue that the challenge of nonhomogeneous DMUs and the changing operating environment can be tackled in construction supplier evaluation using DEA via methods that are already practiced in other industries. Fig. 1 depicts the suggested process.

In the next section, using data from real construction projects, we clearly show how a supplier operating environment can change from one project to another, which can lead to different performance evaluation data profiles in supplier evaluation. The main aim of the analysis is to illustrate some of the discussed challenges of supplier evaluation in the construction supply chain context. Collecting sufficient project information for modeling purposes and testing the proposed conceptual process is left for the future studies.

Illustration of Challenges for Supplier Performance Evaluation in the Changing Operating Environment

To illustrate the discussed challenges with supplier evaluation in a construction context, we obtained projects and suppliers' data from a large international company working in the Finnish construction market. This company executes construction projects associated

Table 4. Factors and solutions related to the changing operating environment among DMUs

Study	Environmental factors	Proposed solution	Application	Number of DMUs
Banker and Morey (1986)	• Age of the store • Allocated advertising expenditures to the store by the headquarters • Store's location (i.e., urban and rural) • Existing drive-in window	• One-stage analysis, treating inputs as exogenously fixed variables along with normal inputs and outputs in Banker et al. (1984) (BCC) model	Chain of fast food restaurants in the United States	60
Fried et al. (1999)	• Ownership form • Location	• Four-stage analysis, joint use of DEA and tobit regression	US nursing homes	990
Muñiz (2002)	• Studying more than 10 h a week • Image for future prospects • Family income • Transfer between teaching centers • Only child	• Modified three-stage DEA method based on Fried and Lovell's (1996) model	Public high schools in Spain	62
Avkiran (2009)	• Interest rates	• Four-stage analysis based on DEA slack-based measure model. It follows Fried et al.'s (1999) proposed approach: running DEA model, applying tobit regression, adjusting the data to capture environmental effect, rerunning the DEA model	Australian and New Zealand banks	120
Yang and Pollitt (2009)	• Vintage of generating units • Calorific value of coal • Unit scale • Combined heat and power	• Four different DEA-based models to deal with uncontrollable variables are tested, where Fried et al.'s (2002) three-stage model is considered to be superior compared to other approaches	Chinese coal-fired power plants	221
Johnson and Ruggiero (2014)	• Student poverty	• Joint use of DEA and Malmquist Productivity Index • Incorporate the environmental variable into Malmquist Productivity Index and decompose to efficiency change, environmental harshness change, and technical change • Grouping schools in five different classes based on some standards	Kindergarten through twelfth-grade public schools in Ohio	604
Aggelopoulos and Georgopoulos (2017)	• Size • Location	• Bootstrap input-oriented profit DEA model • Grouping branches based on size and location	Greek bank branches	362

Table 5. Nonhomogeneity among DMUs

Study	Cause of nonhomogeneity	Proposed solution	Application	Number of DMUs
Cook et al. (2013)	Dissimilar output sets	Develop a new DEA-based methodology to compare the DMUs based on common outputs (i.e., different subgroups)	Steel fabrication plants	47
Li et al. (2016)	Dissimilar input sets	Propose a new three-step procedure based on DEA approach	China's provinces	31
Zhu et al. (2018)	Dissimilar input sets	Apply a four-step process using cross efficiency DEA concept	Standard & Poor's (S&P) 500 corporations	39

with different building types and infrastructure developments, where we limited our data analysis to the former segment. We directly obtained the data related to project information, suppliers' financial transactions, and suppliers' evaluation feedback from the company. For the purpose of this study, we merged the recorded projects' general information with the suppliers' financial transactions data. We further limited the investigated projects, focusing on those projects in which the supplier with the highest financial transaction history with the company has participated (we refer to the supplier as Supplier A to preserve its anonymity). As a result, 12 projects were selected for our analysis.

Using data from these 12 projects, we empirically show how a supplier's operating environment changes from one project to another. The longitudinal data on project characteristics and purchases of the contractor cover the time span from 2010 to 2016, allowing us to compare changes in the supplier's operating environment. Projects 11 and 12 (Table 6) are still being executed and will be completed by the upcoming year(s). Table 6 provides the associated characteristics of these 12 projects from three standpoints representing project product and location characteristics, project organization characteristics, and buyer–supplier transaction characteristics, as formerly discussed in the second section in this paper. We next elaborate on each characteristic in turn.

General project characteristics encompassed type, size, and location of each project. Project building types were categorized into shopping center, educational institution, retail, sports hall, and residential. Further, size was considered both from the project duration and the contract sum perspectives. According to the contractor estimation, the initial planned duration of the projects varied from 14 to 28 months. The contract value of the projects also ranged from 5 to more than 100 million euros. This large variation among the projects may explain the contractor's diversity of operations and

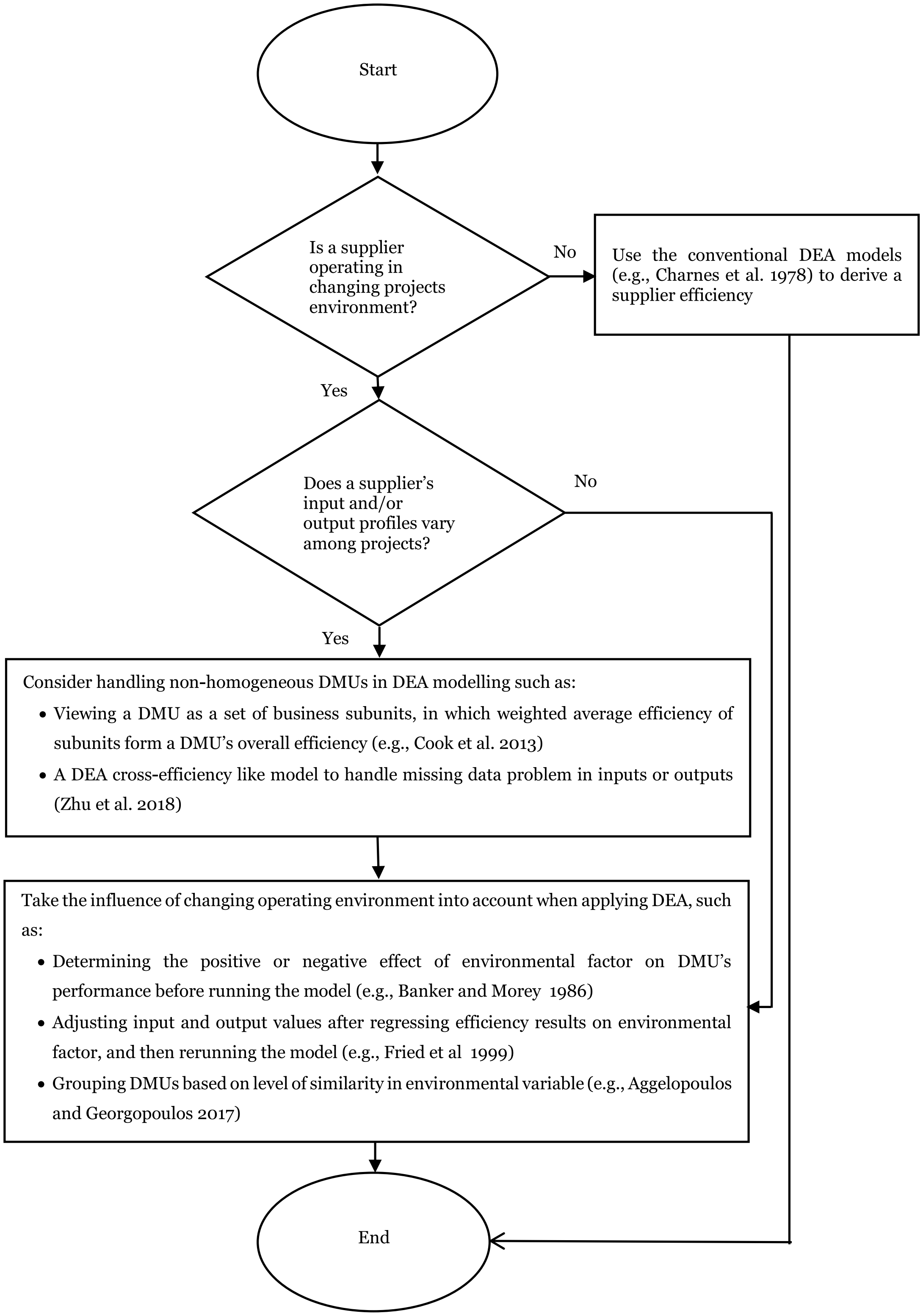

Fig. 1. Proposed process to concurrently deal with the changing operating environment and nonhomogeneous DMUs.

technical and financial capabilities. In addition, projects were scattered in three main parts of the country: west, east, and south. While construction is a location-based activity, different geographical operations of the projects also indicate the contractor having a varying ability in hiring and allocating required suppliers for each project.

Moreover, project organization characteristics referred to client type, delivery method, number of suppliers, and number of shared suppliers in each project. Regarding the projects' ownership, the clients represented three different types: corporations, residential householders, and the public sector. Different types of companies, individuals, and associations possess the ownership of each project. Four different delivery methods were covered: design-build, design-bid-build (single prime and multiple primes), construction management at risk, and integrated project delivery. The design-build and

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Table 6. Supplier A's operating environment characteristics for 12 projects

	Project product and location characteristics					Project organization characteristics			Buyer–supplier transaction characteristics			
		Size										
Project	Type	Duration (months)	Contract sum (million euros)	Location	Client type	Delivery method	Number of suppliers	Number of shared suppliers	Number of orders from all suppliers	Purchase volume from all suppliers (million euros)	Number of orders from shared suppliers	Purchase volume from shared suppliers (million euros)
1	Shopping center	28	+100	Western Finland	Corporate	Design-build	218	Base for comparison	793	70.570	N/A	N/A
2	Educational institution	25	10–15	Western Finland	Public	Design-bid-build/single prime	105	30 (29%)	266	7.509	154 (58%)	3.332 (44%)
3	Housing	20	10–15	Southern Finland	Residential	Design-bid-build/single prime	100	27 (27%)	515	6.193	387 (75%)	1.522 (25%)
4	Housing	21	10–15	Southern Finland	Residential	Design-build	93	24 (26%)	568	5.029	398 (70%)	1.002 (20%)
5	Housing	17	5–10	Southern Finland	Residential	Design-build	103	31 (30%)	255	4.167	154 (60%)	1.370 (33%)
6	Housing	15	5–10	Southern Finland	Residential	Design-build	77	27 (35%)	189	4.624	126 (67%)	1.944 (42%)
7	Housing	18	5–10	Southern Finland	Residential	Integrated project delivery	111	31 (35%)	237	4.352	115 (49%)	1.065 (24%)
8	Retail	13	5–10	Southern Finland	Corporate	Construction management at risk	87	30 (34%)	223	3.998	130 (58%)	0.700 (18%)
9	Housing	18	5–10	Western Finland	Residential	Integrated project delivery	149	38 (26%)	333	3.918	150 (45%)	0.860 (22%)
10	Housing	18	5–10	Southern Finland	Residential	Integrated project delivery	107	27 (25%)	248	3.243	138 (56%)	0.627 (19%)
11	Sports hall	14	0–5	Southern Finland	Public	Design-bid-build/multiple prime	98	19 (19%)	97	1.945	19 (20%)	0.404 (21%)
12	Housing	15	0–5	Eastern Finland	Residential	Integrated project delivery	79	22 (28%)	79	1.590	22 (28%)	0.282 (18%)

integrated project delivery methods were the most commonly practiced methods. While in the design-build method the risk with suppliers is a burden solely borne by the contractor, this risk is shared by the client in integrated project delivery. In the latter, a joint contractor and client responsibility for an effective coordination of supplier relationship is more important.

The involved number of suppliers in each project also varied a lot. This may indicate a varying relationship complexity among the suppliers. The number of suppliers ranged from 218 in Project 1 to 77 in Project 6. On the other hand, the possibility of moving a large number of the same suppliers from one project to another is desirable. This is due to the accumulation of suppliers learning from each other and multilateral trust establishment. Therefore, moving the same suppliers from one project to the next was also recorded. From all the participating suppliers in Project 1, in the best scenario, 38 could join Project 9 and, at the other pole, only 19 of the same suppliers took the part in Project 11. This shows that each project employed a large number of new suppliers and only a limited number of suppliers have the opportunity to contribute to other projects of the contractor.

Furthermore, supplier relationship characteristics specify the number of orders and purchase volume from all suppliers, and the number of orders and purchase volume from shared suppliers. This part considers purchasing attribute of the contractor from suppliers in each project. The highest and lowest number of orders were 793 and 79, while the corresponding purchasing values of the same projects were 70.570 and 1.590 million euros. Finally, reviewing the number of orders and purchasing value from the shared suppliers, remarkable variation can be seen in the operating environment. Project 4 with 398 and Project 11 with only 19 orders from the shared suppliers are among the notable figures for this subsection. A similar high variety can be identified in purchasing share from the shared suppliers varying between 18% and 44% of all purchases.

Having discussed how a supplier's operating environment can change stemming from a diversity of construction projects and their specific characteristics, we next present a supplier's evaluation feedback in such projects. For doing so, considering the data availability and also to illustrate differences in a supplier evaluation feedback data profile, we focused our attention on the supplier that was in the second position after Supplier A regarding the volume of financial transactions with the company (we refer to the supplier as Supplier B to maintain its anonymity). These data were derived from a qualitative supplier evaluation feedback system of the contractor in 2016. For this year, we extracted 44 building projects on which Supplier B received evaluation feedback.

Table 7 depicts the 12 criteria that were used for supplier evaluation in construction sites by the contractor. All of the criteria can be considered as outputs, which means the higher the better for supplier performance in DEA terminology. Supplier B's evaluation data structure is also provided in Table 8. The data range style is from 1 to 5, where 1 represents the worst and 5 indicates the best performance. Each evaluation or its average in projects with more than one evaluation can be considered as one DMU.

Considering the varying nature of the projects' characteristics, some output values were not equally available across all the evaluations or projects, as explained previously. For example, while the acquired construction projects by the contractor are usually geographically dispersed and have different ownership structures, location may change projects' priorities and client requirements may vary across the projects. In such settings, despite the diversity of locations and client types, project managers are responsible for the projects' success from the contractor side. They also can make or influence purchasing decisions from suppliers trying to optimize

Table 7. Criteria for supplier evaluation

Symbol	Definition
y_1	Attitude to occupational safety
y_2	Cleanliness, order, and environmental consideration
y_3	Compliance with safety instructions
y_4	Activity in promoting safety
y_5	Supervisor expertise and availability
y_6	Compliance with agreed time tables
y_7	Additional claims in relation to the contract
y_8	Billing and payment terms in accordance with the contract
y_9	Compliance with the agreement
y_{10}	Quality of the product and/or service
y_{11}	Development activity (style of collaboration, way of working)
y_{12}	Corrective actions regarding possible comments and complaints by the buyer

Table 8. Supplier B's evaluation feedback in 44 projects

Project	y_1	y_2	y_3	y_4	y_5	y_6	y_7	y_8	y_9	y_{10}	y_{11}	y_{12}	Number of evaluations
1	—[a]	—	—	—	4	5	5	5	5	4	4	5	3
	4	—	4	—	5	5	5	4	4	4	—	5	
	—	—	4	—	5	5	5	5	5	4	—	5	
2	4	4	4	—	4	4	—	5	5	4	—	—	3
	5	5	5	—	5	4	—	3	5	4	—	—	
	4	4	4	—	4	5	—	5	5	4	—	—	
3	5	—	4	—	4	4	5	4	4	5	4	5	3
	4	—	5	—	2	4	5	4	4	5	—	5	
	4	—	5	—	5	5	4	4	5	4	4	4	
4	—	—	—	—	—	4	4	4	4	4	—	4	3
	—	—	—	—	—	4	4	4	4	4	—	—	
	4	—	4	—	4	4	—	4	4	4	—	—	
5	4	4	4	4	4	4	4	4	4	4	4	4	3
	4	4	4	4	3	4	4	4	4	3	4	4	
	4	4	4	3	—	4	—	3	4	4	4	4	
6	4	4	4	3	4	5	—	4	4	4	3	—	3
	4	4	4	3	4	5	4	4	4	4	4	4	
7	4	4	4	4	4	4	—	4	4	4	3	—	2
	4	4	4	4	4	4	—	4	5	4	4	4	
8	5	5	5	4	5	5	—	5	5	4	5	5	2
	4	4	4	3	4	4	—	4	4	3	4	4	
9	4	5	4	—	5	5	5	5	4	4	—	—	2
	3	3	—	3	5	5	5	4	5	4	—	5	
10	4	4	4	4	4	2	4	4	3	2	4	4	2
	3	3	3	2	4	4	5	5	4	4	4	5	
11	—	—	—	—	—	4	5	5	4	5	—	5	2
	4	—	4	3	4	3	4	4	—	4	3	4	
12	5	4	5	—	4	4	4	4	4	4	—	3	2
	5	5	5	4	5	5	5	5	5	5	5	5	
13	4	4	4	3	4	4	4	4	4	4	3	4	2
	3	4	4	3	4	4	4	4	4	4	3	4	
14	4	3	4	3	4	4	4	4	4	4	3	4	2
	3	4	3	4	4	4	4	4	4	4	3	4	
15	4	3	4	4	4	4	4	4	4	3	4	4	2
	3	4	—	3	4	4	4	4	4	4	3	4	
16	4	3	3	3	3	2	4	4	3	4	4	3	2
	4	4	4	3	3	4	5	4	4	3	3	3	
17	—	—	—	—	4	4	4	4	4	3	4	4	2
	4	4	4	4	4	4	4	4	4	3	4	4	
18	4	4	4	4	4	5	4	5	4	4	4	4	2
	5	3	4	4	4	3	5	4	4	3	4	4	
19	4	4	4	4	4	4	4	5	5	4	3	4	2
	—	—	—	—	4	4	4	4	5	3	3	4	
20	—	—	—	—	4	4	—	4	4	4	—	—	2
	4	4	4	—	4	4	4	4	4	4	—	4	
21	4	4	4	3	4	5	4	4	4	3	3	3	2
	5	5	4	5	4	4	5	5	5	5	3	4	
22	5	5	5	5	5	5	5	5	5	5	5	5	1
23	—	—	5	—	—	5	—	5	5	5	—	—	1
24	4	—	4	—	4	4	5	4	4	5	—	5	1
25	5	—	4	4	4	5	4	4	5	4	3	4	1
26	—	—	5	—	5	5	5	5	5	5	4	5	1
27	4	4	4	4	4	4	5	5	5	2	4	5	1
28	4	—	—	—	—	5	5	5	4	3	3	5	1
29	4	3	3	3	3	3	2	4	4	2	2	2	1
30	4	4	4	4	4	4	5	4	4	4	4	4	1
31	—	—	—	—	5	5	—	5	5	5	4	—	1
32	5	5	5	5	—	5	5	5	5	5	5	5	1
33	5	4	5	—	5	4	5	4	5	4	—	5	1
34	4	3	4	4	4	4	4	5	5	5	4	4	1
35	—	—	—	—	2	1	—	4	4	1	1	2	1
36	—	—	5	—	—	5	—	5	5	4	—	—	1
37	3	4	4	5	5	5	5	5	5	5	5	5	1
38	5	5	5	5	5	5	5	5	5	5	5	5	1
39	—	—	—	—	4	2	5	5	3	5	4	3	1
40	4	3	4	4	4	4	5	5	5	3	3	5	1
41	5	4	4	5	4	4	5	5	5	4	4	5	1
42	5	4	5	4	4	4	4	5	5	4	4	4	1
43	5	—	5	—	5	5	5	5	—	5	—	5	1
44	2	4	2	2	4	3	4	4	4	4	3	4	1
Sum													71

[a]Not relevant or among the priorities of this project.

project outcomes. In doing so, project managers may treat a supplier differently based on the relative and changing importance of evaluation variables. In other words, the project manager can decide to emphasize some specific criteria compared to others in a predefined standard supplier evaluation framework. Accordingly, a supplier may obtain evaluation feedback on all the criteria for some projects and may not receive evaluation for some criteria in other projects. This clearly indicates how changing the project environment can result in nonhomogeneity among DMUs in the efficiency evaluation process.

Table 8 presents evaluation feedback for Supplier B in 44 construction projects. For most of the projects this supplier obtained one evaluation per project, but in some cases it received two or three evaluations. This can be related to the duration of the projects or different material or service alternatives that might be provided by this supplier. Reviewing the table in greater detail shows that Supplier B's evaluation data were not available for one or more variables in a number of projects. For instance, consider first the series of evaluation concerning y_1, y_2, y_3, and y_4 in Project 1 or y_4, y_7, y_{11}, and y_{12} in Project 2. Due to the changing operating environment, feedback was not assigned to some of the criteria in these projects. This can result in different evaluation data profiles for Supplier B, called nonhomogenous DMUs in the previous section. Given that, in construction projects the problem with nonhomogeneity among DMUs should be taken into account in designing and evaluating the efficiency of suppliers using DEA.

Conclusions

Gaining an understanding of suppliers' important role in projects, we extended current research on supplier evaluation in construction from different perspectives. First, we contributed to supplier evaluation in construction by discussing DEA, a well-established tool developed and applied in a diverse set of fields, for improving construction SCM practice. In doing so, the challenges for supplier evaluation in the construction context were highlighted. The study explained various origins for changing the operating environment between projects that would affect supplier evaluation from three standpoints: project product and location characteristics, project organization characteristics, and buyer–supplier transaction characteristics.

Second, we contributed to the DEA literature by joining the nonhomogeneous DMU research stream to the changing operating environment studies. The recent DEA research highlights occasions that input and/or output bundles of DMUs differ from each other. In a similar spirit, we argued that there might be evaluation variables that are not relevant to specific projects or are not among projects' priorities for supplier evaluation. This can result in situations in which a supplier has no data for those variables in some projects, where this can give rise to a problem with input and/or output data profiles. Building on that, in this study we contended that nonhomogeneity in a supplier evaluation is due to changing the project environment.

Third, reviewing the prior studies in the changing operating environment and nonhomogeneity among DMUs, we suggested a process that can be used for a supplier efficiency evaluation in the presence of environmental factors and different input and/or output profiles. We drew a flowchart that outlined the required steps using appropriate DEA models for supplier evaluation in construction projects.

Finally, using data from a real-world context from Finland, we supported our discussed challenges regarding supplier evaluation in construction projects. Initially, we investigated 12 projects to empirically illustrate how moving from one project to another can lead to a different operating environment for a supplier. In the second stage, we provided supplier evaluation feedback from 44 different projects to show how changing the project environment may cause varying evaluation data profiles.

This study was also subject to several limitations, which in turn provide avenues for further research. First, besides the discussed prior studies from the changing operating environment and nonhomogeneity of DMUs, it would be ideal if one could use the proposed conceptual process in construction projects and then show the effect of environmental factors on a supplier performance. Second, while evaluation feedbacks are subjectively assigned to a supplier through construction site managers in different projects, we did not cover discussions related to qualitative data and possible problems and related solutions for such types of data in DEA. Future studies can expand our research to cover this topic with great detail. Finally, future research might explore supplier evaluation variables that are most relevant to different construction projects despite the change in operating environment.

Data Availability Statement

Data generated or analyzed during the study are available from the corresponding author by request. Information about the *Journal*'s data-sharing policy can be found here: http://ascelibrary.org/doi/10.1061/(ASCE)CO.1943-7862.0001263.

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