Digitalization Opportunities Road Mapping Tool (DORMT©): A Framework to Assess Digitalization Opportunities in Construction Organizations

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Abstract

The construction industry is entering the digital age, which offers innovative digitalization opportunities (DOs) regarding cost efficiency, project management, and improved client experience. In their early efforts to implement DOs, construction organizations have had varying degrees of success, and the results caused organizations to question whether they have the appropriate digital strategy and capabilities. Hence, construction organizations need a framework to systematically evaluate the potential benefits of implementing DOs and factors influencing their successful implementation. This paper presents a framework that supports decision makers in construction organizations to assess DOs based on experts' judgement of the factors influencing their successful implementation. The framework incorporates fuzzy arithmetic and linguistic evaluation to capture experts' subjective assessments and is implemented in the Digitalization Opportunities Road Mapping Tool (DORMT©). DORMT©, which allows organizations to evaluate individual DOs, rank multiple DOs, and identify the best options for implementing digitalization within their organization.

Keywords: Fuzzy logic, fuzzy arithmetic, construction, linguistic evaluation, digitalization

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1 Introduction

The digital age has ushered in the proliferation and democratization of data (Wong et al. 2018) and for the past two decades, the use and availability of digital technology has grown exponentially (Bharadwaj et al. 2013). This wave of digital technology adoption has impacted individuals and businesses across all sectors of the global economy. Despite the opportunities presented in digital technology, the construction industry has been slow to adopt and integrate new technologies (Gerbert et. al. 2016). Since the 1950s, industries such as agriculture and manufacturing have experienced productivity gains of up to 15 times, while the construction sector has largely remained unchanged (Barbosa et. al. 2017). Researchers and industry experts agree on the need for increased uptake in digital technology, which stand to significantly benefit the construction industry (Barbosa et. al. 2017; Lu et al. 2015).

Consumer and business digital adoption were accelerated as a result of the social distancing requirements due to the novel coronavirus and COVID–19 pandemic (Baig et al. 2020). Biörck et al. (2020) observed that construction firms were thrown into the deep end of "ConTech" (a term meaning "all construction technology") and forced to quickly adopt new and readily available technologies. Biörck et al. (2020) also stated that the COVID–19 pandemic helped contractors realize how efficient and fast online platforms can be, especially with an ongoing shortage of skilled laborers and restrictions on how many people can be on site at a given time during a pandemic. Both Baig et al. (2020) and Biörck et al. (2020) concluded that digital technology has ceased to be optional, and it has become the differentiator across many industries.

For the successful adoption and implementation of digital technology in the both the short and long terms, construction organizations must be able to systematically assess the benefits and success factors associated with the many digital technology alternatives available. CII (2011) research team RT 258 developed a detailed process and tool to allow construction organizations to assess and evaluate the benefits and hinderances associated with various information integration opportunities. The tool focused on improving information integration between project participants, which is only a subset of digitalization. A similar tool developed by Kang et al. (2015) was limited in its application to information integration opportunities and lacked the capability to evaluate multiple opportunities within the same tool. Despite the progress in digitalization implementation research in the construction industry and an ample supply of digital technologies, there is an existing gap in research on the use and adoption of effective digitalization implementation frameworks. For effective adoption and implementation of DOs, the construction industry needs an easy-to-use tool that helps practitioners identify and deal with the barriers they encounter during the planning and implementation phase associated with DOs.

This paper presents a framework for assessment and ranking of DOs by construction organizations. The framework provides a comprehensive list of factors used to linguistically evaluate the potential benefits and possibility of successful implementation of DOs. Using linguistic scales and fuzzy arithmetic, the framework generates an overall benefits and success factor scores for a DO under evaluation. The framework is implemented in the Digitalization Opportunities Road Mapping Tool (DORMT©), which guides construction organizations through the planning and implementation phase of DOs. DORMT© enables construction organizations to assess individual DOs and help identify the best alternative from multiple DOs based on their scores and ranking.

2 Literature review in digitalization implementation

2.1 Digitalization and the digital continuum

In previous research, digital technologies were also referred to as information communication technologies. According to Bharadwaj et al. (2013), digital technologies are combinations of information, computing, communication, and connective technologies. Lu et al. (2015) categorized information communication technologies as comprising web, wireless, virtual/augmented reality, building information modelling (BIM), and data exchange and management technologies. For the sake of consistency, this paper refers to all information communication technologies as digital technologies.

Within the construction industry, digital technologies have been developed for use and application across the entire lifecycle of physical assets: namely, the planning, designing, construction, assembly, operations, and maintenance stages (Hautala et al. 2017). Digital technologies are central to the required transformation that will improve construction productivity and efficiency through digitalization, innovative technologies, and new construction techniques (Bašková et al. 2019).

A clear distinction must be made between digitization, digitalization, and digital transformation. Figure 1 has been developed to describe a digital continuum in which these three terms can be applied.

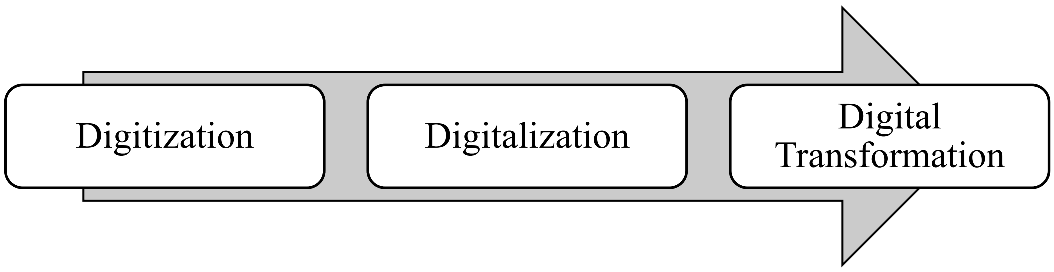


Figure 1. The digital journey continuum

An organization's journey through the continuum begins with digitization, moves into a digitalization phase, and ultimately matures into digital transformation. Barbosa et al. (2017) provided a concise definition of the initial phase, digitization, as "the act of developing digital assets, expanding digital usage, and creating a more digital workforce." Digitalization is the next phase on an organization's digital journey. Although digitalization is at times confused with digitization, digitalization is the process of utilizing digital technologies to incorporate, manage, use, and analyze digital data in order to drive business objectives and create value (Gerbert 2016). Digitalization focuses on the use of the digital data to drive objectives, whereas digitization is primarily the act of creating digital data. The final stage in the digital journey continuum is the digital transformation stage. Westerman et al. (2011) defined digital transformation as "the use of technology to radically improve performance or reach of enterprises". They also stated that major digital transformation initiatives are centred on "re-envisioning customer experience, operational processes and business models." Digital transformation therefore focuses on re-envisioning changes to how a company operates in its entirety (Westerman et al. 2011).

Understanding the digital continuum reveals the important distinction between digitization, digitalization, and digital transformation. This paper focuses on the digitalization phase in construction via a tool that can help organizations assess the benefits and the drivers associated with successful implementation of DOs.

2.2 Implementation of digitalization opportunities (DOs)

Past studies of digitalization implementation have highlighted some of the challenges that organizations may encounter during the adoption and implementation phase. Ghaffarianhoseini et al. (2017) determined that BIM can present barriers to adoption that may include lack of demand, interoperability issues, and high costs. Many organizations have also experienced a low return on investment (ROI), especially small firms that are not highly engaged in the BIM process. Successful adoption of BIM requires investments in software, hardware, and training (Ghaffarianhoseini et al. 2017). When reviewing the critical success factors of BIM for a precast concrete manufacturer, Phang et al. (2020) concluded that the whole supply chain ecosystem must fully embrace technologies and BIM processes to realize the full benefits of digitalization. Papadonikolaki (2018) explored the impact of internal versus external BIM adoption drivers on BIM implementation in projects by analyzing three case studies and determined that successful BIM implementation was achieved by internally motivated organizations, rather than by those that were externally mandated to adopt BIM by client demands or market pressures. The studies by Ghaffarianhoseini et al. (2017), Phang et al. (2020), and Papadonikolaki (2018) emphasize the importance of evaluating all factors that determine the successful implementation of digital technologies.

Sepasgozar and Davis (2018) investigated the issue of technology adoption in the construction industry from the point of view of both the vendors providing technologies and the customers adopting those technologies. They proposed the methodological cube Construction Technological Adoption Process (CTAP) cube to assess new technology investigation, adoption, and implementation. The study was limited to the interaction of vendors and construction organizations and lacks simplicity to be implemented by construction organizations alone in the pre-implementation phase of technology adoption.

Love and Mathews (2019) highlighted the importance of adequately assessing the benefits of technology prior to investments in order to understand how digital technologies will generate business value and improve competitiveness. As part of a benefits management system, they constructed a generic business dependency network (BDN) to visualize and organize the relationships between capabilities, changes, and benefits to be considered prior to adoption of new digital technologies. The main components of a BDN are: identifying the role of technologies, assessing change enablers and the causes for sustained change, evaluating business benefits, and noting the investment objectives. The BDN framework can similarly be used by construction organizations and owners to ensure that investments in digital technologies are effectively used to drive business objectives and generate value (Love and Mathews 2019), but it does not address the barriers for successful implementation of digital technologies. The studies by Love and Mathews (2019) and Sepasgozar and Davis (2018) concluded that construction organizations need to evaluate digital technologies prior to implementation.

Some efforts have been made in the past to address challenges and improve implementation of digital technologies in construction, including the research done by CII (2011), Perrier et al. (2020), Alaloul et al. (2020), Maskuriy et al. (2019), and Schönbeck et al. (2020). The CII's (2011) research focused on both the assessment of the state of information integration in the construction industry and development of a Capital Projects Information Integration Maturity Model and Integration Opportunity Assessment Tool. The Integration Opportunity Assessment Tool focused on only one subset of digitalization, information integration, which was defined as "the sharing of information among project participants to support effective execution."

Studies by Maskuriy et al. (2019), Perrier et al. (2020), Schönbeck et al. (2020), and Alaloul et al. (2020) investigated the current state and challenges of implementing digital technologies in the construction industry. Maskuriy et al. (2019) explored the implementation of digital technologies in construction management-related activities such as market study, conceptual planning, investment management, and project preparation. They observed that construction organizations need a method to evaluate digital technologies before they are implemented. Perrier et al. (2020) proposed a classification of existing literature on applications of digital technologies in the construction industry to allow for a better analysis of trends and gaps in research related to digital technologies. Similarly, Schönbeck et al. (2020) investigated the extent to which research in construction addresses information and communication, automation, and industrialization technologies by performing a quantitative analysis of more than two thousand journal papers in construction. Both Perrier et al. (2020) and Schönbeck et al. (2020) suggested that more research on the successful implementation of digital technologies in the construction industry is needed. Alaloul et al. (2020) conducted a comprehensive literature review to identify the main problems that delay the implementation of digital technologies in the construction industry and concluded that the successful implementation of digitalization technologies depends as much on external factors (e.g., social, economic, security, legal, and political) as internal factors (e.g., technical infrastructure and human resources).

The studies discussed in this section support the need for a structured process that construction organizations can follow to evaluate digital technologies before implementing them. Such a process should include an assessment and understanding of the construction organization's internal characteristics as well as external factors affecting the implementation of digital technologies. In addition, many different digital technologies are available for implementation in construction, each with a different level of potential success and benefits. Thus, a framework is needed that supports decision makers in construction organizations in assessing and choosing from multiple digitalization opportunities (DOs). This paper proposes such a framework to systematically formalize the evaluation of DOs for the construction industry.

3 Proposed framework for evaluation and ranking of DOs

The proposed framework is a procedure based on fuzzy linguistic evaluation of sets of criteria that are used by a construction organization to assess a DO as shown in Figure 2. The first step is to identify and categorize comprehensive list of benefits and success factors through extensive literature review and opinions from industry experts. Benefit factors are the potential benefits a DO presents to a construction organization. Success factors are criteria for assessing the complexity of and the organizational readiness to implement a DO. The ssecond step is to select the linguistic variables and the corresponding fuzzy sets used for expert evaluation of the benefits and success factors. In the third step, experts perform the linguistic evaluation by assessing each benefit and success factor of a DO. In step four, fuzzy arithmetic is performed to aggregate the fuzzy linguistic evaluation of all the factors assessed in order to generate the overall benefit and success scores as a fuzzy set. In the fifth and final step, defuzzification is performed on the aggregated fuzzy scores to generate crisp values (in range of 0–100 percentile) of the benefit and success scores. In the case of multiple DOs, DOs are ranked based on their benefit and success scores.

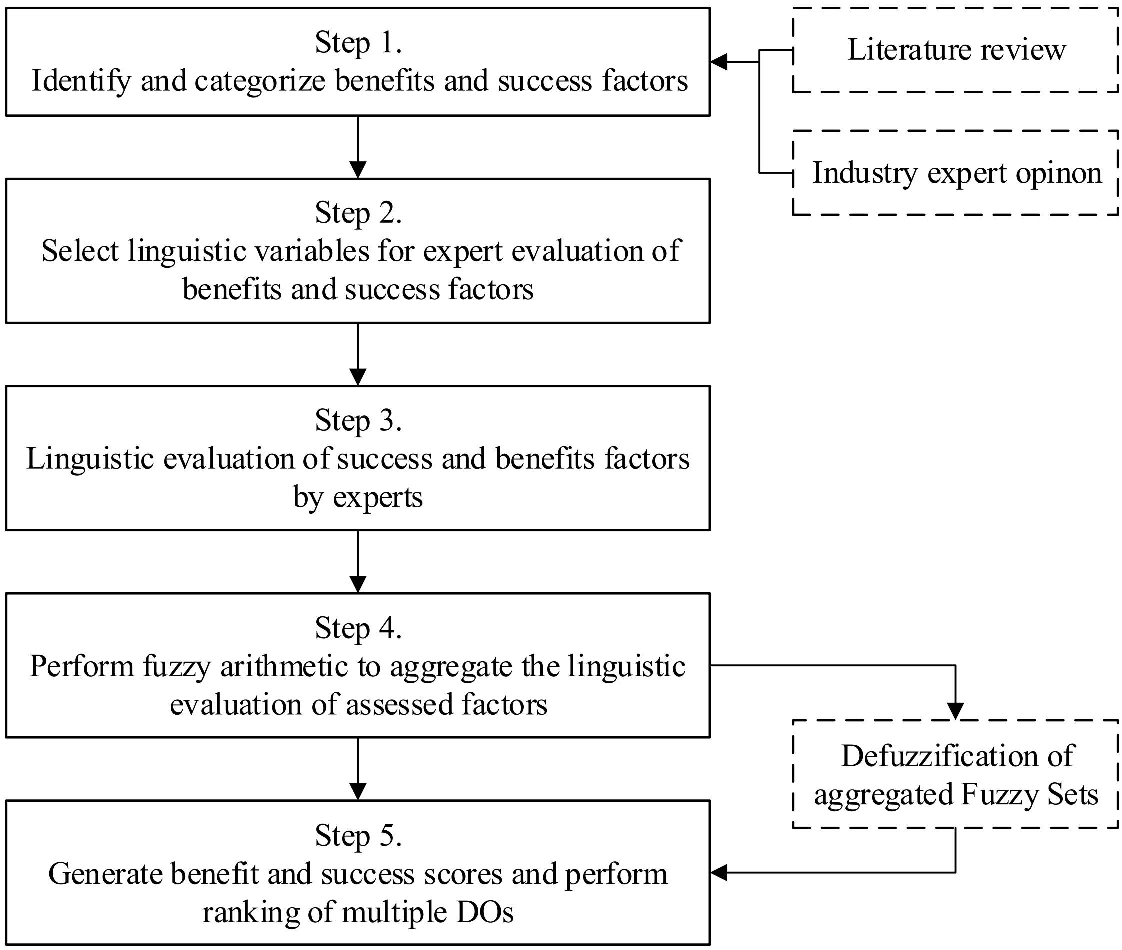


Figure 2. Framework for evaluating and ranking digitalization opportunities (DOs)

By plotting each DO on a two-axis Benefit-Success score chart, several DOs can be ranked by highest benefits score and/or highest success score. Graphic representation of a prioritized list of DOs will aid construction decision makers in identifying the best alternative among multiple

DOs. The proposed framework provides construction decision makers with the capability to identify which categories of success factors have low scores and need to be improved to enhance successful implementation of DOs. Furthermore, decisions makers can conduct sensitivity analysis for the same DO under different scenarios, to explore how improvements in the various categories of success and benefit factors can support successful implementation of the DO.

3.1 Identification and categorization of benefits and success factors of DOs

Demissie (2020) conducted an extensive literature review and compiled a list of potential benefits and success factors that could be used to assess DOs in construction organizations. The initial list consisted of process-, technology-, organizational, and people-related factors pulled from relevant literature that had been shown to be critical in successfully implementing DOs (Demissie 2020). This list of factors was then presented in a workshop to nine construction experts involved in projects in Canada. These experts had experience in construction and digitalization, represented different types of construction organizations (e.g., owners, contractors, and provincial government), and held various positions in their organizations, such as senior management, project management, and senior advisors.

The experts reviewed the list (Demissie 2000), proposed additional factors they thought may affect DO implementation in construction, and reached consensus on the proposed additional factors. The primary list of factors was then updated to include the additional factors. This process allowed for the development of a comprehensive list of factors that not only considers the literature in construction and digitalization domains, but also captures the opinions of digitalization and construction experts. The list included 98 total evaluation criteria for assessing the benefits and success factors that could lead to the successful DO implementation. A breakdown of the categories of the benefits and success assessment criteria are shown in Table 1 and Table 2, respectively.

Table 1. Benefit assessment criteria

Category	Evaluation criteria
Improved Processes	Reduces cost
	Improves productivity
	Improves work sharing/resource levelling
	Shorter schedule
	Improves quality
	Reduces rework & workmanship errors
	Improves the identification of interdependencies & conflicts
	Provides on-site information
	Enables real-time communication
	Enables tracking of construction process
	Enables detection of deviations
	Reduces non-value adding activities
	Improves recyclability & reusability
	Enables early commencement
	Enhances adherence to work processes
	Improves customer satisfaction
	Improves regulatory compliance
	Enhances understanding of performance status
	Enhances predictability of performance
	Increases adaptability to varying business conditions
	Improves data quality
	Enables concurrent use of data
	Enables easy access to information for all users
	More user-friendly than existing tools/databases
	Reduced data versioning problems
	Increased use of established data standards (current processes)
	Increased use of commercially proven applications
	Eliminates redundant existing software applications
Improved Outcomes	Improves alignment of employee behaviours
	Improves management decision-making
	Increases competitiveness
	Increases revenue
	Improves management of resources
	Increases market share
	Enables entry to new market(s)
	Increases innovation
	Improves speed to market
	Improves functionality
	Improves reliability
	Improves data security

	Enables leveraging of data
	Increases collaboration
	Improves work environment
	Increases use of industry-wide data standards
	Improves market readiness
	Improves dispute resolution & risk management
	Reduces administrative burden
	Enhances employee morale/work environment
	Improves workforce engagement
	Improves attraction & retention of talented employees
	Enhances professional development
	Improves skill, knowledge & experience sharing
	Reduces organization’s cultural differences
	Enhances organizational readiness & flexibility
	Enhances satisfaction of stakeholders
	Improves diversity & inclusion

Table 2. Success factor assessment criteria

Category	Evaluation criteria
Organizational Infrastructure	There is clear support from upper management to implement the DO. There are champions at all levels / in all groups. There are cooperative stakeholders. There are clear business processes. Implementing this DO is very cost effective. There will be adequate budget for implementation. There is sustained technology support available for implementation. There will be a sustained training available during implementation. There are flexible business procedures / contractual agreements / labour agreements. There is collaboration and knowledge sharing among employees. The organization promotes benefits of digital technology There is the capability to specify the right architecture & scalable infrastructure. There is the capability to achieve full organizational readiness, compliance & data sharing. There is good alignment of resources & information flow. There is a clear legal ownership of data. There are supportive local customs & laws. There are supportive industry-wide standards
Stakeholder Skills & Attitudes	There is pre-existing shared vision, culture and trust among department, teams, and employees. Change management system is in place. There is commitment to data entry procedures. Accountability of stakeholders is established. Roles and expectations are specified.

	There are basic technological capabilities of the user community. There is proper utilization of data. There is readiness of people. Relevant digital skills are upgraded. There are sufficient & talented experts in the organization. Organization's experts are engaged with digitalization implementation. Experts are involved in their area of expertise. People are aware about the change in digitalization implementation opportunity. People's success and effectiveness are measured. There is collaboration & knowledge sharing among stakeholders. There is proactive knowledge sharing among stakeholders. Trust, rapport, & a sense of community exist among stakeholders.
Technical Infrastructure	Available data as required Compatible data structure Adequate data security Interoperability of data Complementary digital competencies Expert knowledge is integrated with digitalization activities

Furthermore, the list of benefit and success factors were used to develop a questionnaire for face validation of the factors and their measurement methods by construction experts. The questionnaire was designed to allow for the evaluation a given DO with respect to each benefit and success factor, to derive an overall benefit and success score for that DO. Using the questionnaire, feedback from construction experts was collected, and the list of factors and their measurement methods were finalized.

3.2 Linguistic evaluation and fuzzy aggregation of benefit and success scores of DOs

Evaluation of benefits and success factors based on experts' knowledge is inherently uncertain, making it challenging to assign crisp numerical values to the level of impact of each individual factor. Fuzzy logic allows for a generalization of classical set theory that makes it possible to model complicated, uncertain, and ill-defined concepts (Chan et al. 2009), making it an appropriate technique for addressing the uncertain nature arising from the subjective judgment of experts. Furthermore, fuzzy logic allows mathematical operators and programming to apply to the fuzzy domain (Wang 2010). The methodology for evaluating the overall scores based on experts' knowledge necessitates establishing linguistic variables and corresponding fuzzy sets, then implementing suitable fuzzy computation with these linguistic variables to aggregate the expert evaluations. Finally, a defuzzification technique is applied to generate crisp overall benefit and success scores for DOs.

3.2.1 Linguistic variables for evaluation of benefits and success factors

Linguistic variables are better suited to represent aspects of the real world that cannot be directly assessed in a quantitative form, but rather in a qualitative one, i.e., with vague or imprecise knowledge. The fuzzy linguistic approach represents qualitative aspects as linguistic values by means of linguistic variables (Herrera and Martínez 2000a). The fuzzy linguistic approach has been applied successfully in different areas, such as multiple criteria decision-making (MCDM) techniques (Mardani et al. 2015; Kedir et al. 2020), airline service quality evaluation (Perçin 2018), supplier evaluation (Wang 2010), selection of a third-party logistics (3PL) provider (Jovčić et al. 2019), construction workforce motivation and performance (Raoufi and Fayek 2018), and sustainable supplier selection and evaluation in an agri-food value chain (Liu et al. 2019).

Fuzzy set terms used in fuzzy linguistic evaluation approach are typically odd-numbered, such as 3, 5, 7, or 9 (Herrera and Martínez 2000a). In general, a five-term set has practical applications (Wang 2010) and the proposed framework adopts a five-term set to evaluate both benefits and success factors. For the evaluation of success factors, an expert's level of agreement is first asked as, "To what extent do you agree that the factor exists in your organization?" The agreement evaluation of each success factor can be assigned one the following five terms: "Strongly Disagree" (SD), "Disagree" (D), "Neither Agree nor Disagree" (NA/D), "Agree" (A), or "Strongly Agree" (SA) (see Figure 3a). The impact level of success factor is then asked as, "To what extent does the factor impact the successful implementation of this digitalization opportunity (DO) within your organization?” The impact evaluation of each success factor can be assigned one of the following five terms: “Very Weakly” (VW), “Weakly” (W), “Moderately” (M), “Strongly” (S), or “Very Strongly” (VS) (see Figure 3b). Table 3 shows both the agreement and the impact scales for sample success factor evaluation statement under “Technical infrastructure” category.

Similarly, a question posed for the evaluation of benefits is, “To what extent does the implementation of this digitalization opportunity (DO) have an impact on providing the following benefits to your organization?” The impact evaluation of each benefit factor can be assigned one of the following five terms: “Very Low” (VL), “Low” (L), “Medium” (M), “High” (H), or “Very High” (VH) (see Figure 3c). A sample list of benefit evaluation statements along with the impact scale is presented in Table 4.

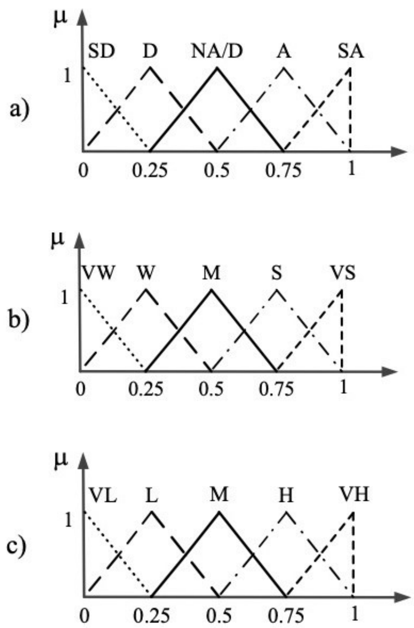


Figure 3. Linguistic terms to evaluate success and benefit factors: **(a)** agreement level of success factors, **(b)** impact level of success factors, and **(c)** impact level of benefit factors

Table 3. Sample agreement and impact level evaluation statement for success factors

Success Factors	Agreement						Impact				
	Not Applicable **(N/A)**	Strongly Disagree **(SD)**	Disagree **(D)**	Neither Agree nor Disagree **(NA/D)**	Agree **(A)**	Strongly Agree **(SA)**	Very Weak **(VW)**	Weak **(W)**	Moderate **(M)**	Strong **(S)**	Very Strong **(VS)**
	0	1	2	3	4	5	1	2	3	4	5
Technical infrastructure											
* Data are available.											

Table 4. Sample impact level expert evaluation statement for benefit factors

Benefit Factors	Impact						
	Not Applicable (N/A)	No Impact (NI)	Very Low (VL)	Low (L)	Medium (M)	High (H)	Very High (VH)
Improved process within company/organization		0	1	2	3	4	5
1 Reduces cost							

Fuzzy sets are typically able to use "linguistic variables and membership functions with varying grades to model uncertainty inherent in natural language" (Chan et al. 2009). The framework adopts triangular fuzzy numbers (TFNs) as a useful means of quantifying the uncertainty in linguistic terms due to their common application in engineering (Pedrycz and Gomide 2007), intuitive appeal, and computational-efficient representation (Wang 2010). A positive triangular fuzzy number (PTFN) is defined by a lower limit a, an upper limit c, and the core value b, where $a \leq b \leq c$, to represent linguistic variables. The points a, b, and c represent the x coordinates of the three vertices of the triangular membership function ($\mu_A(x)$) in a fuzzy set A. A triangular fuzzy number A is represented as a triplet (a, b, c) with a membership function $\mu_A(x)$ as defined in Equation (1).

$$\mu_A(\mathrm{x}) = \begin{cases} 0 & x < a \\ \frac{x-a}{b-a} & a \leq x \leq b \\ \frac{c-x}{c-b} & b \leq x \leq c \\ 0 & x > c \end{cases} \qquad (1)$$

Each linguistic term is assigned one of five TFNs with membership functions as shown in Figure 3. The lower limit a, upper limit c, and core value b of the TFNs are determined by dividing the range of the universe of discourse [0,1] into four intervals corresponding to five TFNs. The three middle TFNs are symmetrical about their core value b, as shown in Figure 3. Furthermore, the overlap between each of the five TFNs captures the concept of gradual transition between the linguistic terms that the TFNs represent (Pedrycz and Gomide 2007).As shown in Figure 3c, to evaluate the impact level of benefit factors, the five linguistic terms of "*Very Low*" (VL), "*Low*" (L), "*Medium*" (M), "*High*" (H), and "*Very High*" (VH) are represented by TFNs (0.00, 0.00, 0.25), (0.00, 0.25, 0.50), (0.25, 0.50, 0.75), (0.5, 0.75, 1.0) and (0.75, 1.0, 1.0), respectively. The linguistic terms used to evaluate the agreement and impact levels of the success factors are represented with the same TFNs shown in Figure 3a and b, respectively.

3.2.2 Computing with linguistic variables and aggregation of overall benefit and success scores

Membership functions of the linguistic terms are used to compute aggregated overall benefit and success scores. The fuzzy linguistic assessments of each factor by an expert are aggregated, using the most common, mean operator (Herrera et al. 2002) and each factor has equal weight. For the overall benefit score using the mean operator, based on the extension principle the aggregation of experts' evaluation of benefit score is computed using Equation (2).

$$\frac{1}{n}\sum_{i=1}^{n} L_i = \left(\frac{1}{n}\sum_{i=1}^{n} a_i,\ \frac{1}{n}\sum_{i=1}^{n} b_i,\ \frac{1}{n}\sum_{i=1}^{n} c_i\right) \quad (2)$$

where i ($i \in N$) is a fuzzy number representing the linguistic evaluation of the i^{th} benefit and *n* is the total number of benefits.

To aggregate success scores, the first step is to multiply the agreement evaluation with that of the impact level, which can be done through either the α-cut approach (Gao et al. 2009) or the extended fuzzy arithmetic using the algebraic product *t*-norm (Gerami Seresht and Fayek 2018). Results from either approach for the multiplication of triangular fuzzy numbers of agreement and impact level are not triangular fuzzy numbers. The product has a nonlinear membership function. As a result, the mean operator cannot be applied directly to aggregate the overall success score. To overcome this computational difficulty, this paper adopts linguistic approximation based on Euclidean distance to each fuzzy set of the product, to approximate it to the nearest impact level linguistic term (Herrera and Martínez 2000b). Figure 4 illustrates the approximation of a fuzzy number *A* to the closest linguistic term. To implement the linguistic approximation based on Euclidean distance, only the core and support of the agreement-impact product fuzzy number are required.

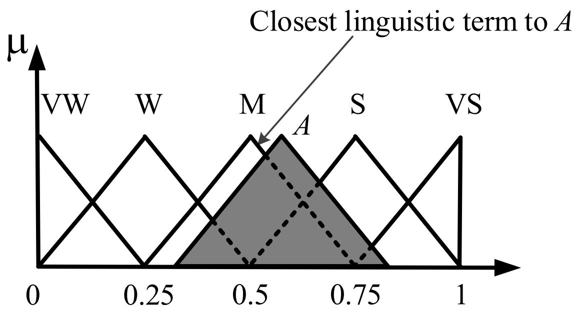


Figure 4. Approximation of fuzzy number *A* with a linguistic term

For fuzzy number A=(a_A, b_A, c_A) resulting from the product of agreement and impact assessment of a given success factor, using Equation (3), the approximation of *A* is *M*, meaning the extent a success factor impacts the successful implementation of a DO accounting for the agreement is "Medium" (see Figure 4).

$$d(L_i, A) = \sqrt{P_1(a_i - a_A)^2 + P_2(b_i - b_A)^2 + P_3(c_i - c_A)^2} \quad (3)$$

where L_i s$_l$ is the fuzzy number of linguistic terms in Figure 4; (a_A, b_A, c_A) is the membership function of As$_l$; (a_i, b_i, c_i) is the membership function of L_i; and P_1=0.2, P_2=0.6, and P_3=0.2 (Herrera and Martínez 2000b).

Next, the overall success score is computed in the same way as the overall benefit score using the mean operator; see Equation (2). The aggregated overall benefit and success scores can be represented in the form of fuzzy sets, linguistic terms, or defuzzified crisp values. In the proposed framework the scores are defuzzified using the Centroid method in the range of (0,1) and scaled to 0–100 percentile. The aggregated overall benefit and success scores are used to rank multiple DOs.

4 Digitalization Opportunities Road Mapping Tool (DORMT©)

DORMT© is a Microsoft Excel-based tool developed using Visual Basic (VB) to guide individual organizations in navigating the evaluation and adoption of innovations, specifically focused on the digitalization aspect of innovation. The tool is an implementation of the proposed framework that allows organizations to evaluate and rank DOs based on the potential benefits of successful implementation and possibility of success and/or organizational readiness. The tool provides a practical method of assessing and ranking the implementation of multiple DOs.

Three expert consultation stages were performed during the development of DORMT©. The first stage involved consultation with an industry expert who had more than 40 years of experience in the construction industry, to develop the methodology and structure of the framework for assessing DOs, which provided conceptual validity of the research methodology. The second stage involved nine construction experts performing face validation on the list of benefit and success factors and their measurement methods. This feedback from experts was incorporated into the tool. In the third stage, DORMT© was presented to the same industry expert involved in the conceptual validation of the research methodology to validate its applicability, functionality, and ease of use, and this person's suggestions were implemented in the final version of DORMT©.

4.1 DORMT© description

DORMT© is structured in eight main components that help define the scope of and describe the DO to be evaluated, implement the proposed framework based on expert evaluation, and produce assessment results through summary reports and a ranking table and graph. A process map illustrating the tool's components and workflow is shown in Figure 5. The introductory page contains general information about the tool and instructions on how to use the tool. In each component, users can use navigation buttons to sequentially move through other components of the tool.

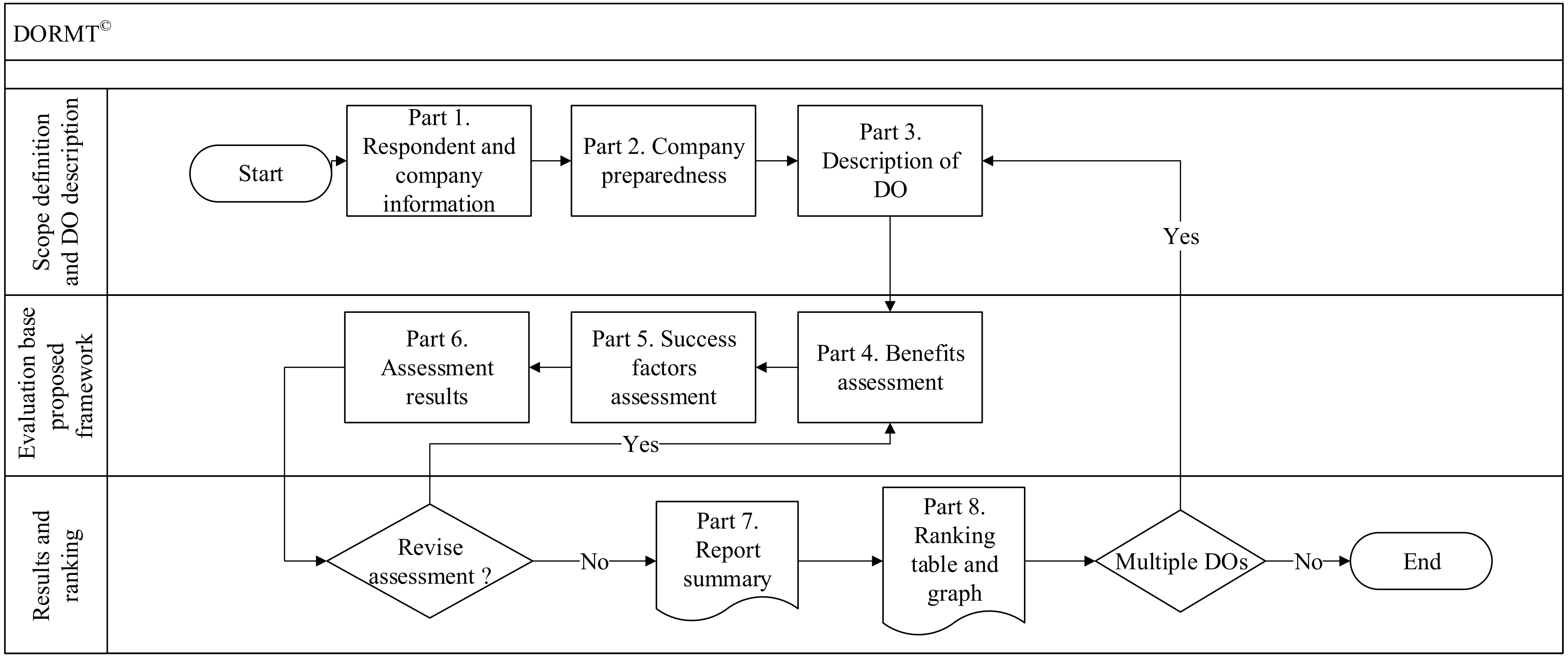


Figure 5. DORMT© process map

In component 1, the respondent and company information are recorded, and then component 2 helps evaluate the company preparedness to implement DOs. Component 3 includes description of the DO and highlights the primary objective of implementing the DO under evaluation. Component 4 assesses the benefits and contains a list of assessment questions that are used to evaluate the benefits of a DO to an organization (see Figure 6). Similarly, component 5 assesses success factors and contains a list of assessment questions to evaluate the factors that will lead to successful implementation of a DO in an organization (see Figure 7). The questions are categorized and evaluated based on the linguistic scales of the proposed framework. For component 4, benefits assessment, each question is evaluated on the basis of impact level that can be assigned one of the following seven options: “Not Applicable,” “No Impact,” “Very Low,” “Low,” “Medium,” “High,” or “Very High.” For component 5, success factors assessment, each question is evaluated on the basis of its agreement and impact level. The agreement evaluation can be assigned one the following six assessment terms: Not Applicable,” “Strongly Disagree,” “Disagree,” “Neither Agree nor Disagree,” “Agree,” or “Strongly Agree.” The impact evaluation can be assigned one of the following five options: “Very Weakly,” “Weakly,” “Moderately,” “Strongly,” or “Very Strongly.” The tool allows experts to provide additional benefit and success factors to be considered in the assessment.

Component six, assessment results, provides a table that contains a score for each benefit and success factor category and a count of the total number of questions answered (see Figure 8). The overall benefit and success scores are then graphed onto the Success-Benefit Score chart. In components 7 and 8, information from the multiple cases that have been saved and submitted is reviewed, and the ranking of the multiple DO assessments.

Part 4: Assessing the Benefits of Implementing Your Digitalization Case

Case Number	1

To what extent does the implementation of this digitalization opportunity (DO) have an impact on providing the following benefits to your organization? Check all that apply and rate

0	**No impact**
1	**Very low** impact (e.g., localized impact; only individual employees impacted)
2	**Low** impact (e.g., localized impact; only one individual project impacted)
3	**Medium** impact (e.g., several projects impacted)
4	**High** impact (e.g., division-wide impact)
5	**Very high** impact (e.g., significant impact; organization/company-wide impact)

		Not Applicabl	No Impact 0	Very Low 1	Low 2	Medium 3	High 4	Very High 5
Improved Process Within Company/Organization								
B.1.1	Reduces cost	☐	☐	☐	☐	☐	☐	☐
B.1.2	Improves productivity	☐	☐	☐	☐	☐	☐	☐
B.1.3	Improves work sharing / resource levelling	☐	☐	☐	☐	☐	☐	☐
B.1.4	Shorter schedule	☐	☐	☐	☐	☐	☐	☐
B.1.5	Improves quality	☐	☐	☐	☐	☐	☐	☐

Figure 6. Component 4. Benefits assessment

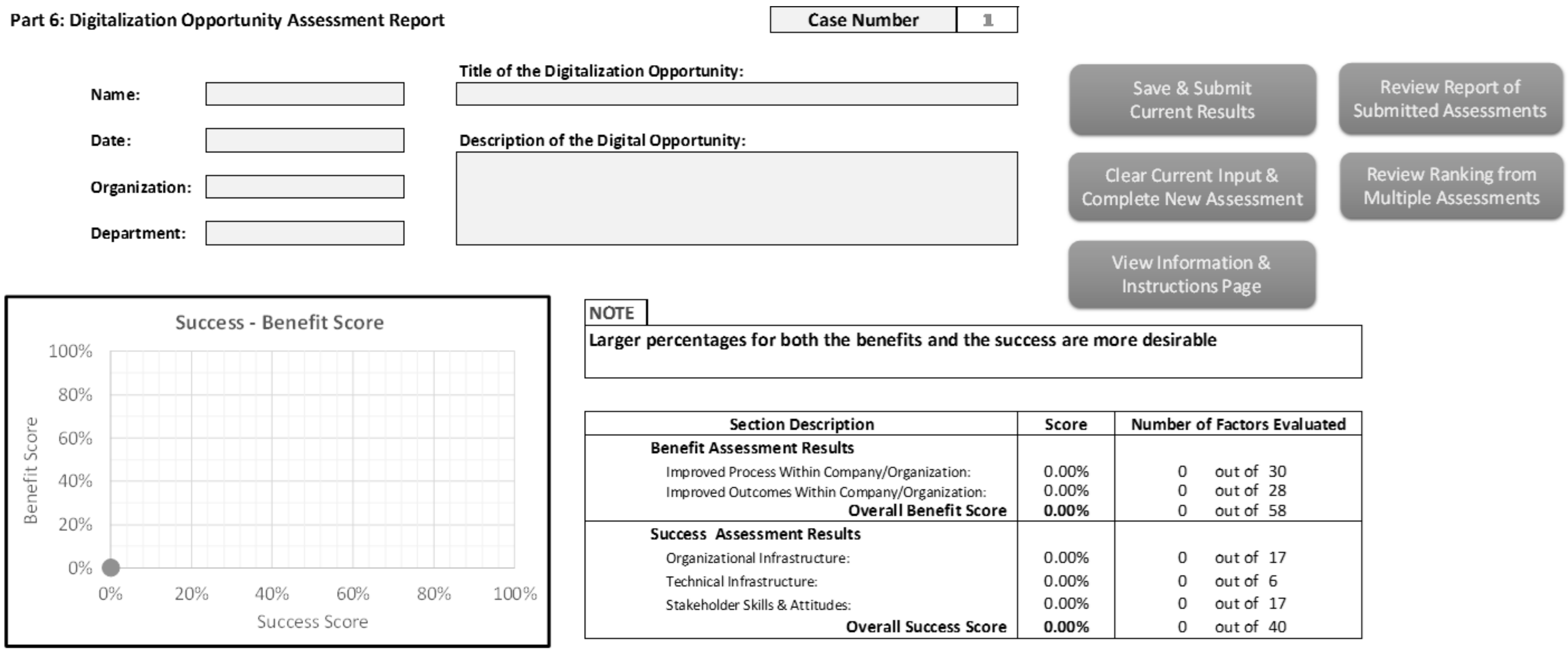
Part 5: Identifying and assessing the Factors affecting the successful implementation of your Digitalization Case | Case Number | 1

Agreement: To what extent do you agree that the given factor exists in your organization? Rate each factor on a scale of 1 to 5.	
0	**Not Applicable** (N/A) or **No Impact**
1	**Strongly Disagree** that this factor exists in my organization
2	**Disagree** that this factor exists in my organization
3	**Neither Agree nor Disagree** that this factor exists in my organization
4	**Agree** that this factor exists in my organization
5	**Strongly Agree** that this factor exists in my organization

Impact: To what extent does the given factor impact the successful implementation of this digitalization opportunity (DO) within your organization? Rate each factor on a scale of 1 to 5.	
1	**Very Weakly** impacts successful implementation of this DO
2	**Weakly** impacts successful implementation of this DO
3	**Moderately** impacts successful implementation of this DO
4	**Strongly** impacts successful implementation of this DO
5	**Very Strongly** impacts successful implementation of this DO

		Agreement						Impact				
		Not Applicable 0	Strongly Disagree 1	Disagree 2	Neither Agree nor Disagree 3	Agree 4	Strongly Agree 5	Very Weakly 1	Weakly 2	Moderately 3	Strongly 4	Very Strongly 5
Organizational Infrastructure												
S.1.1	There is clear support from upper management to implement the DO.	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
S.1.2	There are champions at all levels/in all groups.	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
S.1.3	There are cooperative stakeholders.	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

Figure 7. Component 5. Success Factors assessment



Part 6: Digitalization Opportunity Assessment Report

Case Number | 1

Name:

Date:

Organization:

Department:

Title of the Digitalization Opportunity:

Description of the Digital Opportunity:

Save & Submit Current Results

Review Report of Submitted Assessments

Clear Current Input & Complete New Assessment

Review Ranking from Multiple Assessments

View Information & Instructions Page

NOTE

Larger percentages for both the benefits and the success are more desirable

Section Description	Score	Number of Factors Evaluated
Benefit Assessment Results		
Improved Process Within Company/Organization:	0.00%	0 out of 30
Improved Outcomes Within Company/Organization:	0.00%	0 out of 28
Overall Benefit Score	**0.00%**	0 out of 58
Success Assessment Results		
Organizational Infrastructure:	0.00%	0 out of 17
Technical Infrastructure:	0.00%	0 out of 6
Stakeholder Skills & Attitudes:	0.00%	0 out of 17
Overall Success Score	**0.00%**	0 out of 40

Figure 8. Individual DO assessment results

4.2 Interpreting individual DO assessment results

An interpretation graph aids in identifying the likelihood of successful implementation from the benefit and success scores of a given DO (see Figure 9).

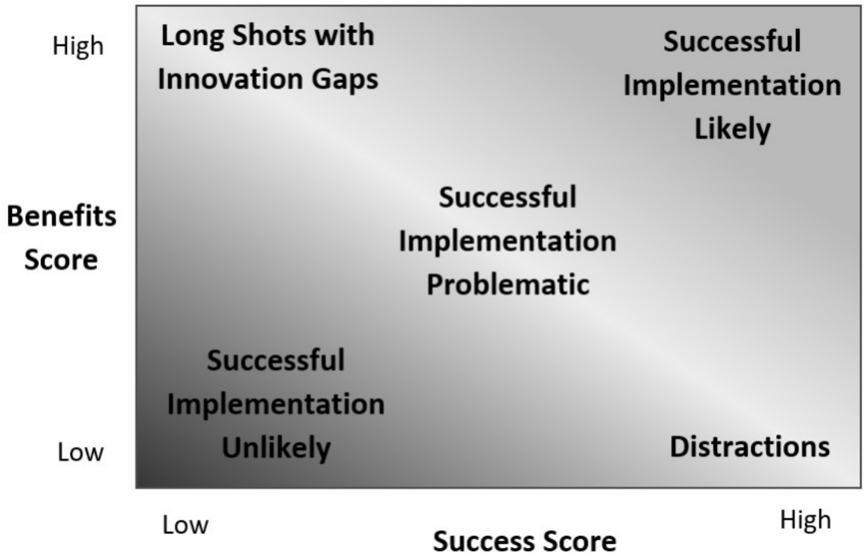


Figure 9. Interpretation graph

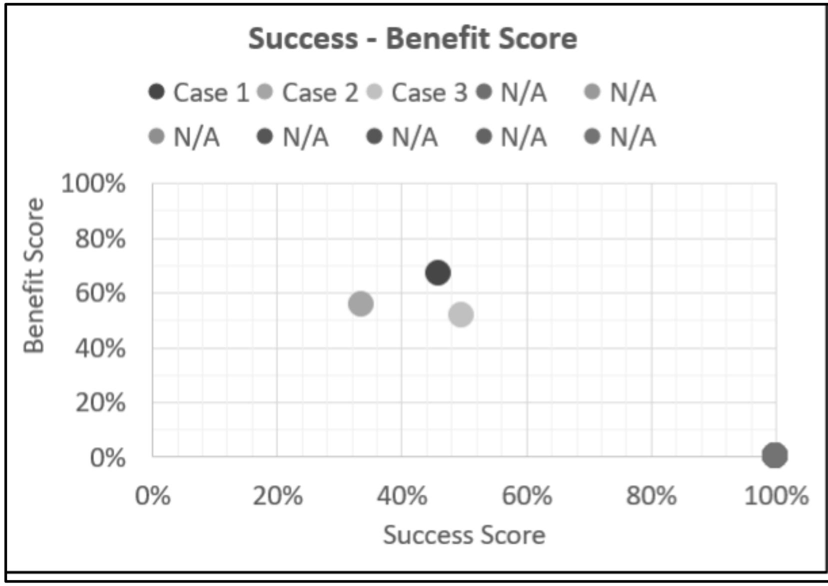
Higher percentage scores from both the benefits score and the success factor score are more desirable and indicate DOs that are more likely to be successfully implemented. A mixed set of the benefits score and the success factor score resulting in high-low or low-high scores may reveal DOs that are either distractions or that possess large innovation gaps, as marked in yellow in the graph. Low benefit factor scores and a low success factor score indicates that successful implementation of a given DO is unlikely.

Implementation efforts within organizations should be focused on high value-added activities to improve productivity. DOs categorized as distractions indicate technologies that even when implemented would provide very few benefits to the organizations. Therefore, activities that have high success scores but low benefit scores are categorized as distractions and should be avoided. Conversely, DOs with high benefit scores and low success scores are categorized as long shots with significant innovation gaps. DOs in this category should be reviewed for potential innovation opportunities. Innovations or changes to the DO being assessed can improve the success scores and should be focused on one of three subparts: organizational infrastructure, technical infrastructure, or stakeholder skills and attributes.

4.3 Multiple DO assessments

A report summary with the saved individual assessments is provided in the component 7, the Report Summary, which allows the option of deleting previously saved cases and proceeding to the final multi-DO ranking component. The saved and submitted cases from the report summary are automatically populated in the final component that produces the ranking table and graph. The output from this component is a chart that contains a graphed score for each DO, a ranking number based on the benefit score, and a ranking number based on the success score. The chart contained in this component can also be interpreted by referring to the interpretation graph shown in Figure 10.

It is important to note that there are no minimum responses required from the component 4, the Benefit Assessment, or component 5, the Success Factor Assessment. An individual assessment will display results when at least one question for any given category in the benefit or success assessment components has been completed. Furthermore, DORMT© can be used to also identify areas of improvement that will need to be corrected or considered in order to ensure the successful implementation of a DO.



NOTE
Larger percentages for both the benefits and the success are more desirable

Section Description	Di		
	Case 1	**Case 2**	**Case 3**
Benefit Assessment Results			
Improved Process Within Company/Organization:	64.86%	68.65%	58.02%
Improved Outcomes Within Company/Organization:	68.91%	41.23%	43.94%
Overall Benefit Score	**67.01%**	**55.63%**	**51.70%**
Ranking Based on Benefit Score	**1**	**2**	**3**
Success Assessment Results			
Organizational Infrastructure:	58.33%	33.75%	58.47%
Technical Infrastructure:	35.71%	11.11%	45.83%
Stakeholder Skills & Attitudes:	42.08%	42.31%	46.08%
Overall Success Score	**45.96%**	**33.65%**	**49.58%**
Ranking Based on Success Score	**2**	**3**	**1**

Figure 10. Multiple DO assessment results and ranking (values are for illustrative purposes only)

5 Application of proposed framework

The proposed framework with DORMT© was tested for its applicability with a wide range of DOs to select from by academic experts with at least 6 years of construction experience. One case study was for a 5D BIM modelling technology to be implemented by a civil works team in a construction company. The 5D BIM modelling opportunity uses new tools and software to enhance current 3D detailed design of projects by integrating cost and scheduling factors and allowing real-time updates to project progress. To illustrate the details of the linguistic evaluation procedure, a sample of the experts' assessments for agreement and impact level of success factors under the technical infrastructure category, as provided in Table 5, are discussed throughout this section.

Table 5. Sample expert evaluations of technical infrastructure success factors

Success Factors – Technical Infrastructure	Agreement	Impact
Available data as required	NA/D	M
Compatible data structure	D	VS
Adequate data security	A	VS
Interoperability of data	D	VS
Complementary digital competencies	A	VS
Expert knowledge is integrated with digitalization activities	D	S

The success score aggregation is done in two steps. In the first step, the agreement evaluation is multiplied with that of the impact level using the algebraic product *t*-norm. Applying linguistic approximation based on Euclidean distance (Equation (3)) to each fuzzy set of the product, the nearest impact level linguistic term is computed. Table 6 presents the impact level resulting from the linguistic approximation of the experts' evaluation.

Table 6. Linguistic approximation of experts' evaluation of technical infrastructure success factors

Success factors – technical infrastructure	Expert evaluations		Product of agreement and impact assessment: Fuzzy sets	Linguistic approximation: impact level
	Agreement	Impact		
1	NA/D	M	(0.063 0.250 0.563)	W
2	D	VS	(0.000 0.250 0.500)	W
3	A	VS	(0.375 0.750 1.000)	S
4	D	VS	(0.000 0.250 0.500)	W
5	A	VS	(0.375 0.750 1.000)	S
6	D	S	(0.000 0.188 0.500)	W

Next, the overall success score is computed using the mean operator (Equation (2)). The result is a fuzzy set of (0.2917 0.40625 0.4375). In DORMT©, the scores are defuzzified and presented on a 0–100 percentile scale. The defuzzified success score for technical infrastructure expert evaluation will be 0.37847, or 37.85%. Applying similar steps for the rest of success factor categories, the aggregated overall success score is computed. The final results from the assessments of the 5D BIM modelling implementation case study are summarized in Figure 11.

Section Description	Score	Number of Responses Completed
Benefit Assesment Results		
Improved Process Within Company/Organization:	64.93%	24 out of 33
Improved Outcomes Within Company/Organization:	68.91%	26 out of 31
Overall Benefit Score	**67.00%**	50 out of 64
Success Assesment Results		
Organizational Infrastructure:	55.67%	12 out of 20
Technical Infrastructure:	37.85%	6 out of 9
Stakeholder Skills & Attitudes	37.45%	15 out of 20
Overall Success Score	**44.15%**	33 out of 49

Figure 11. 5D BIM Modeling DO assessment scores

The 5D BIM modelling DO resulted in a 67.00% overall benefit score and a 44.15% overall success score. Considered relative to the interpretation graph as shown in Figures 9 and 12, these results indicate that this organization is likely to experience problematic success during the implementation phase.

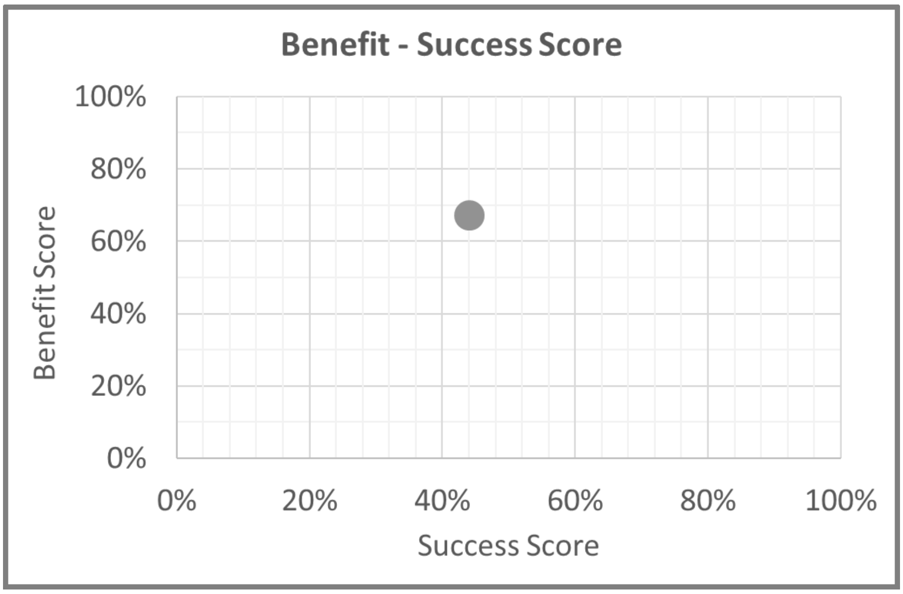


Figure 12. 5D BIM Modeling DO overall benefit and success score

A higher success factor score would increase the likelihood of successfully implementing this DO. Within the Success Factor assessment, the Technical Infrastructure and Stakeholder Skills and Attitudes categories scored the lowest at 37.85% and 37.85%, respectively. These two categories present the best opportunity for company to improve the likelihood of successfully implementing this 5D BIM modelling DO.

6 Conclusions and future work

The construction industry, commonly referred as "brick and mortar" industry, is facing a wave of digitalization opportunities (DOs). The digital push is accelerating, and with it increases the challenges it presents to industry players on how to identify the best alternative from a pool of available DOs. Construction organizations need to develop a real digital strategy to evaluate the potential benefits and possibility of success in the implementation of a DO. This paper proposes a framework based on fuzzy linguistic evaluation to assess and rank multiple DOs. Individual or multiple DOs are assessed based on experts' evaluation of both the potential benefits of implementing DOs and factors influencing the successful implementation of DOs.

Incorporating linguistic variables and fuzzy arithmetic, the framework is capable of capturing subjective uncertainties of experts' evaluations.

The proposed framework is implemented in a tool, the Digitalization Opportunities Road Mapping Tool (DORMT©), that supports construction decision makers in the assessment and selection of DOs that are available to their organization. The tool is user friendly, and the results from the assessment can be easily interpreted, allowing organizations to adopt it in their planning practices. DORMT© is effective in highlighting success factors that need and/or would require improvement to the user, which can help direct an organizations effort towards enhancement measures. The tool also provides the capability to assess and rank multiple DOs, thus aiding construction organizations in identifying the best alternative. Assessing and prioritizing multiple DOs will further help organizations prioritize their investments and allocate their resources in a way that can lead to creating and/or maintaining an organization's competitive advantage.

Future work will explore the development of additional built-in capabilities of DORMT©, to allow for weighted assessment of benefits and success factors. A multi-user assessment of a single DO feature will be included, allowing multiple experts to evaluate the same DO, which will then be aggregated to generate an overall benefit and success score. In addition, further validation of the overall benefit and success scores derived from DORMT© will be done using case studies from construction organizations. The overall benefit and success scores derived from DORMT© for each DO can be compared to the success of organizations' implementation of the DO. In addition, the impact of using DORMT© on the successful implementation of DOs will be investigated by collecting data from construction organizations implementing DOs using the recommendations provided by DORMT©, to demonstrate how DORMT© influenced digitalization success within the organization.

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8 Competing interests statement

The authors declare there are no competing interests.

9 Contributors' statement

Yisshak Tadesse Gebretekle: Conceptualization, Methodology, Software, Formal analysis, Investigation, Writing - Original draft, Writing – Review & editing, Visualization.

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Mohammad Raoufi: Conceptualization, Methodology, Formal analysis, Writing – Review & editing, Supervision.

Aminah Robinson Fayek: Conceptualization, Methodology, Resources, Writing – Review & editing, Supervision, Project administration, Funding acquisition.

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11 Data availability statement

All data generated or used during the study appear in the submitted article.

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