Digitalization Index: Developing a Model for Assessing the Degree of Digitalization of Construction Projects

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Abstract: The construction industry is one of the least digitally advanced industries. Although the industry is project-based, a project-level assessment of digitalization is lacking. The aim of this paper is to develop a digitalization index to assess the degree of digitalization of construction projects. Relying on the outcomes of a workshop with 11 participants and questionnaire responses from 113 site managers in Sweden, four activities; visualized drawings and three-dimensional (3D) models on sites; updated drawings, models, and system documents; created and updated work disposition plans; and updated time resource plans were selected, and a digitalization index enabling a simple assessment of the degree of digitalization of construction projects was constructed based on the degree of digitalization of the data management processes involved in these four activities. The approach to determine the digitalization index was demonstrated in a case study of a new construction project. For future studies, an accurate and simple assessment of the degree of digitalization of projects should increase the opportunities to study the association between the degree of digitalization and project performance. With longitudinal assessments, digitalization trends in the construction industry can be reported. **DOI: 10.1061/(ASCE)CO.1943-7862.0002145.** © *2021 American Society of Civil Engineers.*

Author keywords: Construction management; Construction site; Digitalization; Digitalization index.

Introduction

There is no doubt that we are living in an era of digitalization. Processing and manufacturing companies are experiencing digitalization in line with industry 4.0, which is allowing the use of concepts like the Internet of Things and automation to improve productivity and safety but also to reduce the environmental impact (Hasan et al. 2018). The construction industry is part of this digital transformation, and many new technologies are being introduced by technology suppliers and construction firms. These include building information modeling (BIM), big data, cloud storage, multidimensional design [e.g., four-dimensional (4D) and five-dimensional (5D)], prefabrication, robotics, three-dimensional (3D) printing, artificial intelligence, and intelligent buildings (Sykes 2018). Nevertheless, the construction industry is considered one of the least digitally advanced industries in terms of its digital assets, digital usage, and digital workforce engagement and is ranked joint last with agriculture and hunting in a list of 22 industries (Gandhi et al. 2016). However, the tools (and models) used to assess the *degree of digitalization* are associated with inherent design flaws.

Previous work has focused mainly on assessing digitalization at the industry and company levels. At the industry level, there are many examples of industry reports and academic studies comparing levels of digitalization (e.g., Gandhi et al. 2016; Gruszka et al. 2017; Schober et al. 2016; Sykes 2018). Other work uses industry-level surveys to show which technologies are being used and in which areas in construction projects (Blanco et al. 2017; Samuelson and Björk 2014). In addition, the construction industry is decentralized, fragmented, and project-based, which results in contracting firms operating more as ecosystems working on autonomous projects. Comparing the ongoing projects in a contractor firm in terms of their digitalization would help to identify where digitalization might lead to improvements (Sezer and Bröchner 2019).

A project-level assessment of the degree of digitalization is lacking, and company and industry level models are too blunt to facilitate actions to improve digitalization. Before discussing the existing attempts to improve digitalization in the construction industry, we first need to assess the degree of digitalization at the project level to allow the identification of the problems. Project rankings based on the degree of digitalization can help to identify best practices. Therefore, the aim of this paper is to develop a digitalization index to assess the degree of digitalization of construction projects.

There are a few examples of project-level assessment models. A pioneering study by O'Connor et al. (1999) proposed the technology use and integration index (TUI), which is based on three levels of technology use for 68 tasks. Reporting the degree of digitalization for so many activities is time-consuming and exhausting and becomes an even bigger problem if the assessor is the site manager. *Lack of time* is a frequent reason given by site managers for not engaging in this activity (Sezer and Bröchner 2019). A simpler index to assess the degree of digitalization of projects is necessary. This index and its outcomes can make it feasible for researchers to compare projects with different degrees of digitalization to identify their differences and associate levels of digitalization with productivity, safety, and environmental performance. In practice, construction companies can identify projects with high and low levels of digitalization in order to try to improve the latter.

The paper is organized as follows. The next section presents previous work assessing the degree of digitalization and technology implementation to provide a better understanding of the pros and

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Note. This manuscript was submitted on January 15, 2021; approved on May 11, 2021; published online on July 29, 2021. Discussion period open until December 29, 2021; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Construction Engineering and Management***, © ASCE, ISSN 0733-9364.

cons of these previous models. This is followed by a section describing the research design and a section presenting the proposed assessment model. The final section concludes the paper and proposes some directions for future research and some theoretical and practical implications.

Previous Research

Previous studies include assessments of the use of information technology (IT) and information and communication technologies (ICT) in the construction industry, the digital maturity of construction companies and technology usage, and integration indexes at the project level. Most of this work provides a snapshot of digitalization in the industry. The IT barometer developed by Samuelson (2002) is used to assesses the construction industry's usage of IT tools, including the perspective of architects, engineers, property managers, and contractors. The IT barometer is used to assess the extent of IT infrastructure and work that is carried out with the help of computers, digital information exchange, BIM usage, computer aided design (CAD) usage, electronic document management, and electronic document interchange usage. The IT barometer is also used to understand the effects of and motives for using IT, the perceived benefits and disadvantages of using IT, and planned IT investments (Samuelson and Björk 2014). IT-barometer surveys have been applied in several different countries, including Luxembourg (Kubicki and Boton 2014) and Jordan (El-Mashaleh 2007). Other work at the industry level investigates the use of computers, IT, and automated devices by construction workers and the views of construction workers, managers, and technology providers in Alberta, Canada (Hewage et al. 2008). The literature includes comparisons of IT adoption by 20 developing and developed countries (Nourbakhsh et al. 2012a), IT use by construction professionals, such as architects, consultants, and contractors (Shrestha et al. 2011), ICT use by Swedish site managers (Sezer and Bröchner 2019), IT use in Malaysian (Gaith et al. 2009) and Nigerian (Oladapo 2007) construction industries, and ICT use in the Turkish construction industry (Sarshar and Isikdag 2004).

At the company level, digital maturity is a frequently used term. An example of assessing the digital maturity of construction companies is a recent online platform (Letsbuild 2020), which is based on people, processes, data, and technology and provides a seven-level ranking based on the following: business as usual, present and active, formalized, strategic, converged, innovative and adaptive, and guiding star. Other company-level examples not focused specifically on the construction industry include a simple, single measure of digital maturity called the digital quotient (Catlin et al. 2015), which examines such aspects as strategy, capabilities, culture and organization, and talent.

At the project level, there are previous examples that use terms such as *technology use and integration index* and *automation and integration scales*. O'Connor et al. (1999) developed automation and integration measures based on three levels of technology use; Yang (2008) used four levels to assess the degree of automation; and Kang et al. (2008) defined levels of technology use based on the categories of *automation technology* and *integration technology*, with each involving an assessment at five levels. The levels they describe are based on a scale in which tasks are carried out manually to tasks being carried out by automation, in which Level 1 includes no electronic tools to complete a work function, Level 2 includes some use of electronic tools, and Level 3 includes fully automated systems to perform the work function. These assessment levels have been used in other studies to investigate the relations between technology use and various outcomes, including the relation between project performance and technology use at the project phase and project levels (O'Connor and Yang 2004) and project stakeholder success (Yang and O'Connor 2005), and to compare different-sized projects and the effects of technology use on costs and schedules (Yang et al. 2006) in the US and Taiwan contexts (Yang et al. 2007).

Based on the literature, it can be concluded that there is a greater focus on assessing digitalization at the industry and company levels than at a project level. However, the construction industry is project-based, and the company and industry level models are not sufficiently fine-grained to identify where greater digitalization would provide benefits. One of the limitations of previous attempts to measure digitalization in construction projects is that they require assessment of the degree of technology use for more than 50 activities, which is cumbersome. The assessments and the levels are rather abstract, meaning that a task supported by technology could involve different levels, such as inputting data or analyzing and reporting data. Frequency tends to be overlooked, and technology is not necessarily used always at the highest degree of technological use (e.g., always at Level 3) but rather a combination of different degrees in different frequencies (e.g., rarely at Level 1 and often at Level 2). A clear takeaway from previous studies is that a simpler and less exhaustive project-level digitalization index is needed to allow the benchmarking of a degree of digitalization in projects.

Research Design

The research design includes a literature review to identify construction site activities. This resulted in a list of 27 activities. To reduce the number of activities included in the assessment model, a workshop and questionnaire study were organized. The final model was based on the results of these steps.

Literature Review

The aim of the literature review was to identify construction site activities that were based on keyword searches and previous studies (e.g., Samuelson 2002, 2008; Samuelson and Björk 2014). This also included forward and backward citation methods (Hu et al. 2011) to add relevant publications. By removing duplicates (e.g., *assigning tasks on construction sites* is removed because it is already covered as *create, prioritize, and assign tasks to craftsmen*) and merging similar activities (e.g., *registration of waste volumes*, *registration of waste sorted onsite*, and *waste reuse and recycling systems* are merged as *follow up and improve waste management during the project*), a list with 27 activities was created.

Workshop Design

To reduce this list of activities to a more manageable number, we conducted a 3-h workshop involving 11 participants (not including the workshop organizers). We sent the invitation to 209 individuals who were members of a Swedish organization interested in construction logistics and digitalization. It includes actors from different parts of the construction supply chain and the construction industry. The 11 workshop participants represented a range of actors, including clients, IT suppliers, contractors, consultants, shipping agencies, academics, and plumbing and ventilation subcontractors.

The participants were split across two groups who were asked to define and discuss which construction activities should be digitalized and why. Participants' reasons for identifying particular activities included *which activities are useful to digitalize*, *which activities are easy to digitalize*, *for which activities digitalization would support links to clients and subcontractor*s, and *for which* *activities employees are able to use the technology and have access to hardware*. Their selection criteria were similar to the unified theory of acceptance and use of technology (UTAUT) (Venkatesh et al. 2003).

According to the UTAUT, there are four constructs that determine acceptance and use of technology: performance expectancy (usefulness), effort expectancy (ease of use), social influence, and facilitating conditions. Based on the UTAUT constructs, all activities fulfilling these four conditions should already be digitalized and, therefore, can be used to assess the degree of digitalization of construction projects:

- The activity is useful to digitalize (performance expectancy).
- The activity is easy to digitalize (effort expectancy).
- There are pressures from different stakeholders to digitalize the activity (social influence).
- There are facilitating conditions (such as organizational support, education, and IT infrastructure) to digitalize the activity.

Questionnaire Design

The study also involved a questionnaire to reduce the 27 activities. The survey was administered to site managers who have the best understanding of onsite operational work and a good understanding of the daily work activities performed by different actors (Sezer and Bröchner 2019). Thus, we assumed that site managers would be able to identify those activities that are useful and easy to digitalize, activities in which there is pressure for them to be digitalized, and activities in which digitalization is feasible based on workers' capabilities.

The list of site managers was compiled using LinkedIn, which has been used by previous studies (e.g., Ahmad et al. 2018; Kubicki et al. 2019). A search was made to identify site managers in Sweden using alternative Swedish titles, including *platschef* and *produktionschef* (both refer to site managers). All the LinkedIn profiles were checked to eliminate site managers not working on new construction and renovation projects (e.g., infrastructure). According to a construction market research company, three of the largest contractors in Sweden had 881 active projects in 2018, where only half of these projects were new construction and renovation projects (Byggfakta 2018). Therefore, the whole population of new construction and renovation site managers is expected to be relatively small in Sweden. The questionnaire and two reminders were sent to a total of 350 Swedish site managers. We received 83 complete responses and 30 partial responses to the first part of the questionnaire. This translates into a response rate of 32%. Response rates for these kinds of questionnaires can vary between 12% and 40% (Ahuja et al. 2010; Chalker and Loosemore 2016; Samuelson and Björk 2014; Sezer and Bröchner 2019). Chalker and Loosemore (2016) explain low response rates in the construction industry due to high workloads and that site managers are often forced to prioritize construction site tasks. Sezer and Bröchner (2019) attempted to increase the response rate by combining an online and a postal survey of site managers but achieved only a 34% response rate.

The questionnaire design was based on the UTAUT. It started with questions about gender, age, experience, firm size, and type of construction projects that were most frequent in the last 5 years. The main part of the questionnaire was organized into four parts:

- usefulness of digitalizing an activity (performance expectancy)—digitalization allowed faster task performance and increased productivity compared to traditional working;
- simplicity (effort expectancy)—digitalization would be easy to implement, use, and learn compared to traditional ways of working;
- pressure for digitalization (social influence)—whether customers, subcontractors, suppliers, or other firm members (such as colleagues and management) were pushing for digitalization of some activities; and
- conditions for digitalization (facilitating conditions)—whether organizational knowledge and the technical infrastructure (including training and support) required for digitalization were in place.

Respondents were asked to indicate any activities they felt should have been included in the original 27. Only two respondents suggested additional activities. The respondents were asked to select five activities from the list of 27 activities and rank them on a scale from 1 to 5 based on the preceding conditions (e.g., 5 indicates most useful to digitalize and 1 least useful to digitalize).

Table 1 presents the respondents' demographics. The majority (91%) were male, and three were aged over 61 years. All had at least 3 years of experience in the construction industry, and most (80%) had more than 10 years of experience. Only 20% of respondents reported having worked on renovation projects ($n = 23$). Most were from larger contractors (83%) with at least 250 employees.

The questionnaire analysis includes descriptive statistics and nonparametric Mann-Whitney and Kruskal-Wallis tests. The four main parts of the questionnaire—(1) usefulness, (2) ease of use, (3) pressure of digitalization, and (4) facilitating conditions—received 113, 92, 84, and 83 responses, respectively. The sum of the rankings of the 27 activities in each part was normalized. Summing the normalized values, we identified five highly ranked activities. Mann-Whitney and Kruskal-Wallis tests were employed to ensure that subgroups of site managers with different genders, years of experience, types of project experience, and employments in different-sized companies did not rank these activities differently. The Kruskal-Wallis test allows the comparison of multiple independent groups; the Mann-Whitney test allows the comparison of two independent groups (Pett 2015). In this study, the Kruskal-Wallis tests checked whether site managers in different age groups valued these five activities differently, and the Mann-Whitney test checked whether site managers of different genders, with different numbers of years of experience, working in different types of projects, and employed by different sized of companies, saw these five activities differently. The small sample sizes in certain groups (e.g., only 10 female respondents) should not be a problem, considering that nonparametric tests, including Mann-Whitney, are appropriate even with very small sample sizes (Pett 2015).

Table 1. Respondent demographics

Characteristics	N (%)
Gender	
Male	103 (91%)
Female	10 (9%)
Age	
≤30 years	21 (18%)
31–40 years	34 (30%)
41–50 years	28 (25%)
51–60 years	27 (24%)
≥61 years	3 (3%)
Years of experience	
≤2 years	0 (0%)
3–10 years	23 (20%)
≥10 years	90 (80%)
Project type	
New construction	90 (80%)
Renovation	23 (20%)
Size of company	
Large	94 (83%)
SME	19 (17%)

Note: SME = small and medium sized enterprise.

Model Creation

To construct the model to assess digitalization of the activities based on the questionnaire responses, first, we examined how the technology was used in a construction site activity, and second, we examined the data management processes that were involved. After identifying the data management processes employed, the degree of digitalization of each of them was examined. Data management processes may involve different degrees of digitalization; they may be combined and used to different degrees and at different frequencies. We then examined with what frequency was this degree of digitalization exploited. Keywords were used to search the literature, and the snowballing technique was used. After interrogating the literature to address the first question, new searches were conducted to address all the other issues in turn.

Developing a Model to Assess the Degree of Digitalization

Activities Identified to Digitalize

Full List of Activities Based on the Literature Review

The full list included 27 activities with potential for digitalization (see Table 2, which also provides information on the source of information).

Ranking of Activities

The next step involved identifying which activities were useful and easy to digitalize, had higher pressure, and had the best facilitating conditions to be digitalized.

The respondent data were normalized, as described previously, and each part (usefulness, ease, pressure, and facilitating conditions) had different numbers of responses. The next step in the analysis to identify activities was to calculate a total *digitalization need* value for each activity. This was done by summarizing the 1–5 rankings for usefulness (U), ease (E), pressure (P), and facilitating conditions (C) of all the respondents (n) for each activity (x), as in Eq. (1)

$$\text{Total}_x = \sum_{i=1}^{n} U_{x,i} + E_{x,i} + P_{x,i} + C_{x,i} \quad \forall\ x = 1, \ldots, 27 \qquad (1)$$

Table 3 presents the total values for all 27 activities and shows that the top five activities that should already be digitalized in construction projects are the following: visualize drawings and 3D models onsite; update drawings, models, and system documents; update time and resource plans; create and update work disposition plans; and keep site diaries.

To ensure that subgroups, such as male groups and female groups of site managers, did not rank these activities differently, we applied Mann-Whitney and Kruskal-Wallis tests. The Mann-Whitney test showed that different genders, different years of

Table 2. Gross list of potential activities to digitalize

Activities	Source from literature
Collect, update, and save all project documents	Al Qady and Kandil (2014); Blanco et al. (2017)
Create and report on the environmental impact of the construction project	Kimoto et al. (2005); Tam et al. (2006)
Create and update work disposition plans	Getuli et al. (2020); Luo et al. (2019)
Create material quantity lists	Love et al. (2016); Nourbakhsh et al. (2012b)
Create, prioritize, and assign tasks to craftsmen	Blanco et al. (2017); Nourbakhsh et al. (2012b)
Delivery monitoring and handling of delivery notes	Atkin et al. (1996); Blanco et al. (2017); Hinkka and Tätilä (2013); Nourbakhsh et al. (2012b)
Ensure that craftsmen in the project have the right expertise	Li et al. (2012); Nourbakhsh et al. (2012b)
Follow up and improve energy consumption during the project	Santos et al. (2019); Tam et al. (2006)
Follow up and improve waste management during the project	Santos et al. (2019); Sezer and Bröchner (2019); Tam et al. (2006)
Follow up the presence of staff and visitors and the use of protective equipment	Atkin et al. (1996); Nourbakhsh et al. (2012b)
Follow-up and management of deviations	Atkin et al. (1996); Blanco et al. (2017); Nourbakhsh et al. (2012b)
Follow-up of working hours for craftsmen	Blanco et al. (2017); Cheng et al. (2013); Nourbakhsh et al. (2012b); Sezer and Bröchner (2019)
Implement problem-solving at the construction site and communicate these	Nourbakhsh et al. (2012b); Sezer and Bröchner (2019)
Keeping site diaries	Atkin et al. (1996); Nourbakhsh et al. (2012b); Sezer and Bröchner (2019)
Monitoring and control of the progress of the project	Blanco et al. (2017); Kimoto et al. (2005); Matthews et al. (2015); Nourbakhsh et al. (2012b)
Perform and save quality self-checks	Atkin et al. (1996); Kim et al. (2008); Nourbakhsh et al. (2012b); Wang (2008)
Purchase of materials and services	Atkin et al. (1996); Hinkka and Tätilä (2013); Nourbakhsh et al. (2012b)
Safety information and training for staff	Atkin et al. (1996); Blanco et al. (2017); Jeelani et al. (2018); Kimoto et al. (2005); Li et al. (2018); Zhou et al. (2012)
Share information between construction projects and companies	Blanco et al. (2017); Nourbakhsh et al. (2012b); Yang et al. (2012)
Track and report incidents and accidents	Blanco et al. (2017); Li et al. (2018); Nourbakhsh et al. (2012b)
Track materials and equipment at the construction site	Blanco et al. (2017); Nourbakhsh et al. (2012b); Razavi and Haas (2010)
Tracking subcontractors' progress and payments	Atkin et al. (1996); Nourbakhsh et al. (2012b)
Update and follow up on contract compliance with suppliers and subcontractors	Blanco et al. (2017); Ibem and Laryea (2014)
Update and follow up on contract compliance, including contract changes/variations, with the client	Blanco et al. (2017); Ibem and Laryea (2014)
Update drawings, models, and system documents	Blanco et al. (2017); Kimoto et al. (2005)
Update of time and resource plans	Atkin et al. (1996); Matthews et al. (2015); Nourbakhsh et al. (2012b); Sezer and Bröchner (2019)
Visualize drawings and 3D models on site	Blanco et al. (2017); Liang et al. (2011)

Table 3. Normalized sum of ranks of 27 activities

Activities	U	E	P	C	Total	Rank
Visualize drawings and 3D models on site	283	206	230	260	979	1
Update drawings, models, and system documents	148	160	170	187	664	2
Update of time and resource plans	158	109	136	150	553	3
Create and update work disposition plans	118	192	61	173	543	4
Keeping site diaries	31	216	61	99	407	5
Collect, update, and save all project documents	97	91	83	68	339	6
Update and follow up on contract compliance, including contract changes/variations, with the client	65	44	139	67	314	7
Track and report incidents and accidents	47	82	100	74	302	8
Follow-up and management of deviations	55	61	110	74	300	9
Perform and save quality self-checks	78	41	87	63	269	10
Monitoring and control of the progress of the project	69	27	82	41	219	11
Follow-up of working hours for craftsmen	63	79	24	52	218	12
Purchase of materials and services	60	55	51	46	213	13
Create material quantity lists	60	75	9	67	211	14
Track materials and equipment at the construction site	49	20	22	52	142	15
Delivery monitoring and handling of delivery notes	35	43	23	30	131	16
Safety information and training for staff	35	26	23	31	115	17
Create, prioritize, and assign tasks to craftsmen	56	12	5	37	110	18
Update and follow up on contract compliance with suppliers and subcontractors	30	14	55	11	110	19
Share information between construction projects and companies	23	21	26	27	97	20
Ensure that craftsmen in the project have the right expertise	18	39	28	10	95	21
Follow up and improve waste management during the project	11	45	13	12	82	22
Tracking subcontractors' progress and payments	27	11	38	1	77	23
Create and report on the environmental impact of the construction project	7	1	48	19	76	24
Implement problem-solving at the construction site and communicate these	35	0	17	20	73	25
Follow up the presence of staff and visitors and the use of protective equipment	7	23	26	14	70	26
Follow up and improve energy consumption during the project	0	0	22	12	34	27

Note: U = usefulness; E = ease of use; P = peer pressure; and C = facilitating conditions.

experience, different types of projects, and employment in companies of different sizes had no significant effect on opinions related to the five activities mentioned previously (at $p < 0.05$ level). The Kruskal-Wallis test checked whether site managers in different age groups had different opinions of the five activities; we found no significance (at $p < 0.05$ level). However, when subgroup rankings were compared, we found that four of the preceding activities were always in the top five, but *keeping site diaries* was excluded from the top five activities for nine of the subgroups (e.g., ranked 7th by site managers working in large contractors and 6th by female site managers). Therefore, only four activities were selected: visualize drawings and 3D models on sites; update drawings, models, and system documents; create and update work disposition plans; and update time and resource plans. The next step in the process involves identifying a method of assessment of the degree of digitalization of the four identified activities.

Assessing the Degree of Digitalization of Activities

To identify a method to be used to assess the degree of digitalization of the four selected activities, we started with answering the following questions: (1) how is the technology used to carry out a construction site activity, and (2) which data management processes are used to carry out the activity? To address these questions, we relied on the terminology and ideas proposed in previous assessment models. Xie et al. (2011) proposed a progress monitoring system and described technology use for monitoring, collecting, analyzing, and reporting data. Kim et al. (2013) referred to three steps involved in developing a mobile system for onsite construction management: site monitoring, task management, and information sharing. Shirowzhan et al. (2020) considered the data management process to include data acquisition, data transmission, data storage, data processing, data fusion, and computation, visualization, and dashboarding. We concluded that the data management processes related to a construction site activity included (1) data acquisition (collection), (2) data entry, (3) data analysis (including data storage, process, and computation), and (4) reporting (including dashboarding).

We next try to assess the degree of digitalization of these processes. O'Connor et al. (1999) developed automation and integration measures based on three levels of technology use defined as Level 1—no electronic tools used to complete a work function, Level 2—some use of electronic tools, and Level 3—fully automated system to complete the work function. Yang (2008) adds another level related to assessing the degree of automation by splitting Level 2 into (1) the use of a few somewhat uncommon electronic or mechanized tools; and (2) the use of several specialized electronic or mechanized tools. The scale proposed by Kang et al. (2008) relies on the categories of *automation technology* and *integration technology*, each assessed on five levels. Boute and Van Mieghem (2020) identify four categories: (1) digital, (2) automated, (3) smart, and (4) automated and smart to describe levels for digitalization, automation, and smartness. Their levels for automation are based on no automation (no machine or bot), automation with human control/supervision, automation with conditional autonomous control, automation with autonomous control in certain environments, and automation with full autonomy. Their smart category includes the following: no feedback-control, explicit instructions contingent on one feature, explicit instructions contingent on multiple features, and machine learning. Thus, previous research bases these levels on a scale from manual operation (no digitalization) to full autonomy using machines.

Therefore, we assess the digitalization of each activity on three levels for the four data management processes: acquisition, entry, analysis, and reporting as Level 1 analog and manual, Level 2 digital and manual, and Level 3 digital and automated (Table 4).

Table 4. Assessment of digitalization of identified construction activities

Degree of digitalization	Data acquisition	Data entry	Analysis	Reporting
Level 1	Manual inspections	On paper	On paper	On paper
Level 2	Digitized inspections requiring user interpretation	Digitized manually	Manually with software	Digitalized but manually distributed
Level 3	Digitized inspections with no requirement of user interpretation	Digitized automatically	Automatically with software	Automated

Digitalization Index

Accurately assessing the degree of digitalization requires consideration of the frequency of the data management process (acquisition, entry, analysis, and reporting) and the degree of digitalization of the construction project. These data management processes may be carried out at different degrees of digitalization and different frequencies, such as often at Level 3 and rarely at Level 1. Previous studies rely on a 5-point Likert scale to assess the frequency of IT use, ranging from never to always (Koekemoer and Smallwood 2007), frequency of ICT use ranging from never to very often (daily) (Isaksson et al. 2009), frequency of BIM use on a scale ranging from never to occasionally to often (Eadie et al. 2013), and frequency of hardware use on a scale ranging from never to always (Sezer and Bröchner 2019). These studies compare usage among different groups and identify the most frequently used hardware. However, our objective is to determine the frequency and degree of digitalization of a data management process, meaning that responses related to frequency should sum to 100%. To make the assessment simple and not too time-consuming, we used a 5-point Likert scale ranging from 1 (1%–20% of the time) to 5 (81%–100% of the time).

Therefore, the degree of digitalization of the data management processes (DDDMP) of a particular construction activity i (m number of activities in total) is determined by the degree of digitalization (D, Level 1–3) and frequency (f, 1–5) of the data management process j (4 in total), as in Eq. (2)

$$\mathrm{DDDMP}_{i,j} = D_{i,j} \times f_{i,j} \quad \forall\ i = 1, \ldots, m \quad \text{and} \quad j = 1, \ldots, 4 \tag{2}$$

The degree of digitalization of a construction activity (DDCA) i (identified as useful, easy, pressurized, and facilitated to be digitalized) is, therefore, the sum of the four DDDMPs, as in Eq. (3)

$$\mathrm{DDCA}_i = \sum_{j=1}^{4} \mathrm{DDDMP}_{i,j} \quad \forall\ i = 1, \ldots, m \tag{3}$$

The project digitalization index is then the sum of the DDCA for each construction activity (i) identified as useful, easy, pressurized, and facilitated to be digitalized. This is captured in Eq. (4)

$$\text{Digitalization index} = \sum_{i=1}^{m} DDCA_i \tag{4}$$

This can be simplified into Eq. (5)

$$\text{Digitalization index} = \sum_{i=1}^{m} \sum_{j=1}^{4} D_{i,j} \times f_{i,j} \tag{5}$$

Based on the index, construction projects can score on a scale starting from completely *analog and manual* (80), a blend of *analog and manual* and *digital and manual* (120), completely *digital and manual* (160), a blend of *digital and manual* and *digital and automated* (200), and finally completely *digital and automated* (240).

For easier interpretation, the index can be normalized into a scale of 1–100 by relying on the maximum value [Eq. (6)]

$$\text{Normalized digitalizatn index} = \frac{100}{240} \times \sum_{i=1}^{m} \sum_{j=1}^{4} D_{i,j} \times f_{i,j} \tag{6}$$

Model for Assessing the Degree of Digitalization of Construction Projects

Fig. 1 depicts the model assessing the degree of digitalization of construction projects. It starts by identifying which construction activities should be assessed. This is based on the UTAUT filter for the activity, meaning that activity should be useful, easy, have pressure, and have the potential to be digitalized. The assessment starts by assessing the data management process (acquisition, entry, analysis, and reporting) based on the criteria of being analog and manual, digital and manual, and digital and automated for each construction activity. The last step involves calculating the project's digitalization index based on the frequency of the degree of digitalization.

Validation of the Model and the Index

In order to validate the model and the index, a questionnaire was designed and sent to a site manager from one of the largest contractors in Sweden. The questionnaire was designed to apply the digitalization index on the last construction project of the site manager and, therefore, asked the degree of digitalization and frequency of data management processes (acquisition, entry, analysis, and reporting) for four activities (visualization and 3D modeling on sites; updating drawings, models, and system documents; creating and updating work disposition plans; and updating time and resource plans), including a total of 16 questions. The project was a large, new construction project with a contract sum over MSEK 250 (USD 29,000,000), and the site manager was male and in their mid-40s.

Based on the responses from the site manager, the project's digitalization index was calculated. First, the degree of digitalization of the data management processes was calculated [Eq. (2)]. The site manager combined different frequencies with different degrees of digitalization; for instance, for a visualization of the drawings and 3D models, the site manager reported that they collect data with (1) manual inspections 41%–60% of the time, (2) digitized inspections requiring user interpretation 1%–20% of the time, and (3) digitized inspections with no requirement of user interpretation 1%–20% of the time. Based on this, the degree of digitalization of the data acquisition process for the visualization of drawings and 3D models ($\mathrm{DDDMP}_{d,v}$) was calculated

$$\mathrm{DDDMP}_{d,v} = (1 \times 3) + (2 \times 1) + (3 \times 1) = 8$$

The same equation was used for calculating the degree of digitalization for data entry (5), analysis (8), and reporting (8). Second,

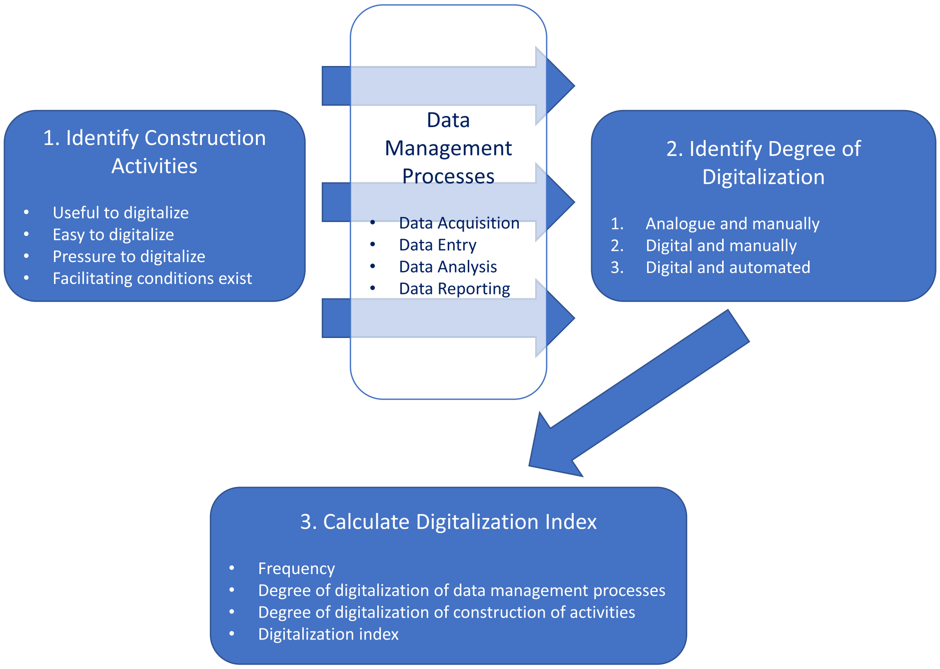

Fig. 1. Model for assessing the degree of digitalization of construction projects.

the degree of digitalization of visualization of drawings and 3D models (DDCA_v) was calculated by summing the degree of digitalization of four data management processes [Eq. (3)]

$$\mathrm{DDCA}_v = 8 + 5 + 8 + 8 = 29$$

By applying the same equation, the degree of digitalization of updating drawings, models, and system documents (32), creating and updating work disposition plans (36), and updating time and resource plans (37) were calculated. Third, the degree of digitalization of the project was calculated by summing the degree of digitalization of four activities [Eq. (4)]

$$\text{Digitalization index} = 29 + 32 + 36 + 37 = 134$$

Two days later, a semistructured interview was done with the same site manager, which lasted around 30 min to investigate (1) whether the index was accurately reflecting the degree of digitalization of the construction project; and (2) whether there were any technical difficulties, misunderstandings, or suggestions for improving the assessment. At the beginning of the interview, the site manager was asked to describe the construction project's degree of digitalization, and the site manager stated the following: "In this project, we do not have those traditional paper-based drawings; we collect everything, including drawings and details we need from computers. We go in models and such, check them, and then we print them out on paper. We are more digitalized than paper-based. But we do not have any automation in this project." Following that, the digitalization index of the project (134) was shown to the site manager on the scale starting from completely *analog and manual* (80), a blend of *analog and manual* and *digital and manual* (120), completely *digital and manual* (160), a blend of *digital and manual* and *digital and automated* (200), and finally completely *digital and automated* (240). The site manager agreed that the project was located accurately, being close to a blend of *analog and manual* and *digital and manual*. When it comes to technical aspects, the site manager mentioned that it would be easier if the questionnaire automatically summed up the frequencies to 100% or reminded them that the sum of the frequencies should be 100%. No recommendations for improvements were given by the site manager, who acknowledged that the measurement was easy and that it took only 6 min to fill in the questionnaire.

Conclusions

The construction industry is in an era of digitalization, but despite efforts to introduce new technologies, it is one of the least digitally advanced industries. The construction industry is project-based, but we know little about how much construction projects are digitalized. This paper developed a digitalization index to assess the degree of digitalization of construction projects.

Previous examples such as the TUI index and automation and integration scales had two main problems: (1) they require an assessment of the degree of technology use for more than 50 activities, which is cumbersome, and (2) assessments are done rather abstractly, meaning that respondents were asked to report their degree of technology use for an activity in which data processes (such as inputting, analyzing, and reporting data) and frequency tend to be overlooked. Unlike previous examples, the digitalization index developed in this paper requires an assessment of the degree of digitalization for only four activities, which lasts around 5–6 min. To keep the assessment simple and not too time-consuming for site managers, four activities were identified based on the responses to a questionnaire drawing on the UTAUT. These activities were (1) visualization and 3D modeling on sites, (2) updating drawings, models, and system documents, (3) creating and updating work disposition plans, and (4) updating time and resource plans. The proposed digitalization index was built based on the degree of digitalization of the data management processes, leading to a more comprehensive assessment involved in these four activities.

The theoretical contribution of this paper is twofold. First, it contributes by using UTAUT as a filter to reduce construction site activities to assess the degree of digitalization of construction projects and benchmarking among projects. This approach could be applied to other project-based industries where an initial list of activities needs to be defined and then reduced. Second, it provides insights into how the digitalization of construction projects can be assessed. Previous models have focused on assessing digitalization trends at the wider industry level. However, it is equally important to assess digitalization trends at the project level. This paper contributes by proposing a model that shifts the focus from the industry to the project level. The digitalization index can help to identify the low-scoring projects, and these projects can be studied as case studies to explain why their scores are low.

This project-centered assessment also contributes to practice. The digitalization index for projects will allow benchmarking among projects to highlight why some projects score better in terms of digitalization and the problems related to lower levels of digitalization. Furthermore, linking the level of technology use to project performance has been a popular subject in previous studies (e.g., O'Connor and Yang 2004). Therefore, an accurate digitalization index will improve the identification of associations between digitalization and project performance, including productivity, and environmental and safety performance through questionnaires. Applying the digitalization index to longitudinal data will allow observation of digitalization trends in the construction industry.

The study has two limitations. First, the study is based on Swedish site managers. Future research can replicate the model and the UTAUT questionnaire for an international comparison to show whether the same four activities are the highest-ranked among site managers. Second, the index is developed for ongoing and completed construction projects, and it was validated in one almost-completed construction project. The digitalization index can be used for upcoming projects by asking site managers the planned degree of digitalization and frequency of data management processes (acquisition, entry, analysis, and reporting) for the four activities (visualization and 3D modeling on sites, updating drawings, models and system documents, creating and updating work disposition plans, and updating time and resource plans). Before applying the digitalization index via an industry-wide questionnaire, future studies are recommended to validate and pretest the index in several projects, which can include the suitability of the index for upcoming projects.

Data Availability Statement

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

Acknowledgments

The authors acknowledge financial support from the strategic innovation program, Smart Built Environment, funded by Vinnova (Swedish Governmental Agency for Innovation Systems), Formas (Swedish Government Research Council for Sustainable Development), and Energimyndigheten (Swedish Energy Agency).

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