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Assessing the impact of digitalization on the infrastructure construction industry's sustainable development

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ABSTRACT:

Sustainable development is becoming an increasingly more important topic across humanity whereas policymakers, financiers, and industries are required to set it to be increasingly higher in their priorities. The infrastructure construction industry and its stakeholders are among others increasing sustainable development constantly higher in the rank of priorities, but solutions for achieving the objectives have been in short supply. This study aims to answer the question: How is digitalization perceived to impact the infrastructure construction's sustainable development?

As digitalization as a growing trend has been estimated to be one of the most potential technologies enabling the pursuit of sustainable development, this study aims to assess its current impact on the sustainable development of the infrastructure construction industry. Identifying digitalization's current impact and future opportunities could encourage technology developers and stakeholders of the industry to either foster the appliance of digitalization to achieve their sustainable development objectives or ignore the technology

To assess the impact, this study conducted research through a method of survey research the perceptions of the stakeholders who have already applied digitalization solutions extensively in their operations. Additionally, this study explored the future opportunities of digitalization, which eventually was delivered by designing a data model for measuring CO^2e emissions of projects. Eventually, this study discovered digitalization to have already a relevant impact on enabling sustainable development in the industry, especially by enhancing the management of projects and communication among stakeholders, and identified several development opportunities, which could enable the industry to achieve increased sustainability.

KEYWORDS: Infrastructure construction, digitalization, sustainable development

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TIIVISTELMÄ:

Kestävän kehityksen kasvattaessa merkitystään yhtenä ihmiskunnan tärkeimmistä tavoitteista, poliittisten päättäjien, rahoittajien ja yritysten on kasvavissa määrin asetettava se myös omissa tavoitteissaan etusijalle. Myös infrarakennusteollisuus ja sen sidosryhmät ovat nostamassa kestävää kehitystä jatkuvasti korkeammalle prioriteettilistallansa, mutta ratkaisujen löytäminen tavoitteiden saavuttamiseksi on ollut haasteellista. Työn tavoitteena on vastata tutkimuskysymykseen : Kuinka digitalisaation havaitaan vaikuttavan infrarakentamisen rakennusvaiheen kestävään kehitykseen?

Digitalisaation on arvioitu omaavan paljon potentiaalia kestävän kehityksen edistämiseen, jonka vuoksi tutkimuksessa pyritään arvioimaan sen nykyistä vaikutusta infrarakentamisen kestävään kehitykseen. Digitalisaation nykyisten vaikutusten ja tulevien mahdollisuuksien tunnistaminen voi rohkaista teknologian kehittäjiä sekä alan sidosryhmiä edistämään digitalisaation käyttöä kestävän kehityksen tavoitteidensa saavuttamiseksi.

Vaikutusten arvioimiseksi tutkimuksessa käytettiin kyselytutkimusmenetelmää tutkimaan niiden sidosryhmien näkemyksiä, jotka ovat jo laajasti soveltaneet toiminnassaan digitalisaatioratkaisuja. Lisäksi tutkimuksessa selvitettiin digitalisaation tulevaisuuden mahdollisuuksia, mikä johti projektien CO^2e päästöjen mittaamista kehittävän tietomallin suunnitteluun. Tutkimuksessa havaittiin digitalisaatiolla olevan jo merkityksellinen vaikutus alan kestävän kehityksen mahdollistamiseen, erityisesti tehostamalla projektien hallintaa ja sidosryhmien keskinäistä viestintää, jonka lisäksi tunnistettiin useita teknologian kehitysmahdollisuuksia, joiden avulla toimiala voi saavuttaa kestävämpää kehitystä.

AVAINSANAT: Infrarakentaminen,digitalisaatio, kestävä kehitys

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Abbreviations

3D	Three Dimensional
3P	Profit, People, Planet
BIM	Building Information Modeling
BRE	Building Research Establishment
BREEAM	BRE Environmental Assessment Method
CEEQUAL	Civil Engineering Environmental Quality Assessment and Awards Scheme

CEN	Comité Européen de Normalisation
CO_2	Carbon Dioxide
CO_2e	Carbon Dioxide equivalent
EFDB	Emission Factor Database
ESG	Environmental Social Governmental
GHG	Green House Gas
GNSS	Global Navigation Satellite System
IFC	Industry Foundation Classes
IPCC	International Panel of Climate Change
ISO	International Organization for Standardization
IT	Information Technology
LCA	Life Cycle Assessment
LiDAR	Light Detection and Ranging
PIM	Project Information Management
RTK	Real-Time Kinetic
SDG	Sustainable Development Goal
SME	Small and Medium-sized Enterprise
SYKE	Suomen Ympäristökeskus
TBL	Trible Bottom Line
UN	United Nations
XML	Extensible Markup Language

1 Introduction

This chapter is introductory in its nature, presenting the background of the study in its essence, and elaborates on the perceived research gap, and the questions which aim to eventually provide answers and results to achieve the presented objective of the research. A more thorough theoretical background will be then explored in chapter 2. Furthermore, this chapter will distinguish the limitations of the study and cover the definitions necessary for the scope to be understood.

This chapter will also merely present the research process designed for achieving relevant results with established scientific practices. Furthermore, the methodology of the study will be explored in chapter 3, which additionally covers the analysis of the data. Eventually, the study will proceed to the phase of discussion in chapter 4, where the data will be reviewed in a broader context of the industry. Finally, chapter 5 will summarize and conclude the study.

1.1 Background of the study

During the first decades of 21st-century sustainable development has gained increasing publicity, with topics of discussion varying from gender equality to sustainable investing, and from a sustainable working environment to climate change mitigation (Rodat, 2021, p. 31−32). Public opinion is constantly tending to demand more effort from decision-makers and companies in terms of promoting sustainable development. Those committed to prioritizing sustainability as their primary purpose, are becoming increasingly more successful, whether it is measured in business valuation or as election success.

The infrastructure construction industry has arguably been perceived to be one of the least sustainable industries whether from information transparency, environmental destruction, or gray market point of view (Azhar, 2011, p. 249-251). Obscure expenses of projects, questionable working conditions, and greenwashing to achieve a climate-friendly image are just a few examples to mention, which are infamously often associated with the infrastructure construction industry. To increase the sustainability of the industry, certification and standardization frameworks that promote sustainable development have been developed. One of the most applied frameworks has been CEEQUAL, which aims to provide a holistic assessment of infrastructure projects' sustainability (BRE Group, 2022a).

Digitalization as an emerging trend across industries has been debated to aid the sustainable development efforts, in its ability to provide an opportunity for instance to increase communication transparency, enhance economic efficiency, and improve control of environmental impacts (McManus & Haughton, 2020, p. 996−998). In the infrastructure construction industry, digitalization solutions have been adopted later than in other industries, thus solutions that collectively could enable more sustainable construction projects have been emerging with delay. At the beginning of the 2020s only in a few countries such as Finland and Norway, have digitalization solutions been extensively adopted in the management of infrastructure construction projects.

Sustainability as a broad concept and the different frameworks for evaluating its development and sustainable development in the infrastructure construction industry will be elaborated further in the theoretical background of the study in chapter 2. Digitalization as an emerging trend, its current stage of maturity in the infrastructure construction industry, and key technologies are additionally explored in chapter 2, to establish the framework for assessing digitalization's impact on the sustainable development of the industry.

1.2 Research gap, questions, and objectives

As digitalization solutions could enhance the sustainability of the infrastructure construction industry remarkably, there is an evident need to research that potential impact (Mantovani Ribeiro et al, 2021, p. 243−247). To define the research gap of this thesis, initial sourcing of background literature, insights into the case company employees, and insights of the thesis steering group formed from infrastructure construction stakeholders were explored. Eventually, the research gap was identified and justified through more in-depth sourcing of the background literature. Firstly, it was recognized that studies of digitalization's impact on sustainability have been made on a holistic level, so the background of the study could be research-based. Also, the digitalization maturity development in the industry was seen to be increasing by studies such as Goger's and Bisenberger's (2020), which is favorable for the thesis. The increasing emergence of data through technological advancement in the industry furthermore enables the development of sustainability impact assessment. Also, sustainability as a growing global trend was seen as a beneficial incubator for studying digitalization's impact on infrastructure construction projects through the case company point of view (Rodat, 2021, p. 30−31).

The life cycle stage limitation of the study was decided to be the phase of construction in the infrastructure's life cycle as the amount of unapplied data in Infrakit has been perceived to be significant and thus, its potential for developing the practice of sustainability assessment should be researched. The construction stage of an infrastructure project is defined by Krantz (2019, p. 14) to limit raw material extraction to the beginning of the operation phase of the infrastructure. The construction stage includes phases from A1 to A5 as presented in Figure 1.

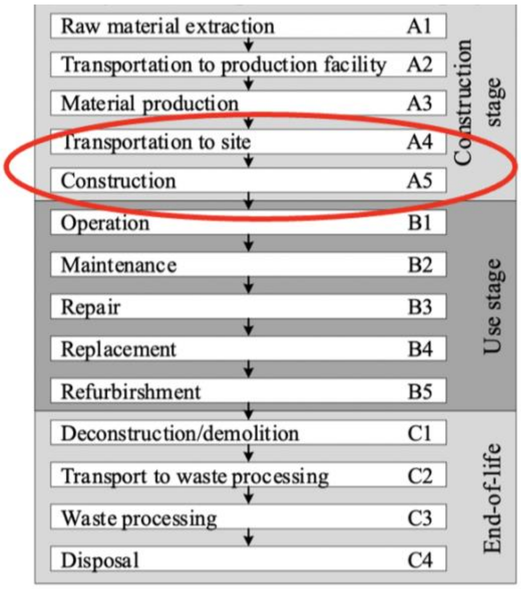

Figure 1. Scope of the study in construction stage adapted from Krantz (2019, p. 14).

As the digitalization of infrastructure construction is not affecting phases A1, A2 and A3, they are additionally being left outside of the study scope. However, the material GHG impact will be derived from those phases. Eventually, in the subject of the infrastructure life cycle, these notations will focus the study scope to consider digitalization's impact on sustainability in the phases of A4 and A5, hence, the material transportation and the construction site action. However, according to Krantz's (2019, p. 14) definition phases B3, B4, B5, C1, and C2 can be also considered to be done by construction contractors and the use of case company digitalization service is possible, thus it is to be mentioned that this study will consider the construction of new infrastructure and repairing old infrastructure as general construction projects as of matter of simplification.

Another limitation of the study was decided in the scope of assessing sustainability. The sustainability assessment will be made with consideration of TBL but leaving out the economic sustainability as it has been the most studied area in digitalization development of infrastructure projects and digitalization has been researched by Blanco and Chen (2014, p. 519) to have 15-20% saving potential on operational costs of projects. Thus, the gap of interest in the research was perceived to be in the social and environmental aspects of digitalization’s impact on infrastructure construction projects' sustainability development. The need of studying these areas of sustainability is being stated also by Mansell et al (2020, p. 48) to pull the holistic sustainability consideration and SDG value creation further as presented in Figure 2.

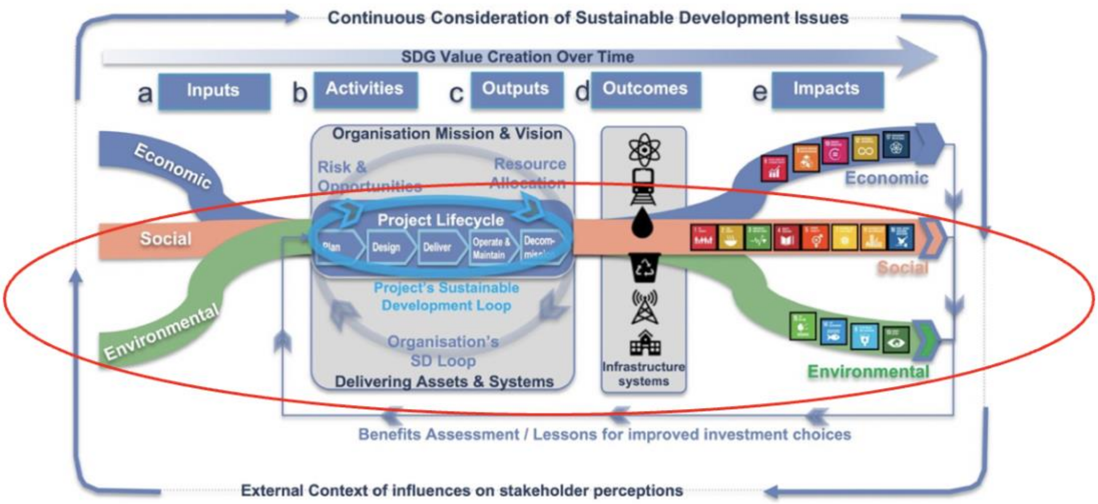

Figure 2. Sustainability development in organizations adapted from Mansell et al (2020, p. 48)

As presented in Figure 2, the streams of social and environmental sustainability and their alignment to SDGs will be limitations of the study. Furthermore, the study aims to aid the organizational loop of sustainable development by providing knowledge on how digitalization may help them in the pursuit of their sustainable development objectives and strategies. As the picture represents, organizations have different levels of sustainable development, one of them is the whole organizational level, and another is the project level. Digitalization’s impact in this context will be analyzed on both levels. The definition of the research questions will thus be derived from previously proposed limitations of the study and the perceived research gap in mind.

The overall purpose of this thesis will be to explore the sustainable development of infrastructure construction and how digitalization may affect it, particularly in the construction phase. The aim was to develop validation through research on how digitalization is perceived to provide infrastructure construction stakeholders an opportunity to achieve their sustainable development goals and how it may mitigate that opportunity. To achieve this objective, the stakeholder perspective must be studied. This issue defines the research question 1:

RQ 1: How is digitalization perceived to impact the infrastructure construction's construction phase's sustainable development in social and environmental aspects?

The availability of relevant information on construction projects' CO_2e emissions limits the proper assessment of sustainability in these projects. Project data must therefore be explored from some point of view and as a digitalization platform, Infrakit gathers data across the project, which provides a favorable position for studying the data. This exploration must be further analyzed on how it can provide relevant information for sustainability assessment. Research question 2 addresses this issue:

RQ 2: How can Infrakit cloud service as a digitalization solution use the emerging data for modeling the environmental sustainability of construction projects, particularly CO^2e emissions?

To conclude the objectives of the study, this assessment aims to increase the knowledge of the impacts and identify the areas in which digitalization solution developers could in the future focus to enable more sustainable projects. Furthermore, the purpose of this study is to help industry stakeholders with ambitious sustainable development objectives to acknowledge, how applying digitalization solutions could enable them to achieve their objectives faster and more comprehensively. Ultimately, stakeholders acknowledging these impacts and applying digitalization solutions could drive the industry towards contributing to global sustainability objectives such as the Sustainable Development Goals of the United Nations, which could eventually also make the industry appear more responsible, sustainable, and attractive for investors and talented workforce.

1.3 Definitions and Limitations

To define the overall limitations of the study, defining the keyword's purpose in the study will function as a broad framework. The first keyword “infrastructure construction” limits the study clearly to focus on the infrastructure construction industry point of view, excluding other industries, holistic global impacts of different supply chains, etc. Furthermore, the industry will be limited only to the construction phase, as elaborated in Figure 1. The second keyword “digitalization” will limit the study to only consider the digitalization’s impact on sustainable development, aiming to exclude other sustainability efforts which are not being impacted by digitalization solutions currently. The third keyword of “sustainable development” needed additional limitations to social and environmental impacts, as elaborated in Figure 2, but overall, it describes the study's focus to assess the sustainable development impact of digitalization. These keywords will be further elaborated on in chapter 2.

A more in-depth impact assessment study will be limited to evaluating digitalization impacts in the framework of CEEQUAL certification, SDGs, and which sustainability themes they consider. This framework and its logic are presented in Figure 3. Additionally, this study will research digitalization’s opportunities to manage the environmental impacts of projects, by conducting a case study exploring the Infrakit cloud-service database. This part of the research will provide concrete information for the case company on what data could be processed to provide information to support the environmental management of the projects and what data should be collected to increase the fidelity of the information used to manage projects.

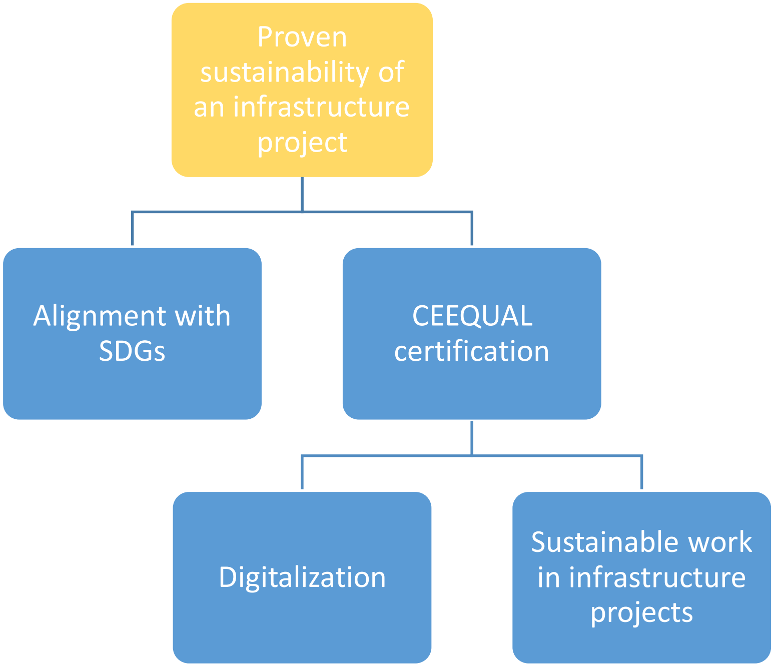

Figure 3. Impact assessment research logic in the framework of this study.

As Figure 3 represents, this study will limit its focus on analyzing the digitalization's impact on sustainable work in infrastructure projects, which is viewed solely through the CEEQUAL certification framework aligned with SDGs. This framework aims to align assessed digitalization impact with the most applied frameworks of sustainable development assessment in the industry, to provide somewhat clear insight on the impact researched. Furthermore, this study will not consider or question CEEQUAL certification nor SDGs validity as frameworks of assessing sustainability.

2 Theoretical background

This chapter presents the background and key literature of the study. It is an exploratory chapter of the key concepts around the study and eventually, this background information justifies the formed research objective and scope. In the chapter, sustainability as a broad field will be narrowed according to research interest and the digitalization maturity stage, particularly in infrastructure construction will be explored. Existing studies made on digitalization's impact on sustainability in general and the major concepts of sustainability assessment will be elaborated on.

2.1 Sustainable development

While humanity has an increasing awareness of its impact on the world around, new issues will be perceived with the knowledge (Rodat, 2021, p. 31−32). As Kouaib et al (2020, p. 1) acknowledge, though sustainability is a difficult term to be defined, it has become one regularly used term in speech around impact awareness and is defined by Scoones (2007, p. 590−591) as: "… an evolvement and development of today's world without compromising the wellbeing of future generations". United Nations, representing the guiding institution of mankind's pursuit of doing better, has broken down our greatest problems to be solved to become more sustainable in what we do in a form of Sustainable Development Goals, SDGs (United Nations, 2020). SDGs include 17 major goals, which can be divided furthermore into three major categories, economic, social, and environmental, also known as the approach of Triple Bottom Line, TBL, which is a very popular sustainability framework as well (Mansell, 2020, p. 45). Figure 4 will present SDG's alignment to the TBL.

Figure 4. SDGs aligned with TBL by Mansell et al (2020, p. 45).

Figure 4 presents the TBL in a "wedding-cake" view with SDGs aligned to each state of sustainability (Mansell, 2020, p. 45). SDGs intention to provide a common mission and objectives for humanity will be fulfilled through aligning our actions with them. As these goals themselves represent the holistic picture, the ambiguity has been declared by deriving them into more minor targets for each SDG, which must be reached to achieve that specific goal (United Nations, 2020). Furthermore, these targets have been given indicators, that will provide more measurability of whether these targets are being worked towards in the actions of industries, policymakers, institutions, and individuals.

For consideration, is sustainability going to be a valuable area of focus in strategical levels of businesses that require focus on high efficiency for increasing profitability and owner-value, several studies state sustainability to be rather a key factor in the future value creation of the company. Rodat (2021, p. 30−35) acknowledges in their study that the European parliament election is to be affected increasingly by issues related to sustainability, and politicians campaigning for focusing on these issues are being elected increasingly. Both Bauer et al (2021, p. 4012−4014) and Fiskerstrand et al (2020, p. 308−309) have stated, that sustainability factors such as Environmental, Social, and Governmental (ESG) ratings of investments are being valued higher by private persons in stock markets, leading to an increased valuation of these companies. Institutional investors and private equity investors seem to follow the same trend according to Park and Jang (2021, p. 18−20). Thus, companies that can increasingly prove their sustainability impact are more likely to receive public support through for example subsidiaries and capital loans, gain higher valuation in stock markets, raise more private equity, and eventually also generate more revenue, as consumption trends are becoming more sustainability-oriented according to Yue et al (2020, p.10−11).

To provide evidence and affect SDG indicators positively in industries, standards and frameworks are being developed to provide guidance and certification (Griffiths et al, 2020, p. 20−23). They have an important role as steering tools, in requiring and rewarding the industry stakeholders to act in alignment with the SDGs. Griffiths et al (2020, p. 22−23) state that in the infrastructure construction industry one of the most applied and potential sustainability assessment frameworks is CEEQUAL, which provides certification for projects to indicate that their work is aligned and thus contributing to the SDGs positively. Applying CEEQUAL certification enables stakeholders of the industry to have a common and comparable approach to measuring infrastructure construction projects' efforts on sustainability. Eventually, it provides evidence of the sustainability actions taken (BRE Group, 2022a). At the phase of analysis CEEQUAL certification’s ability to impact SDG indicators will be compared to the impact assessment conducted in this research.

In the development of sustainability across industries, organizations, and personal lives, digitalization has been perceived to have a positive, though debatable impact as McManus and Haughton state (2020, p. 996−998). According to Azhar (2011, p. 251) In the infrastructure construction industry increased transparency of operations, better monitoring of worksite efficiency, decreased construction mistakes and reduced rate of worksite accidents are just a few traits to mention, where digitalization has been perceived to have a positive impact on the sustainability development.

2.2 Digitalization in infrastructure construction

Digital solutions and tools for measuring and modeling construction work, to enhance the efficiency of work, have been developed at an increasing pace during the last decades as Goger and Bisenberger (2020, p.165−167). Azhar (2011, p. 243) states that one major technological development has been building information models (BIM) which provide accurate modeling and visualization of infrastructure assets in a digital format. Other mentionable technological advancements enabling higher control of quality and implementation of projects are such as Global Navigation Satellite System with Real-Time Kinetics (GNSS−RTK) that provides positional information of the machinery, Light Detection and Ranging (LiDAR) -based real-time tracking systems, point cloud coordinate transformation systems (Wang et al, 2014, p. 418; Kivimäki & Heikkilä, 2015). This development has enabled the pursuit of better-controlled projects and thus better construction of infrastructure with lower costs in the projects according to Goger and Bisenberger (2020, p. 165−167). However, this advancement can be seen rather as digitization than digitalization. The major difference has been stated by Brennen and Kreiss (2016, p. 1) to be: "…digitization as the material process of converting analog streams of information into digital bits." whereas "…digitalization as the way many domains of social life are restructured around digital communication and media infrastructures.". Digitization as a premature phase and enabler of digitalization is pictured in Figure 5.

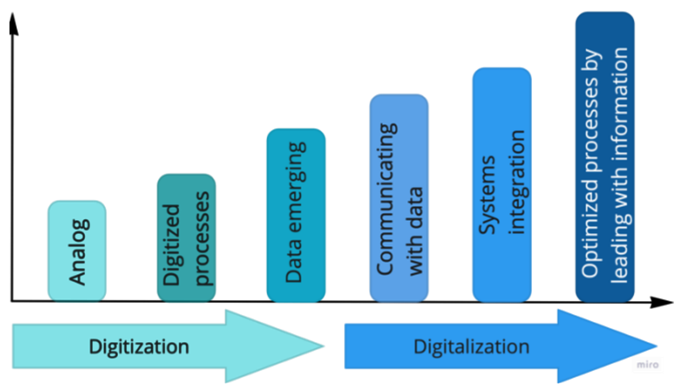

Figure 5. Example on digital maturity phases adapted from Moyer (2019, June 3.).

With acknowledgment of this difference between the definitions, it is viable, that the data that has emerged from these new technologies have established an opportunity for digitalizing infrastructure construction, where the process of building infrastructure can be done with the assistance and guidance of digital communication (Zhang et al, 2021, p. 6−7). Digitalization, thus applying these digital forms of social life's domains into the communication, has been enabled in the infrastructure construction industry by for example cloud-based platforms as stated by Goger and Bisenberger (2020, p. 165−166). Inside these platforms, digital forms of knowledge are being shared via the stakeholders of the construction processes. According to Wojewnik-Filipkowska et al (2021, p. 212), key stakeholders to mention in infrastructure construction projects are owners of the infrastructure, later referred as clients, usually public institutions such as cities, municipalities or governmental organizations, and other local authorities; primary contractors responsible for the implementation of the construction phase; design agencies who produce the implementation plans and designs for the infrastructure; and subcontractors, who are working under primary contractors, executing selected tasks inside the projects.

One case example of a cloud-based platform for managing project information is Infrakit provided by Infrakit Group Oy (Infrakit Group a, 2022). Infrakit Group Oy is a Finnish privately held company, producing a cloud-based service platform to enable the digitalization of infrastructure projects. Founded in 2010, Infrakit has emerged from research made at the University of Oulu as a spin-off. The cloud-platform Infrakit enables the storing of digital information and communication with it between the stakeholders. BIM models, machine telemetry data, digital documentation, and such are being stored and visualized in a cloud platform where the stakeholders have access through subscription contracts. The benefits of this digitalization approach have been perceived to be optimization of the work and project information management, eventually providing cost-saving benefits for the stakeholders. In this study, Infrakit cloud-service will serve as a case example of digitalization in infrastructure construction, serving as a project information management (PIM) platform, which is considered as a web-based system collecting different tools for optimized tracking and communication of the project information according to Zhang et al (2021, p. 6−7).

The infrastructure construction industry has not been applying digitalization solutions widely across the world yet as stated by Hetemi et al (2020, p. 1−2). Arguably the major bottleneck has been the lack of digitization of the industry, as digitalization solutions require firstly digitization of the analog streams as Brennen and Kreiss conclude (2016, p. 1−3). Figure 6 below represents the digitization of industries on a global scale. The digitization maturity has been indicated in traffic-light visualization, where red blocks are representing the lowest level of digital technology adoption and green the highest maturity. The construction industry includes both building and infrastructure construction.

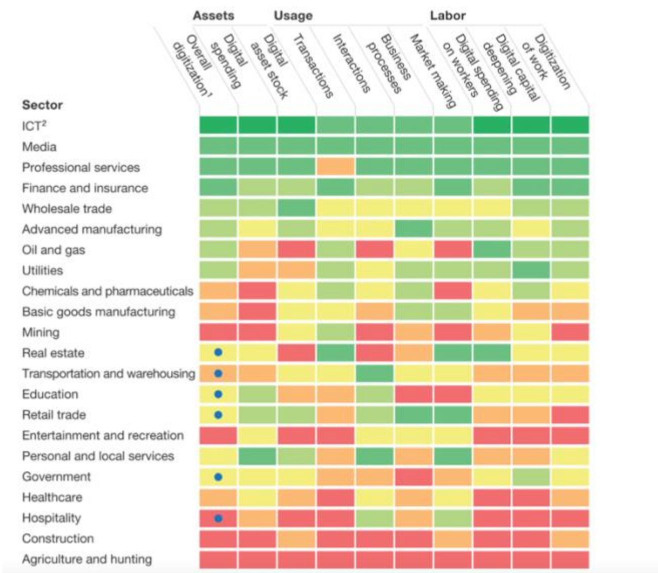

Figure 6. Digitization maturity of different industries (The McKinsey Company, 2016).

Though being to some extent already outdated representation, and not being able to completely extract infrastructure constructions maturity level of digitization, the figure serves as a sign of the comparison of maturity levels between industries. In the latter half of the 2010-decade, digitization and digitalization have been developing especially in Nordic countries at a level where digitalization solutions begin to become commercially viable and the ecosystem becoming more mature according to Goger & Bisenberger (2020, 165−166). Therefore, digitization and digitalization begin to have evidence of their beneficial effects on infrastructure construction and thus it may expect an increasing adopting rate globally. The next chapters are going to present the major digitization and digitalization solutions of the infrastructure construction industry, that are perceived to be central concepts in this study.

2.2.1 Building information modeling

BIM has been originally applied in construction projects of buildings, but with much usability in infrastructure construction projects as well, adoption of it has been increasing (Zhang et al, 2021, p. 1−2). Construction Projects Information Committee, CPIC, defines BIM to be a process conducted throughout the asset lifecycle and presents the physical and functional elements of the asset in a digital form according to Bradley et al (2016, p. 140). As Figure 7 presents, the BIM concept can be commonly divided into elements of collaboration, representation, process & lifecycle. These elements are interconnected to establish innovation and structure for the domain of the project to be efficient.

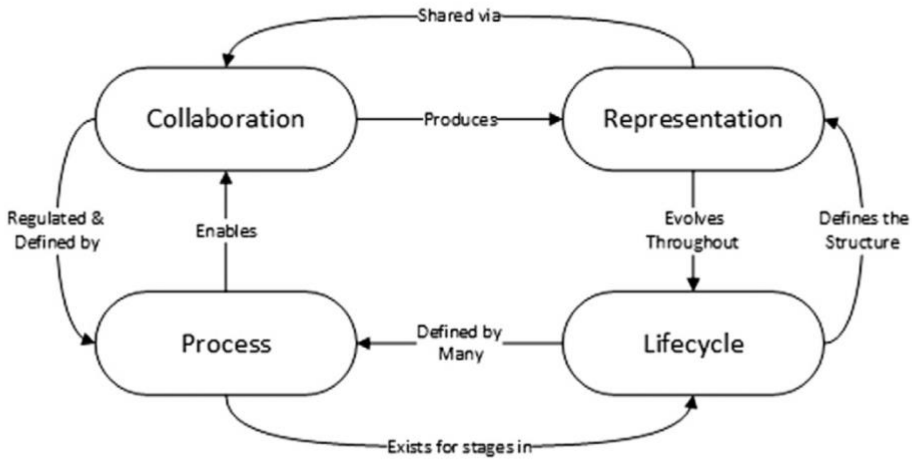

Figure 7. Concept of BIM by Bradley et al (2016, p. 141).

Interaction between the elements of BIM is being elaborated by relation flows, to enable eventually a collaboration through visualized 3D models of the building throughout the processes of designing and constructing the asset (Bradley et al, 2016, p. 140). BIM models in general contain specifications of the asset and can be presented in different formats for different purposes. The often-used format used in BIM models is called LandXML. Figure 8 has a bridge projects' combination model on the left-hand side and a presentation model on the right-hand side. The combination model is an elaboration of all the asset information in one three-dimensional (3D) presented format whereas the presentation model is used mostly for stakeholder communication at a very general level such as communication to media and the public (BuildingSMART Finland, 2019, p. 41).

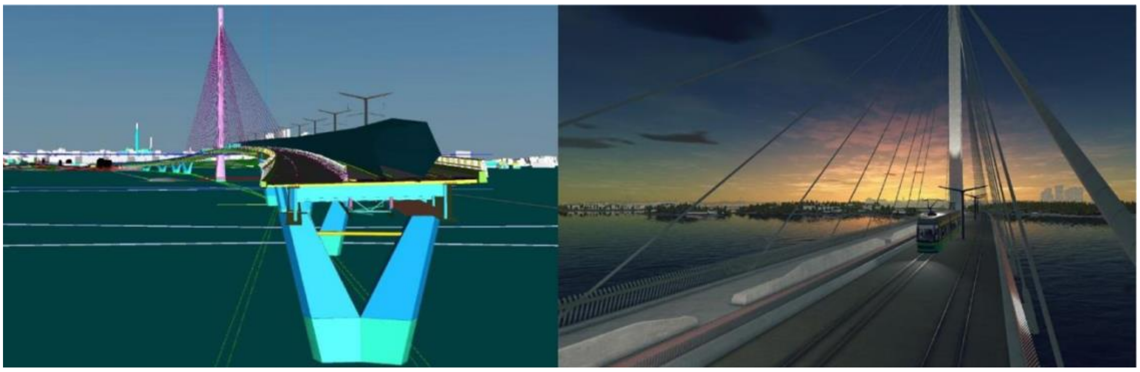

Figure 8. Combination model and presentation model of Crown Bridge project in Finland (BuildingSMART Finland, 2019, p. 41).

BIM models can furthermore have the potential on providing important information on mass volumes of constructed elements, which will enable the development of measuring and modeling of realized greenhouse gas (GHG) emissions of a project (Zhang et al, 2021, p. 6−7). As-built models are providing information about the structures that have been implemented, thus providing an opportunity to calculate the actual mass volumes. The potential of using BIM models in developing environmental sustainability assessments is going to be explored in this study, the attaching sustainability information to BIM models will be merely discussed.

2.2.2 Machinery information

Typical and most often machinery used for the construction of infrastructure are excavators, asphalt pavers, compaction machines, drilling machines, and bulldozers which are used for managing the materials (Goger & Bisenberger, 2020, p. 165−170). Transportation of materials from a material production facility to a construction site is being done with transportation machinery such as trucks and dumpers. In the construction projects, the locations and movements of the machinery are being measured by for example GNSS-RTK technology or with the low-cost option of inertial measurement unit (IMU) technology (El-Mowafy & Kubo, 2018, p. 901). Furthermore, this data can be then applied to managing the project. Figure 9 is an example of machine positioning data collected and applied in a cloud-based PIM platform.

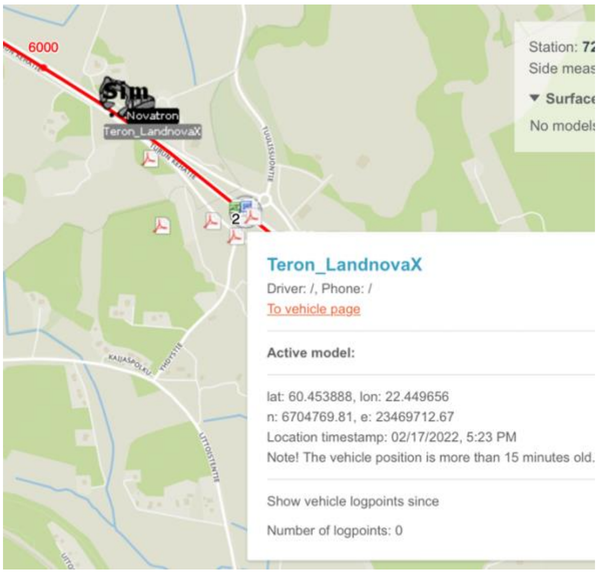

Figure 9. Presentation of machine positioning information in cloud-based PIM platform (Infrakit Group Oy b, 2022).

These measurements provide project management with important information that can be applied for managing quality and project performance measuring (El-Mowafy & Kubo, 2018, p. 901−902). The appliance of telemetry to provide machine use data may have the potential on collecting information and realized data on sustainability impact assessment in terms of GHG emissions, noise and pollution measuring, and such (Krantz et al, 2015, p. 1166−1167; Krantz, 2019, p. 16−17). This study will explore the opportunity of applying currently available telemetry data from the case company’s case project in measuring GHG emissions.

2.2.3 Cloud computing

The emergence of cloud computing as a techno-social innovation has made information technology (IT) a utility and enabled the creation of platforms for common data sharing as Lal and Bharadwaj (2016, p. 567) compose. Cloud-based services are being offered through the concept of cloud computing technology which includes a variating set of IT infrastructure elements such as hardware, software, and network, which eventually grant the customer on-demand access to the service via the internet. Cloud-based services thus are perceived to be one key technological advancement in the emergence of digitalization. Figure 10 presents the applications of cloud computing in the construction industry, which applies also to the construction of infrastructure (Bello et al, 2021).

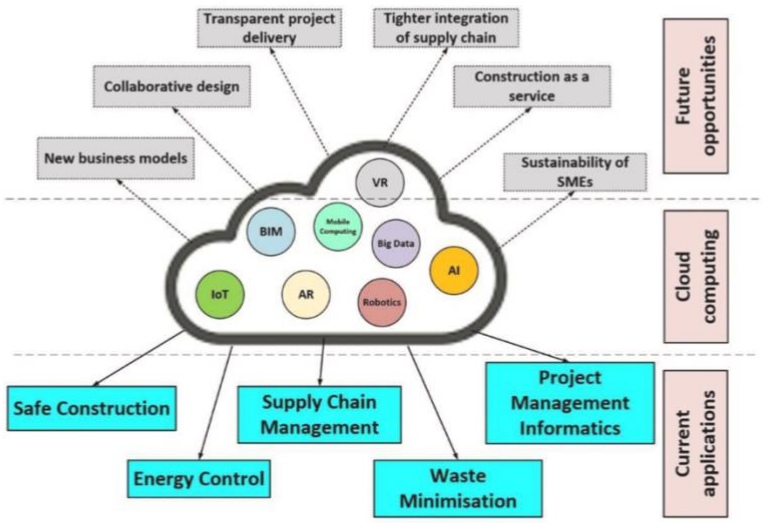

Figure 10. Existing and Future Applications of Cloud Computing in Construction Industry by Bello et al (2021, p. 10).

Considering the sustainability impact of the project, Bello et al (2021, p. 9−10) state that cloud computing provides a safer construction environment, better control of energy, and waste minimization of construction projects, which all contribute to several SDGs. The future opportunities also present this by enabling tracking and enhancing sustainable development of small and medium-sized enterprises (SMEs) which often do not have the opportunity to concentrate on that aside from the core business. The holistic delivery of more transparent projects also enables higher awareness and better adjustability of all the stakeholder actions as Bello et al (2021, p. 10−11) conclude. Cloud computing being a digitalization enabler, will be in this study representing the focus area of digitalization which among the assessment of sustainable development will be made.

2.2.4 Standardization

Standardization of BIM in infrastructure construction, as in any subject, provides common guidelines on working and developing according to BuildingSMART Finland (2022). Industry Foundation Classes (IFC) "…is the common data structure definition of building information models" as BuildingSMART Finland (2022) presents it, which are defined in the ISO 16739 standard by the International Organization of Standardization (2018). Another key standard of BIM is the European Committee of Standardization's CEN/TC 442 Building Information Modelling, based on ISO 19650 standard of managing information over the whole life cycle (International Organization of Standardization, 2020; European Committee of Standardization, 2020).

In Finland, BuildingSMART Finland (2019) Common InfraBIM Requirements is the major guideline that also contributes to driving the international standardization further. To shortly introduce, the Common InfraBIM Requirements give practical guidance on how to structure the information of the models and what are the key elements of BIM. For this study's purposes, acknowledging the current key standards and guidelines give an opportunity on considering their future in terms of life-cycle sustainability assessment information, how that might be integrated into the standardization more comprehensively and how they are also impacting the SDGs.

2.3 Digitalization's impact on sustainability

With the political climate being driven to develop society in a more sustainable direction with more sustainable actions, public institutions are having increasing demands of proving their work towards sustainability objectives such as SDGs (Rodat, 2021, p. 33−35). As mentioned, key stakeholders in the infrastructure construction industry are clients, which most often are public institutions (Wojewnik-Filipkowska et al, 2021, p. 211−213). Thus, clients who maintain, renew, or build new infrastructure are being demanded to present their efforts on sustainability to the public crowd who eventually is giving a mandate for them to act (Rodat, 2021, p. 32−35). This is expected to lead to a situation, where the clients are favoring contractors and participants, who are proving their value creation not only through the cheapest construction bid, but also who can produce sustainably. As Hetemi et al (2020, p. 15−17) state, as digitalization is an aid for stakeholders to communicate better their sustainability efforts, do projects more efficiently and track their progress better, it may provide benefits and negative effects on the sustainability development.

Across the whole picture of digitalization of the global world, its impact on sustainability has become an increasingly studied area where for example Van der Velden (2018, p. 170) and Mantovani Ribeiro et al (2021, 243−247) conclude it to have major positive impacts on sustainable development due to efficiency optimization and organizational management enhancement, whereas McManus and Haughton (2020, p. 997−998) are stating that the production of technology such as smartphones, which are prerequisites for digitalization, is undermining the benefits of digitalization. Nikmehr et al (2021, p. 7−9) consider one harmful side of digitalization in infrastructure projects to be its poor adoption at the strategic level, leading to unrealized benefits in terms of efficiency, but increased use of time to facilitate digitalization. According to them, to reach digitalization’s potential in driving sustainability, the organization is required to make a comprehensive change in its management protocols. When applied correctly, it is seen as “a leveraging tool” that enables better productivity and drives sustainable development toward the SDGs as stated by Hetemi et al (2020, p. 15−17). To understand digitalization’s impact on sustainability in infrastructure construction, key methods for assessing sustainability need to be explored. Thus, the next chapters provide insight into key sustainability assessment concepts around the industry.

2.3.1 Life cycle assessment theory

Life cycle assessment, LCA, is an often-used method for assessing the sustainability impact from a life cycle perspective, also applied often in infrastructure construction projects (Buyle et al, 2013, p. 380−382). LCA is being applied to come up with enlarged awareness of the possible actions that can be taken to mitigate harmful outputs of producing systems (Guinee, 2001, p. 4). LCA framework is standardized in ISO 14040 and has been specified in four steps defining goal and scope, analyzing inventory through existing data inside system boundaries, assessing the impact, and interpreting the results (International Organization of Standardization, 2006). A simplified visual form of the framework by Guinee (2001, p. 4) is presented in Figure 11.

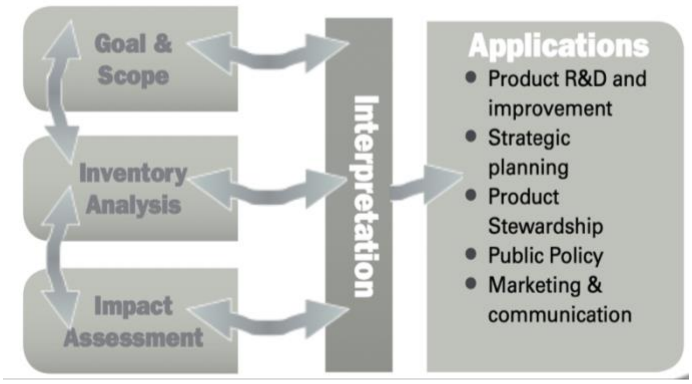

Figure 11. LCA-framework (Guinee, 2001, p. 4).

Though LCA is a holistic approach on a system life cycle level, it may also be applied to more niche parts of the system, as the main core of the framework with these four steps remains (Guinee, 2001, p. 4−6). The quality of the assessment depends highly on the inventory data available, which determines how many assumptions are needed to be made. The assumptions that are made due to the lack of data that provides a more accurate model of the world, lead to a situation where the impact cannot be assessed in such depth. Thus, the increasing amount of data emerging from technological advancement may provide an opportunity for LCA in terms of better inventory analysis and eventually higher accuracy of impact assessment as Mantovani Ribeiro et al (2021, 243−247) state. Thus, this study's interest is to not only acknowledge the framework of LCA in the sustainability assessment but also explore the opportunities that digitalization may provide for the development of LCA in the infrastructure construction industry.

2.3.2 Triple bottom line and sustainable innovation

According to Kouaib et al (2020, p. 1−2) and Mansell et al (2020, p. 44−48), TBL has been one of the most popular approaches for discussing the performance of sustainability development. It divides sustainability into three pillars: economical sustainability, elaborating whether the actions are economically sustainable, thus using the financial resources efficiently and minimizing the waste of procedures; social sustainability, focusing on the perspective of people both on a personal level of a human and societal level; and environmental sustainability, which aims to measure how are we impacting the planet in every level from global and areal to a single form of life. Furthermore, these pillars are being defined as three dimensions of sustainability (3P) as Kouaib et al (2020, p. 1−2) present: profit (economic), people (social), and planet (environmental).

Many concepts and frameworks around sustainability are attached to TBL, as SDGs in Figure 4 and sustainable innovation as examples (Weidner et al, 2021, p. 141 & Mansell et al., 2020, p. 45). Sustainable innovation considers innovation through trade-offs made in TBL, which aims on optimizing the sustainability of the innovations. According to Weidner et al (2021, p. 141−142) and Bauer et al (2021, p. 4012−4014), this trade-off in TBL means, for example, that innovation should pursue environmental integrity but not without acknowledging the economic impact of this, in other words not sacrificing the economic wellbeing in the pursuit. During this study, we will consider the sustainability impact of the approach of TBL mixed with SDGs and consider digitalization’s ability to not only function as a sustainable innovation but also how it enables and fosters sustainable innovation.

2.3.3 Sustainable development goals

UNs SDGs are among TBL very often used as a basis for measuring the sustainability impact, as they provide common goals, which when being pursued are making us work towards a balance of TBL sustainability (United Nations, 2020). There is a total of 17 SDGs divided into 169 targets with their multiple indicators that are being also applied to commercial life increasingly according to Bauer et al (2021, p. 4011−4016). Many investment funds and institutions value businesses that impact the SDGs positively higher according to Park and Jang (2021, p. 18−20). Thus, providing evidence for SDG impacting work and SDG-driven sustainable innovation should be increased in the interest of companies. The goals are presented in Figure 12.

Figure 12. Sustainable Development Goals by United Nations (2020).

For guiding toward SDG-driven work and innovation, these goals are being reframed often in different subjects for them to be more subject-related and easier to understand (Batalhone & Clement, 2018, p. 15). Different standards and certificates provide the subject-related objectives that eventually are leading to alignment with the SDGs and to TBL-based sustainable development. As mentioned in chapter 1.2, this study's assessment of the sustainability impact of digitalization in infrastructure construction aims to connect the perceived sustainability impact to the SDGs.

2.3.4 Standardization and certification of sustainability assessment

Sustainability assessment has various international and European standards, to guide the work towards a direction that is aligned with SDGs. Particularly in civil engineering work which concentrates on infrastructure construction, assessing sustainability has been standardized in ISO 21931, aiming to "bridge the gap between regional and national" methods for assessment as International Organization for Standardization (2019) states. Alongside standards, different methods of sustainability assessment frameworks that provide certification are being developed. In Europe Building Research Establishment's (BRE) Environmental Assessment Method (BREEAM) has been a popular certification for the built environment (Griffiths et al, 2020, p. 20−23). BRE has furthermore accompanied with emerged their certification with the CEEQUAL certification concentrating on civil engineering projects.

Eventually, these subject-specific certifications, standards, and frameworks form a broad collection of drivers and guidelines for sustainability development in constructing infrastructure. The requirement for acquiring these certifications though lies in the hands of clients, as the instances participating in the construction of the industry hardly are willing to acquire certification that provides value for their business as Griffits et al (2020, p. 22-23) analyze. The drivers for their decision-making though, as being elucidated by Rodat (2021, p. 30−35) and Wojewnik-Filipkowska et al (2021, p. 211−213) are emerging from the public opinion, that is requiring sustainable actions and evidence of them. In the context of this study the digitalization's impact on the sustainability of infrastructure construction, and the opportunity for stakeholders to acquire these certifications through using digitalization will be discussed.

2.3.5 CEEQUAL certification

As mentioned, CEEQUAL certification is one of the most common certification frameworks for assessing sustainability in civil engineering projects, thus, elaborating its background and principles is important for the research (Griffiths et al, 2020, p. 20-22). It is specifically concentrating on assessing "…construction of new assets and refurbishing of existing assets" as clarified in BRE Group (2022b, p. 12-13) CEEQUAL manual version 6's scope. CEEQUAL version 6 can assess phases of strategical planning, designing, and construction implementation either separately or as a whole project entity.

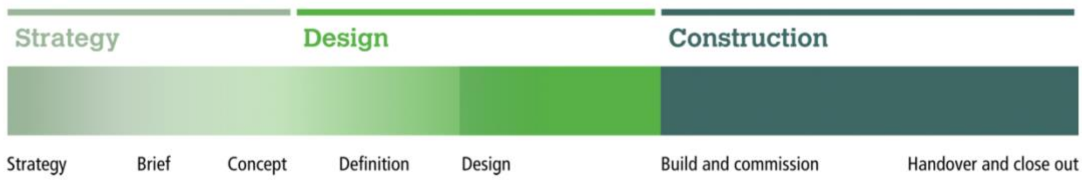

Figure 13. Assessment stages in CEEQUAL version 6 against typical construction project phases (BRE Group, 2022b, p. 13).

Figure 13 presents the phases of an infrastructure construction project. The CEEQUAL assessment eventually provides CEEQUAL version 6 ratings that are ranked through percentual overall scores (BRE Group, 2022b, p. 16). For example, over 90% overall score is considered "Outstanding", between 75% and 89% as "Excellent" and lower than 30% is considered "Unclassified". Furthermore, CEEQUAL version 6 presents minimum standards that must be met to be granted the final rating. These standards are built to ensure that any "…fundamental issues are not being overlooked in the achievement of specific ratings".

Category	Assessment issues
1 Management	1.1 Sustainability leadership
	1.2 Environmental management
	1.3 Responsible construction management
	1.4 Staff and supply chain social governance
	1.5 Whole life costing
2 Resilience	2.1 Risk assessment and mitigation
	2.2 Flooding and surface water run-off
	2.3 Future needs
3 Communities and stakeholders	3.1 Consultation and engagement
	3.2 Wider social benefits
	3.3 Wider economic benefits
4 Land use and ecology	4.1 Land use and value
	4.2 Land contamination and remediation
	4.3 Protection of biodiversity
	4.4 Change and enhancement of biodiversity
	4.5 Long-term management of biodiversity
5 Landscape and historic environment	5.1 Landscape and visual impact
	5.2 Heritage assets
6 Pollution	6.1 Water pollution
	6.2 Air, noise and light pollution
7 Resources	7.1 Strategy for resource efficiency
	7.2 Reducing whole life carbon emissions
	7.3 Environmental impact of construction products
	7.4 Circular use of construction products
	7.5 Responsible sourcing of construction products
	7.6 Construction waste management
	7.7 Energy use
	7.8 Water use
8 Transport	8.1 Transport networks
	8.2 Construction logistics

Figure 14. Categories of CEEQUAL assessment (BRE Group, 2022b, p. 11).

As Figure 14 presents, for calculation of the CEEQUAL scoring in version 6 has components of “Category weightings”, which gives a higher value for issues that are considered more vital and assessment credits, which are considered topic by topic (BRE Group, 2022b, p. 11-12). The categories will include furthermore subcategories as assessment issues, where the sustainability will be assessed topic by topic, and credit scores will be given. Ultimately, the score will be calculated by multiplying the credit score by category weight. In this study, CEEQUAL version 6 will be explored and used in the phases of research methodology design and discussion.

2.3.6 CO_2e databases

As the calculation of GHG emissions is vital for assessing the environmental level of sustainability, collection of CO_2e values in common public databases has been emerging, to represent the GHG emissions per selected unit (Krantz et al, 2015, p. 1165−1168). For the construction industry, one common database used in Finland has been the CO2data-service provided by the Finnish environment center (SYKE, 2022). It aims to provide researched values for each material used often in construction projects and to include complete lifecycle values for each material.

CO2data does not yet include specified infrastructure construction GHG emission calculation unit values, but several components that are being used in building construction are being applied to infrastructure projects also (SYKE, 2022). For instance, major materials applied in infrastructure construction such as asphalt, concrete, and cement have specified values in CO2data. Another database that aims to be holistic, impartial, and consider lifecycle value is the International Panel of Climate Change's, IPCC's, Emission Factor Database, EFDB (EFDB, 2020). As an international organization, IPCC aims this database to function as the central database for all databases providing more in detail information such as CO2data. For purposes of this study, both IPCC's EFDB and SYKE's CO2data will be applied to provide CO_2e emission factors.

2.4 Emission sources in infrastructure construction projects

In infrastructure construction projects, the vast majority of the GHG emissions are emerging from the usage of construction materials, usage of machinery and the reduction of the carbon sinks according to Karlsson et al (2020, p. 19-21). Machinery emissions have been divided between the use of machinery in construction processes ("Working machinery" in Figure 15) and the use of machinery in the transportation of the construction masses ("Material transportation" in Figure 15). The emissions of machinery use are emerging primarily from fuel consumption. Figure 15 divides emissions from the use of material into cement-based products such as concrete, the steel used for reinforcement and construction of the structures, asphalt used for remolding of the asset, and other minor materials. Land use change, hence in this framework, the decrease of forest and such environmental elements that have carbon containment properties.

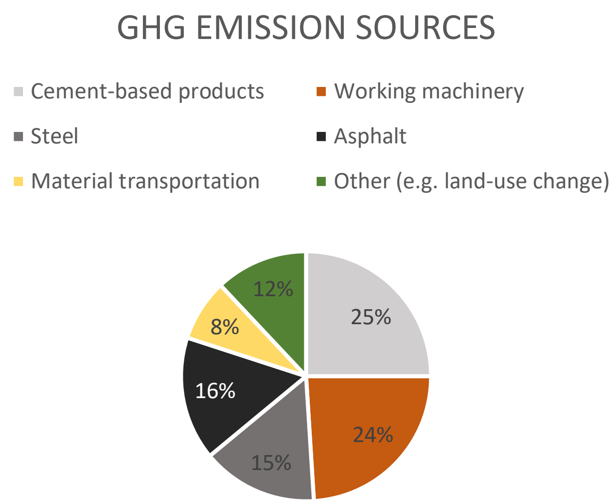

Figure 15. GHG emission sources of an infrastructure construction project adapted from Karlsson et al (2020, p. 19-21).

As Figure 15 presents, the use of material corresponds to 64% of transport infrastructure construction GHG emissions according to Karlsson et al (2020, p. 18-22) whereas machinery use emits 32% of total emissions, and 12% originates from other sources such as other materials and changes in the use of land. However, land-use change GHG emission impact is not as straightforward concept as other sources which literally emit GHG rather than impacts through reduction of carbon sequesters. For this study's purpose these values in general, state the approximations of the major GHG emission sources.

2.5 Theoretical reviews

After the theoretical background has been explored thoroughly, a coherent conclusion on the core issue between sustainable development and infrastructure construction can be constructed within the framework of digitalization's impact on their relationship. As Figure 16 represents, from exploring prior literature within the field of sustainable development it can be identified that to achieve the UN's SDGs, various solutions are required to be developed (United Nations, 2020, & Weidner et al, 2021). Digitalization has been identified to have the potential to act as one of the key fields of solutions, which may aid different industries to enhance their sustainable development (Van der Velden, 2018, & Mantovani Ribeiro et al, 2021).

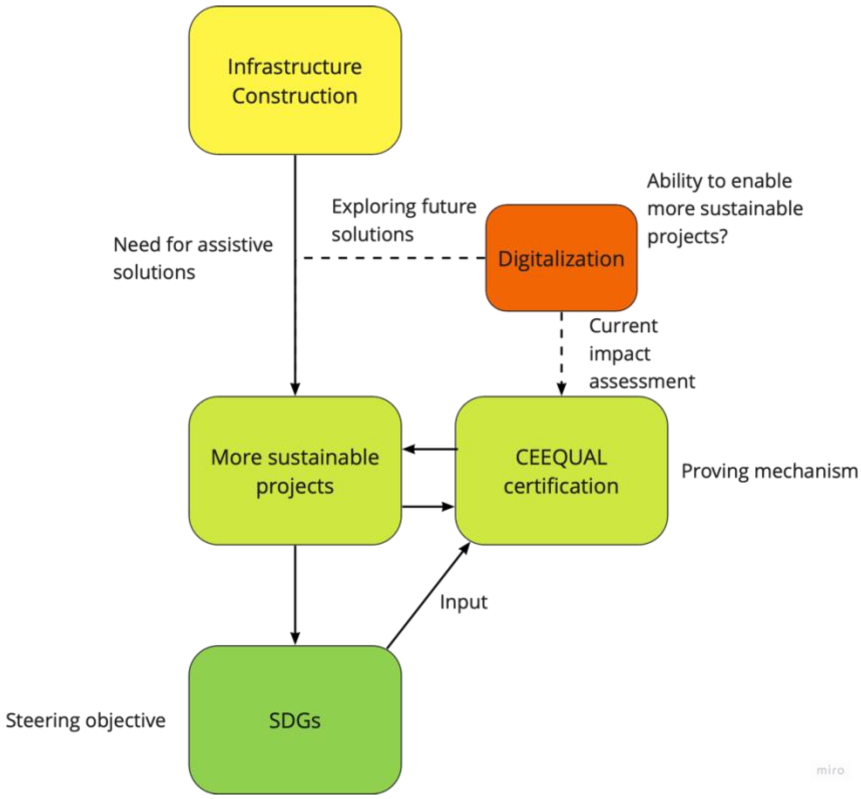

Figure 16. Core issue to be researched constructed from the review of literature.

What emphasizes the necessity of assessing the impact of digitalization specifically in the infrastructure construction industry's ability to enhance sustainable development, is the researched major impact of the industry on the global potential of achieving the established SDGs (Mansell et al, 2020). To construct an industry-relevant assessment it seems coherent to evaluate the impact via its effects on well-established standards which have been constituted to prove the impact on sustainable development, in this context CEEQUAL as Figure 16 presents (Batalhone and Clement, 2018, & Griffiths et al, 2020). It is also favorable to assess the impact through a stakeholder perspective within the project execution level, as there is starting to be already entrenched use of digitalization within Nordic Countries, and there is already evidence of positive impacts from an institutional point of view (Goger and Bisenberger, 2020, & Hetemi et al, 2020). Additionally, several studies identifying the potential to develop digitalization solutions to model GHG emissions of projects establish a favorable opportunity to explore future solution opportunities (Karlsson et al, 2020, & Krantz, 2019).

3 Methodology

This chapter presents the methodology of the study, and it is an explanatory chapter of the design of the research. To achieve the purposed state where the assessment of digitalization's impact on sustainable development can be made, the survey methodology will provide quantitative results to be analyzed with deductive reasoning. With this methodological approach, the RQ1 is expected to have an answer within the scope of the study. Construction of the survey includes exploratory phases Furthermore, the systematic design of a data model and the case project where it will be tested at a proof-of-concept level will be elucidated. This data model and the exploration of the data during the design phase aim to provide an answer to research question 2 by being a qualitative case study.

3.1 Data collection

The data for this research was collected within the email list of the case company, which consists of stakeholders applying the digitalization solution of the case company. This group consists of the same stakeholders that were evaluated to be the most central within this framework in chapter 2. Eventually, the data collection process will be as presented in Figure 17.

Figure 17. Survey design process of the study adapted from Fowler Jr. (2008, p. 4-6).

3.2 Data analysis

The approach for the data analysis followed principles of quantitative inquiry and eventually was an iterative process, where different causalities and entireties were identified. As the questions were identified through exploring the CEEQUAL certification and SDG correlations, some of the questions' grouping were constituted in forehand, to have the opportunity to identify contingencies, correlations, and causalities. The data was furthermore connected to existing theories within the field. The results of the analysis will be elaborated in chapter 4 and a discussion from their basis furthermore will be done in chapter 6.

3.3 Designing the data model

The data model will be designed to provide general insight into how existing and emerging data in Infrakit could be applied to modeling the GHG emissions of a construction project to provide answers for RQ2. The systematic design process will be conducted by applying Wasson's (2015) system design principles for recognizing the key requirements of the stakeholders and thus planning and designing the data application and modeling methods to achieve a stage where the information model can provide further product development a validated knowledge on which kind of decision-making supportive information should be provided.

The process of the data model design will follow Wasson's (2015, p. 703-710) principles of designing a system to a certain degree, simplifying the steps to match the scope of this study. Wasson's system engineering principles begin by defining and allocating the requirements of the system. After this phase, the model is constructed, and its functionality simulated. Wasson's steps 2 and 3 are the validation of the model, which requires iterative work with moving back and forth within all the prior steps of the process. Finally, step 4 four conducts a fidelity analysis, which aims to provide information about the model's applicability to real-life scenarios.

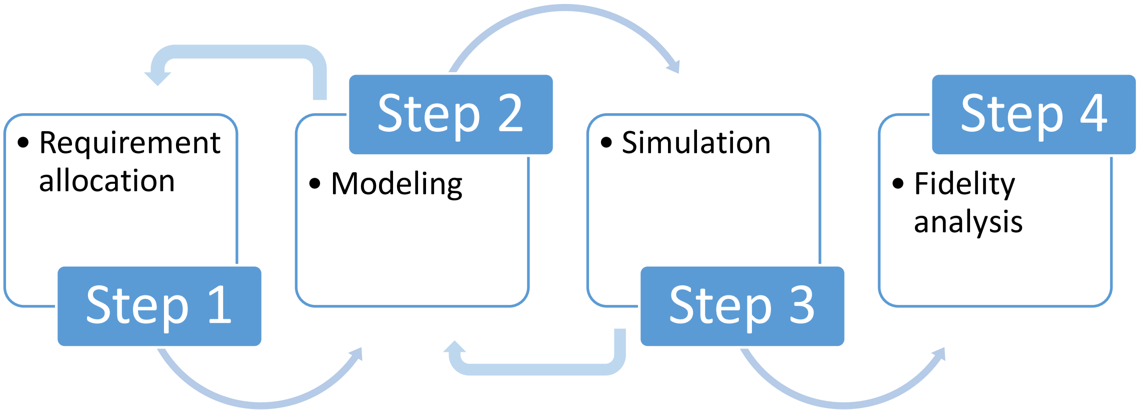

Figure 18. Information model designing process adapted from Wasson (2015, p. 703-710).

As Figure 18 presents, the design process should be iterative, only excluding the fidelity analysis due to the limitation of the study objective to construct a proof-of-concept level data model. Furthermore, the future opportunities of the model and use of the data will be explored in the discussion phase of the study. The modeling and simulation phases will require a case project to provide relevant data to be explored and a model to be tested.

4 Results

This chapter will analyze and discuss the results of the survey, and thus evaluate the perceptions of the stakeholders according to the RQ1. This chapter will also elaborate on and consider the perceived sustainability impact of digitalization and how it may aid stakeholders in the pursuit of acquiring certifications such as CEEQUAL.

The survey received a total of 112 respondents from various stakeholders. The most represented stakeholder segment in the survey were foremen, site managers, supervisors, and project managers either from clients or contractors with over 25% of the respondents. The second most represented were BIM coordinators or project engineers. Figure 19 visualizes the distribution of the stakeholders in the survey.

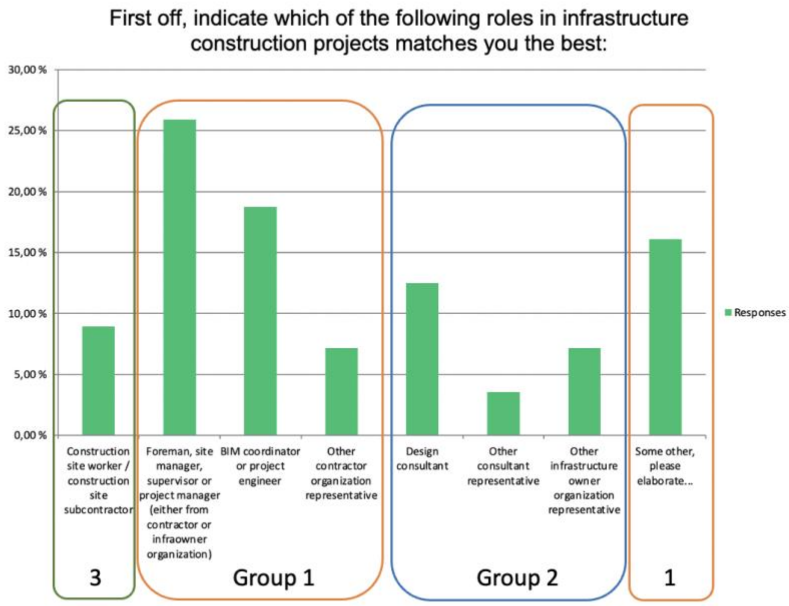

Figure 19. Distribution of the survey respondents by stakeholder group.

The distribution can be seen to represent well all the identified stakeholders that are the most relevant in the context of digitalization in the construction phase of infrastructure construction projects. Furthermore, the exact number of respondents can be viewed in Appendix 4. The next chapters will elaborate on the results and analyses of the questions designed specifically for each stakeholder group. Stakeholders as elaborated in the theoretical background, were grouped, and given separate sets of questions. These groups are presented in Figure 19.

4.1 Stakeholder group 1

Stakeholder group 1 was seen to have a managing role in the construction phase's processes. Their responsibility is to guide and lead the work, having the information of the project as a central source for decision making. They were given a total of 14 questions covering the four main themes of "Safe and healthy working environment", later referred to as theme 3, "High quality of work and efficient use of resources", theme 4, "Transparent projects and good communication", theme 2, which were considering social sustainability in different angles and "Environmental sustainability of projects", latter theme 1, which was considering the environmental sustainability of the projects. The first question aimed to measure the perceived importance of each main theme from the stakeholder group's point of view.

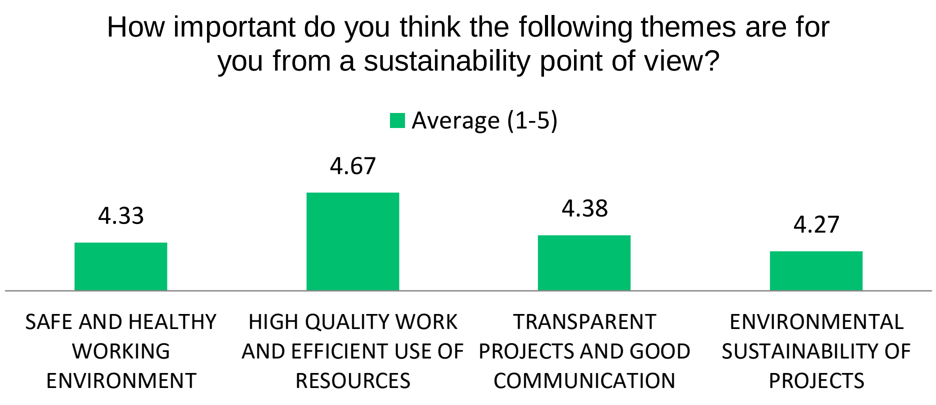

Figure 20. Stakeholder group 1 question 1 results

The importance of measuring differed from the measuring of the impact, which was presented in Figure 20, by having a scale of 1 to 5. On this scale, 1 had a value of “Not important”, 2 “Little important”, 3 “Moderately important”, 4 “Important” and 5 “very important”. From Figure 22 it can be observed that all the main themes of sustainability were perceived as important by the stakeholder group 1 respondent, with all the themes exceeding the average of 4. Minor differences can be discovered among the topics, as “High-quality work and efficient use of resources” obtained the highest average of 4,67 whereas “Environmental sustainability of projects” received an average of 4,27. However, the differences between the topics seem to be rather small, whereas the perceived importance of each of the topics is high. After question 1 measured the importance of each of the sustainability topics, further questions measuring the perceived impact were divided into one of the four themes. Questions 2 to 6 were about “Environmental sustainability of the projects”, 7 to 9 about “Transparent projects and good communication”, 10 to 11 about “Safe and healthy working environment”, and 12 to 14 about “High-quality work and efficient use of resources”. The designed questions for stakeholder group 1 can be found in detail in Appendix 4.

4.1.1 Environmental sustainability of projects

Importance of this sustainability theme was perceived as “important” with an average score of 4,27. Additionally, in CEEQUAL scoring, categories 1 “Management”, 4 “Land use and ecology, 6 “Pollution”, 7 “Resources” and 8 “Transport” are especially considering environmental sustainability impact and actions that affect it as the Figure 14 presents (BRE Group, 2022b, p. 11). In the question number 2 the environmental impact perception can be analyzed through the digitalization’s ability to assist the planning and communicating the use of landmasses of the project.

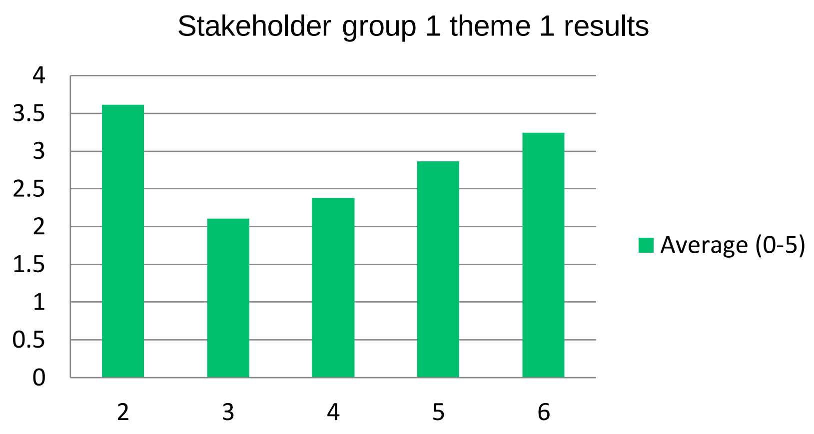

Figure 21. Stakeholder group 1 theme 1 results

The efficient and responsible use of landmasses is especially important in the CEEQUAL category 4, and it impacts category 7 greatly as well, due to the use of energy in the material transportation operations (BRE Group, 2022b, p. 10-12). As Figure 21 presents, stakeholder group 1 perceived digitalization to have a somewhat high impact on the planning and communication of the use of landmasses, as the average score is given was 3,6.

Question 3 was designed to measure the perceived impact of controlling air pollution. Air pollution control is part of environmental sustainability in the sense of protecting biodiversity and has its own category, number 6, in the CEEQUAL manual (United Nations, 2020 & BRE Group, 2022b, p. 11). As Figure 21 presents the average score of 2,1 is indicating that the impact of digitalization on the air pollution measuring and controlling is perceived to be low as the value of 2 indicates "Low impact".

Question 4 aimed to measure the perception of digitalization's ability to impact the awareness of fuel consumption. Being aware of the fuel consumption is an important factor to enable managers of the project to adjust and optimize the operations and their environmental impact as Krantz states (2019, p. 13-16). Awareness of the critical phases in terms of fuel consumption will enable better ability to focus on those construction phases with higher accuracy. CEEQUAL manual considers this matter, especially in category 7. As Figure 21 presents, an average score of 2,4 was responded, indicating that digitalization is perceived to currently have an impact between low and relevant. Digitalization's lack of ability to aid fuel consumption measurement might be stated by this score and as new, more strict requirements for tracing the fuel consumption of projects are emerging in agreements such as the Green deal, this could become one of the future priorities in the development of digitalization solution (Ministry of Environment, 2022).

Question 5 had an objective to measure the perceived impact of tracking and planning the use of recycled materials. The use of recycled materials and enabling it by tracking them provides an opportunity to decrease the material GHG emission impact (Krantz, 2019, p. 13-16). Applying methods that are proven to reduce GHG emissions is considered in category 7 of the CEEQUAL certification (BRE Group, 2022b). As Figure 21 presents, respondents scored this impact with an average of 2,9, indicating that the impact is seen as relevant.

In question 6 the aim was to tap into the stakeholder group's perception of how digitalization has enabled them to track and plan mass hauling and material transportation on the worksite. Tracking and planning of machinery operations optimize and thus reduce the use of machinery, leading to a decrease in GHG impact from mass hauling and material transportation machinery, thus the question slightly differentiates from question 2 (Krantz, 2019, p. 13-17). As Figure 21 presents, digitalization is perceived to have a relevant impact with an average score of 3,2.

4.1.2 Transparent projects and good communication

The theme of "transparent projects and good communication" impacts particularly the social sustainability of projects. Importance of this theme by the stakeholder group 1 was perceived to be "important" with an average score of 4,38. The survey consisted of 3 questions for this theme in this stakeholder group.

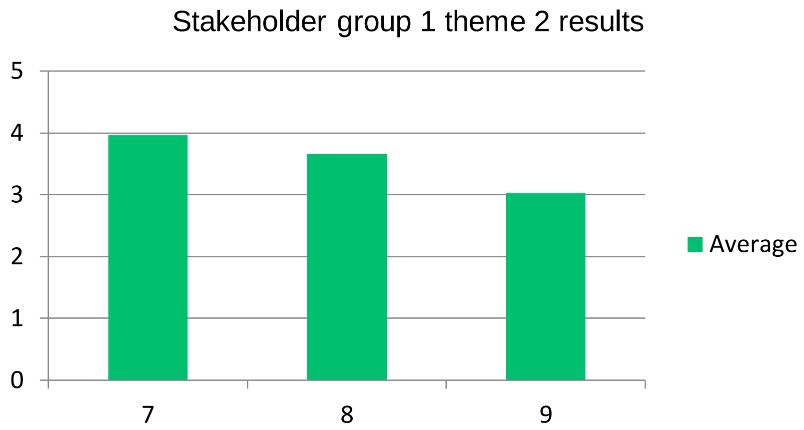

Figure 22. Stakeholder group 1 theme 2 results

Question 7 is purposed to elaborate the stakeholder insight on how digitalization has enabled them to share information such as visual progress or statistics of the project to civil society such as civil council representatives or local habitants. Enabling this communication is an increasingly important aspect of social sustainability in infrastructure construction projects and is one theme in the CEEQUAL within category 3 "Communities and stakeholders" (BRE Group, 2022b). Figure 22 presents the average score of this question to be 4.0. Thus, according to the survey, stakeholders perceive digitalization to have a high impact on sharing the information with civil society, thus digitalization being able to increase the social sustainability of projects remarkably.

In question 8 the objective was to measure the stakeholder perception of how digitalization has aided them to communicate and lead the daily operations of work. For worksite efficiency and social sustainability amongst the employees, it is important to have this ability to ensure that the information flows correctly and on time in the worksite, reducing inefficiencies and frustration (Mansell et al, 2020). Furthermore, this contributes particularly to category 1 of the CEEQUAL manual. The results indicate digitalization to have a rather high impact on leading and communicating the daily work and the average importance score of 3,7 can be observed in Figure 22.

Question 8 aimed to measure the stakeholder information flow enablement impact of digitalization, and how it aids in complying with legal arrangements. For acquiring CEEQUAL certification, especially receiving high scores within the category and increasing the social sustainability of projects being able to share information through the supply chain is important, as it affects many of the categories, especially category 1 (BRE Group, 2022b). As Figure 22 presents, stakeholder group 1 representatives perceive digitalization to have a relevant impact on aiding this transparent information flow and legal compliance by achieving an average score of 3,0.

4.1.3 Safe and healthy working environment

The theme of a “safe and healthy working environment” impacts the social sustainability of projects, especially internal sustainability, and employee satisfaction. The importance of this theme was perceived to be important with an average score of 4,33. The survey consisted of 2 questions for this theme in this stakeholder group.

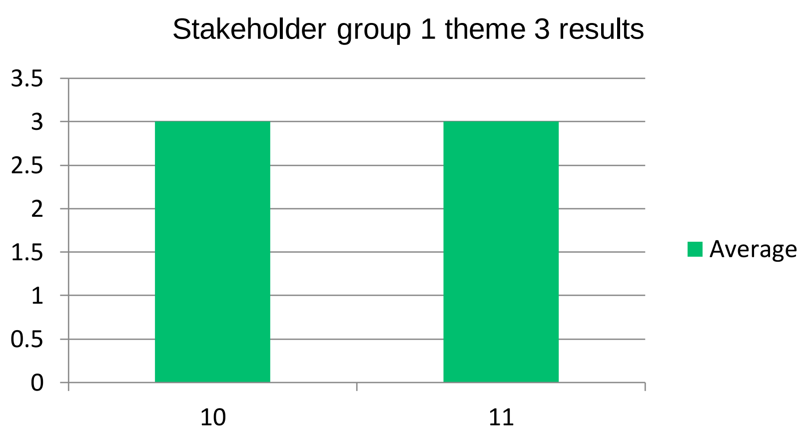

Figure 23. Stakeholder group 1 theme 3 results

Question number 10 measures the perceived digitalization impact on health and safety risk reduction of projects. CEEQUAL category 2 “Resilience” highlights the importance of assessing risks and mitigating them not only in environmental risks but as well in safety and health-related concerns (BRE Group, 2022b). Figure 23 presents the average score to be 3,0, indicating the impact of digitalization is perceived as relevant.

In question, 11 objective is to assess the perceived impact of digitalization on risk management and communication, for instance in certain work phases that require a specific delicacy. This serves as another social sustainability enabler and is part of category 2 of the CEEQUAL (BRE Group, 2022b). As Figure 23 visualizes, the average score of 3,0 indicates the impact to be relevant.

4.1.4 High quality work and efficient use of resources

The theme of “high-quality work and efficient use of resources” impacts both the social sustainability of projects and environmental sustainability, as the efficient use of resources mitigates GHG emissions and other harmful environmental impacts (BRE Group, 2022b). In CEEQUAL scoring, especially categories 1 and 7 are highly impacted by the ability to work with high quality and use resources efficiently. The importance of this theme was perceived to be very important with an average score of 4,67. The survey consisted of 3 questions for this theme in this stakeholder group.

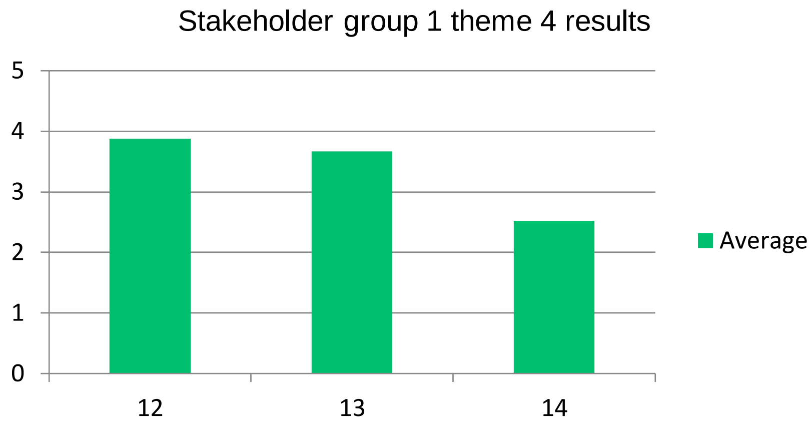

Figure 24. Stakeholder group 1 theme 4 results

Question number 12 measures digitalization’s ability to aid the quality controlling of projects, for instance how it provides real-time information and continuous control. These traits enable the project to deliver increased quality of construction and use of decreased amounts of materials and work (Krantz, 2019, 13-17). As Figure 24 presents, stakeholders perceived digitalization to have a high impact on aiding the control with an average score being 3,9.

Question 13 aims to tap into digitalization’s perceived impact on the management of economical and time resources of projects. In terms of environmental sustainability, these are important, as reduced time and money used in projects are eventually deriving into reduced GHG emissions of projects as the CEEQUAL category 1 also presents (BRE Group, 2022b). Stakeholders perceive digitalization to have a relevant to high impact on aiding the management of these resources, giving it an average score of 3,7 out of 5 as visualized in Figure 24. Finally, the last question for stakeholder group 1 measured the digitalization’s perceived impact on tracking and achieving the project's sustainability objectives. Stakeholder group 1 perceived digitalization to have a rather low impact on this matter compared to other questions as the average was 2,5.

4.2 Stakeholder group 2

Stakeholder group 2 was discovered to have a supporting role in the construction phase, as they were affecting the construction projects more intensively in the previous phase of design and tendering, and in the later phase of maintenance and management. Although, as the stakeholder group consisted of design and other consultants of projects and other client representatives, in model-based construction projects information flows also during the construction phase to these stakeholders, for example when designers are set to update their designs or city council representatives are receiving status updates (Bradley et al, 2016, p. 139-142).

This stakeholder group was given a total of 7 questions covering two of the four main topics, with some of the questions adjusted to match their point of view. This stakeholder group only provided questions on themes “High-quality work and efficient use of resources” and “Transparent projects and good communication” as they were perceived in the workshop to have influence in the construction phase only on these themes. For the environmental questions, these stakeholders were envisioned to only receive the information on environmental impacts in this phase, rather than making any choices that impact the theme, thus belonging to the theme of “Transparent projects and good communication”. Even though design consultants design to have a major impact on the environmental aspect and safety of projects, these effects were scoped to belong to the design phase, and thus are not to be included in this study.

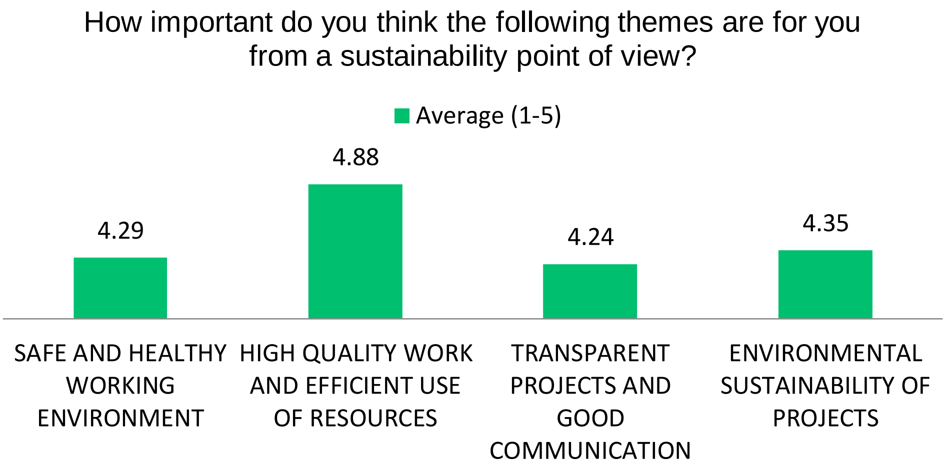

Figure 25. Stakeholder group 2 question 1 results

From Figure 25 it can be envisioned that all the main topics of sustainability were perceived as important also by stakeholder group 2 respondents as it was with the group 1, by all of them exceeding the average of 4. Minor differences can be discovered among the topics, as "High-quality work and efficient use of resources" obtained the highest average of 4,88 whereas "Transparent projects and good communication" received an average of 4,24. However, the differences between the topics seem to be again rather small, whereas the perceived importance of each of the topics is very high. Further questions designed for this stakeholder group are elucidated in Appendix 5.

4.2.1 Transparent projects and good communication

In the theme "Transparent projects and good communication" the stakeholder group represents an important opinion, as the stakeholders of this group include the operating personnel reporting to the city council and other society members. This theme is connected to CEEQUAL category 3 and thus is important information, as it is often representatives of this stakeholder group who are pursuing the certification (BRE Group, 2022b).

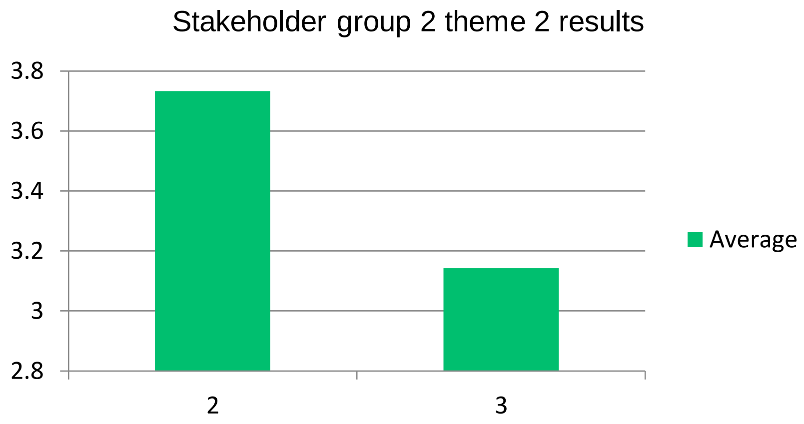

Figure 26. Stakeholder group 2 theme 2 results

Question 2 for this stakeholder group measured their perception of how digitalization has aided them to share visual information about the progress to civil society. It is the exact same question as to the stakeholder group 1 question 7. This stakeholder group gave a slightly lower score to this question, the average being 3,7 as presented in Figure 26, whereas stakeholder group 1 perceived gave it an average score of 4,0. Nevertheless, this stakeholder group as well seems to evaluate digitalization to have high importance in sharing the information for civil society.

In question 3 for the stakeholder group, 2 digitalization's perceived impact on transparent information flow was measured as it was in question 9 for the stakeholder group 1. As Figure 26 presents, stakeholder group 2 perceived digitalization to have a relevant impact on transparent and sustainable information flow with an average score of 3,1, as did also stakeholder group 1 with an average of 3,0. The transparency of information in infrastructure projects though does not always serve the benefits of a business as Weidner et al (2021, p. 139−142) and Bauer et al (2021, p. 4011−4014) present, thus perceiving digitalization to provide help or in some cases mitigate former business opportunities, can be a complex dilemma and depends on the point of view.

4.2.2 High quality work and efficient use of resources

In the theme “High-quality work and efficient use of resources,” this stakeholder group has its impact, as these supportive role stakeholders are impacting the pace and quality of the project. This theme is very connected to CEEQUAL categories 1 and 7 (BRE Group, 2022b). Furthermore, comparing this set of questions to the stakeholder group 1 perceptions is meaningful.

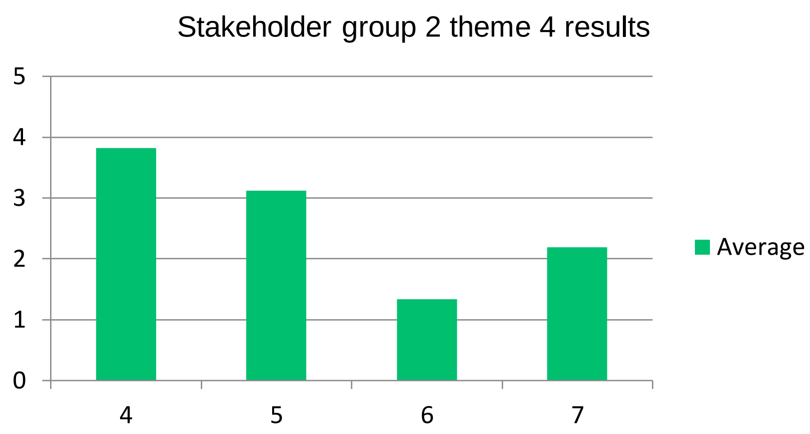

Figure 27. Stakeholder group 2 theme 4 results

In question number 4 of stakeholder group 2, the perception of digitalization's impact on quality control is measured. Figure 27 represents the average score of perceived impact of digitalization, which being 3,8 indicates digitalization has a high impact on quality control. Compared to the similar question 12 of the stakeholder group 1 having an average of 3,9, it seems that the stakeholder groups are quite aligned with their perception.

Question 5 for stakeholder group 2 measured the digitalization perceived ability to assist the management of economical and time resources of a project. Similar to stakeholder group 1 was question 13. Stakeholder group 2 gave an average score of 3,1 indicated in Figure 27, whereas stakeholder group 2 scored with an average of 3,7. It can be evaluated that digitalization thus has had a much higher impact on the construction project managers who are closer to the daily operations of the project, whereas the supportive stakeholders who manage the project are not perceived to have yet such high assistance from digitalization in the management of these resources.

Question number 6 for stakeholder group 2 measured the perceived ability of digitalization to aid the tracking and planning of the use of recycled materials in the project. This question being in the environmental category for stakeholder group 1, it was seen to belong to the resource usage category for this stakeholder group, as these stakeholders are not directly influencing those operations but rather through tendering of the contractors or by the designs they make. As Figure 27 shows, digitalization was perceived to have a very low impact on the tracking and planning of the recycled materials amongst this group of stakeholders. It may just indicate, that either these stakeholders are not necessarily required to be involved in the process or they are not able.

Final question for stakeholder group 2 was the same as the last one for group 1, measuring the holistic tracking and achieving of the project’s sustainability objectives and how digitalization is aiding that. As the Figure 24 and Figure 27 present, as well the stakeholder group 1, perceived it to have a low impact with an average of 2,5, group 2 also saw it to have a rather low impact on supporting the tracking and planning of the sustainability objectives, as the average score was 2,2. Especially with stakeholder group 2, which consists of stakeholders of clients, it might important to be able to track and achieve these objectives with the help of digitalization, as it is increasingly popular and almost mandatory for public instances to have their sustainability objectives planned out and furthermore to prove whether they are achieved or not (Rodat, 2021, p. 30−35).

4.3 Stakeholder group 3

Stakeholder group 3 was seen to have a central operative role in the construction phase, as it includes workers on the site either as contractor employees or subcontractors. They were given a total of 3 questions covering the three main topics of “Safe and healthy working environment”, “High quality of work and efficient use of resources”, and “Transparent projects and good communication” which were considering social sustainability in different angles. Environmental sustainability of projects was not directly asked about in the survey, as it was decided in the survey design workshop that the “High quality of work and efficient use of resources” itself provides the central information of the perception of this stakeholder group on environmental sustainability. The questions were adjusted according to this stakeholder group to match their daily operations and thus to provide the highest quality of results ad Fowler jr. (2008, p. 4-6) advice.

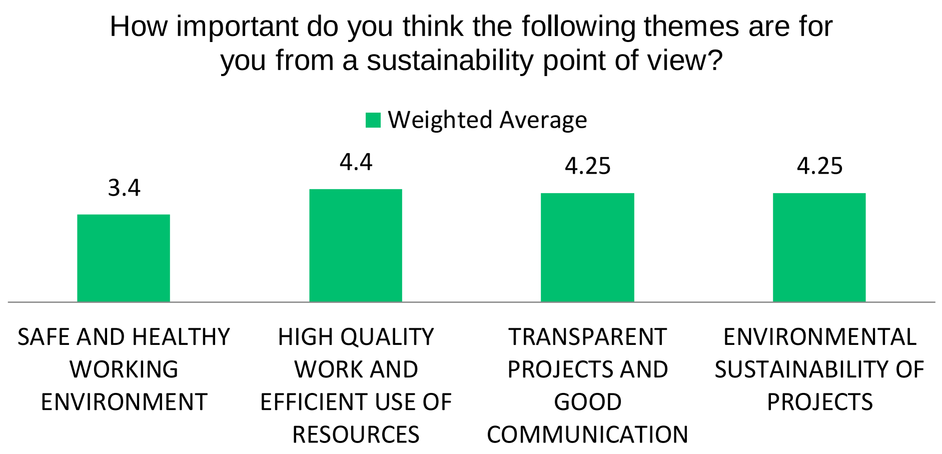

Figure 28. Stakeholder group 3 question 1 results

Figure 28 represents the perceived importance of each sustainability theme from the perspective of stakeholder group 3. Three of the main themes of sustainability were perceived important by the stakeholder group 3 respondents, all of them exceeding the average of 4, and the “Safe and healthy working environment” theme acquired an average importance score of 3,4 which can be interpreted as rather moderate importance than important. Theme 4, “High quality work and efficient use of resources” was valued to have the highest importance among the themes. These other two questions are elaborated on in Appendix 6.

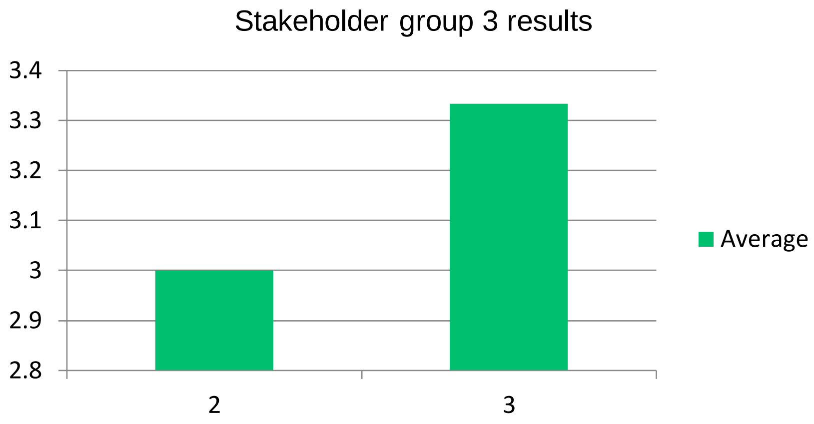

Figure 29. Stakeholder group 3 results

Question 2 for stakeholder group 3 aimed to measure the perceived assistance in the reduction of mistakes provided by digitalization. For stakeholders' intentions to achieve sustainability certifications such as CEEQUAL, it is important to have processes and tools that mitigate the mistakes which furthermore may lead to increased use of fuel and workforce, as this is especially addressed in the categories 1 and 7 (BRE Group, 2022b). As Figure 29 represents, stakeholders perceive digitalization to have a relevant impact on the reduction of the mistakes in construction work, the average being 3,0.

In question 3 for stakeholder group 3, the objective was to measure the perceived assistance digitalization may provide in reducing health and safety risks in construction site workers' daily operations and being aware of them. As Figure 29 represents, stakeholders perceived digitalization to have a relevant impact on this sustainability topic, scoring it with an average of 3,3. Compared to stakeholder group 1, the score is slightly higher, though so little it may not be meaningful to assess the reason.

4.4 Compilation of the results

The purpose of the compilation analysis is to provide more analytical interpretations of the survey research results from a wider perspective and thus a more concluded answer to the RQ1. As the survey questions were derived from the CEEQUAL certification manual, the results could be furthermore concluded within the categories they impact. Many of the questions were providing information on the impact on various categories, thus when analyzing the impact on each category, it was seen as beneficial to recognize the number of questions affecting each category.

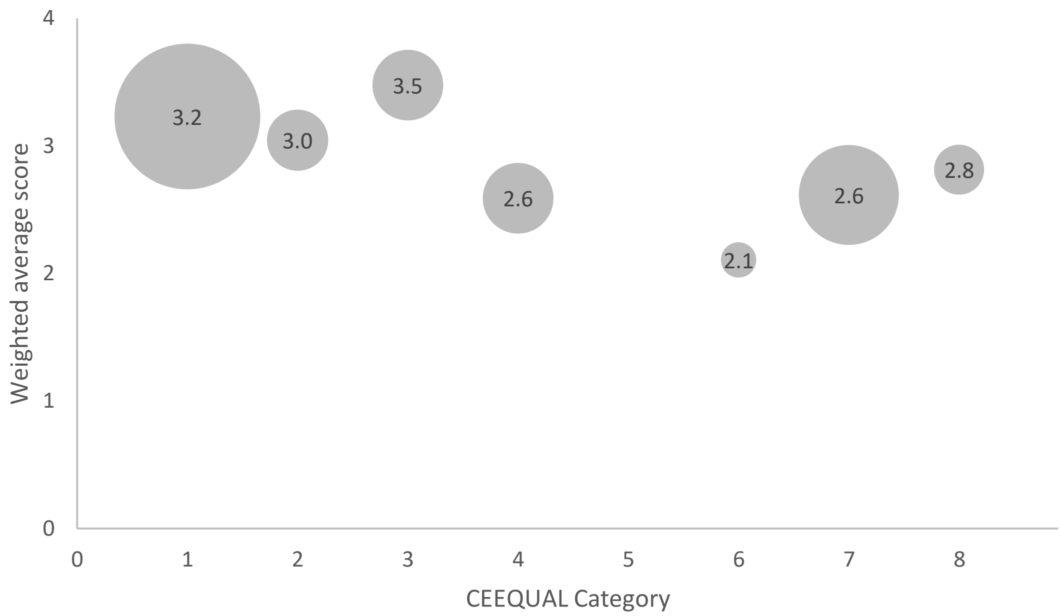

Figure 30. Digitalization impact on CEEQUAL categories.

As Figure 30 presents, to produce category-based analysis, the averages were calculated within the question results impacting the category. Furthermore, as there were three separate stakeholder groups, they were given weights according to the number of respondents. Finally, this analytical approach provided insight given in Figure 30, where it could be recognized that most of the questions were impacting the CEEQUAL category 1 “Management” in some manner (BRE Group, 2022b). Also, category 7 “Resources” was affected by many of the questions, whereas category 5 “Landscape and historic environment” was not affected by any of the questions. Also, category 6 “Pollution” was impacted only by one question, perhaps since digitalization was evaluated to have an opportunity in enabling measurement and modeling of the pollution rates, but not much further. This raises a question, how much was the forming of the survey questions affected and limited by the steering group and author's perspectives, knowledge, and imagination.

However, when analyzing the insights in Figure 30, it could be stated that digitalization might have the greatest potential impact on enabling sustainable management and resource efficiency of projects, for example by aiding supply chain governance as CEEQUAL subcategory 1.4 states, providing tools for sustainable leadership and environmental management which account for CEEQUAL categories 1.1 and 1.2, and furthermore providing tools for controlling resource efficiency of energy usage for example in transportation, as for instance, Krantz (2019) has estimated. When considering the current impact and where it is perceived to be the greatest, construction phase stakeholders seem to consider that digitalization impacts their ability to communicate with the communities and other stakeholders better, as the category 3's, "Communities and stakeholders" weighted average is 3,5. Also, assessing the risks, and taking care of the safety of the construction and personnel, have been perceived to be relevantly impacted by digitalization as the category 2 "Resilience", resulting in an average of 3,0. Furthermore, category 1 received the second-highest perceived impact of digitalization with an average of 3,2. Categories 4, 6, 7, and 8 received seemingly lower average scores, all of them being below 3,0. Though categories 4, 6, and 8 have fewer questions impacting their scores, the questions themselves could be stated to be more exact, as digitalization impact on these could be more tangible, such as measurement assistance. Thus, it could be perceived, that if digitalization is to be developed to help these categories receive higher scores in CEEQUAL and a higher level of sustainability, solutions for land use and ecology management, pollution for measurement and modeling, resource usage controlling, and transport optimization should be implemented.

As the questions were constructed via CEEQUAL and its impact on SDGs, as Figure 30 and Figure 31 present, also digitalization impact on SDGs could be evaluated to answer the RQ1. This impact is though only analyzed through the perspective of how firstly

CEEQUAL is impacting SDGs and its targets and secondly how digitalization impacts these processes. In this analytical approach, it was decided to compare the number of impacted SDG targets and stakeholder perception of the impact in the construction phase. Questions were accounted to impact each category through the CEEQUAL and SDG assessment and the workshop method from Appendix 1 (BRE Group, 2022c).

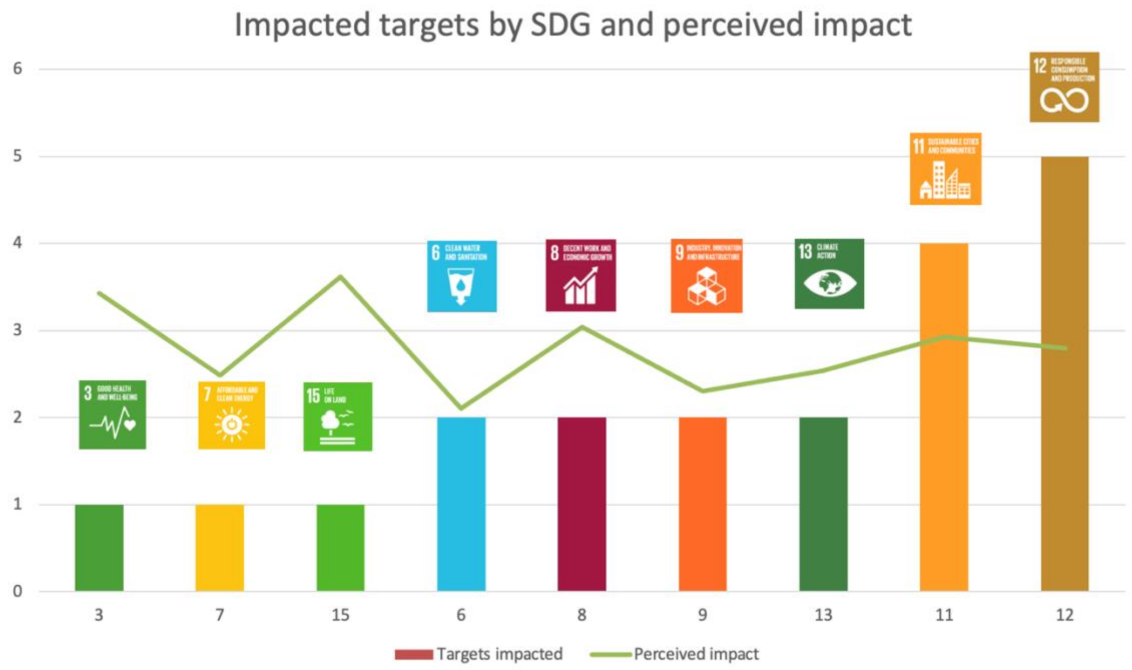

Figure 31. SDG targets positively impacted by digitalization through CEEQUAL impact framework and construction phase stakeholders' perception on the impact.

Figure 31's purpose is to visualize the impact per SDG, where the y-axis is presenting the amount of SDG targets positively impacted by the digitalization, and the line presents the perceived impact per SDG by the stakeholders in the survey research. The impact on an SDG target was justified to exist through a threshold, where the stakeholder average perceived impact had to have a rounded value above 3,0, indicating the impact to be relevant. Thus, if the average perceived impact of all the questions impacting the specific SDG target in the research was below that threshold, digitalization was perceived not to have a positive impact on that target. As Figure 31 represents, SDG 12, responsible consumption, and production had 5 targets where CEEQUAL was justified to have an impact that digitalization is perceived to enhance. As SDG 12 is stated to have an impact on both economic and social sustainability in Figure 4, it is debatable if it is within the study scope of social and environmental sustainability (Mansell et al. 2020, p. 45). Furthermore, each of the SDGs seemed to have also targeted that impact other dimensions of sustainability rather than just the one, which they are stated accountable in Figure 4. Thus, these targets, which BRE Group (2022c) assesses to have an environmental and social impact, were included in this analytical framework, regardless of the SDGs' primary position in the TBL.

From Figure 31 digitalization’s impact on the SDGs could be noted also in an approach, digitalization seems currently in 2022 to have a positive impact on 9 different SDG’s social and environmental aspects. Many of the perceived average scores of the SDGs in total though seem to be below 3, which may indicate that there were some targets that could have been impacted within this framework, but the impact is not yet perceived to exist. For example, SDGs 6, 7, 9, and 13 had one or two targets that were perceived to already have a positive impact from digitalization, but the average impact of the SDG is well below 3,0, thus indicating that there were some targets that could possibly have been impacted according to the steering group and author but were not impacted yet according to the stakeholder perspective. It is notable, that the SDGs dedicated to social and environmental sustainability according to Figure 4 by Mansell et al (2020, p. 45), in Figure 31 are 11, 13, 6, 5, 15, 7, and 3. Between these, it is hard to distinguish whether digitalization has had more impact on environmental or social sustainability, as social SDGs 11, 7, and 3 are affected in 6 targets as are the environmental SDGs 13, 6, and 15.

The third analytical method to analyze the results to answer the RQ1 was the comparison of the importance of each sustainability theme in the survey and their perceived impact. As these themes were formatted with the steering group so that they fit the stakeholder group and are in accordance with the survey research design methods of Fowler jr. (2008) that aim to establish the questions to produce the best quality of response, they are not completely comparable with the SDGs and the CEEQUAL manual categories. However, they were perceived to produce also interesting insight on how the importance and impact are corresponding currently, thus how digitalization can aid the themes compared to their importance.

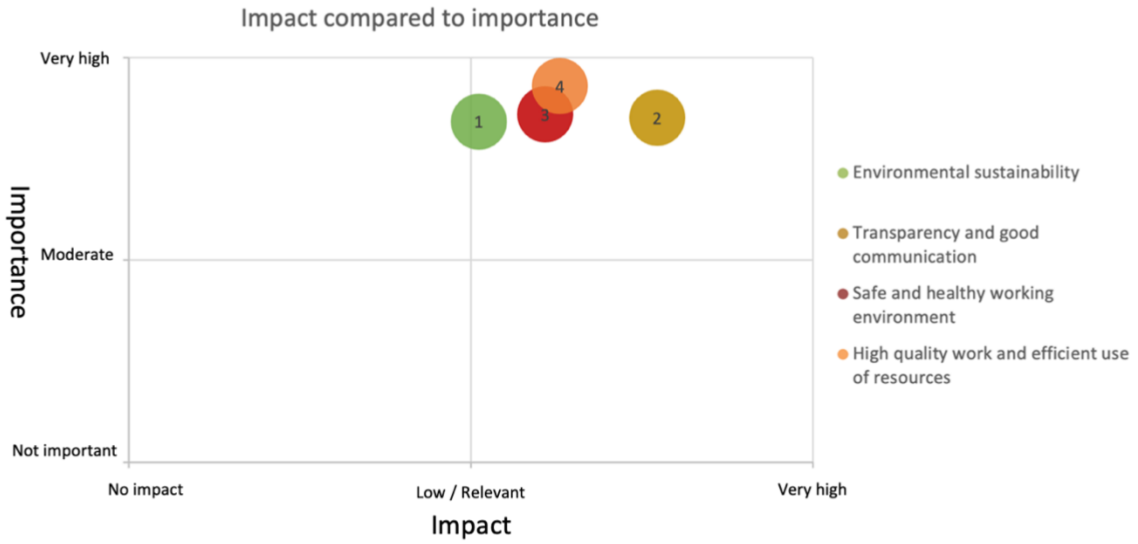

Figure 32. Perceived impact compared to the perceived importance of sustainability themes.

Figure 32 presents the perceived importance compared to the perceived impact of each theme of the survey in a chart. The importance between the categories is not very distinguishable as all the themes received relatively high perceived importance. The only notable difference seems to be theme 4, which can be interpreted to issue from the stakeholder group 1 being the most represented. Stakeholder group 1 including construction project managers, site managers, foremen, and stakeholders responsible for implementing the construction phase, may arguably have the most focus on the efficiency and quality aspect of the projects, as they are accountable for those results. Perhaps category 1 was expected to achieve greater perceived importance, as many stakeholders seem to emphasize specifically their ambitions on enhancing environmental sustainability. A lower score may be interpreted to occur due to the survey intention to focus on construction phase stakeholders, who as being said, may not yet have such clarified objectives for the environmental sustainability as the stakeholder strategies emphasize.

When comparing the perceived impact of digitalization, theme 2 receives a notably higher average impact than other themes. That theme being focused on digitalization's ability to enable more transparent communication between stakeholders and communities, correlation to the CEEQUAL categorical impact in Figure 30 seems viable. With these results altogether combined, it can be stated that the current greatest impact of digitalization on sustainability is emerging from the enhancement of stakeholder communication, which accounts for the social sustainability of infrastructure construction projects. Themes 3 and 4, seem to have a rather similar perceived impact from digitalization, as digitalization may already aid management of safety and health in construction work as well as resource efficiency and quality management to some extent. However, a lower perceived impact on theme 2 may indicate, that digitalization solutions to support these themes have room for improvement. The significantly lowest impact is perceived to be on environmental sustainability. When considering the underlying reasons for this perception, the lack of digitalization solutions to measure and model the environmental impacts such as pollution, CO^2e and other factors may lead to low perceived impact.

4.5 Validity and reliability of the study

When considering the validity of this study, it is to be acknowledged that there is difference between actual sustainability which has realized and what is perceived by the stakeholder. This validity dilemma was aimed to be solved by first recognizing the stakeholder point of views in terms of in what format should the question be asked and furthermore, by designing the question to be suitable for as high quality of answers as viable. Homogeneity and convergence of the research instrument are providing additionally good validity for the results, as it is only measuring perceptions through quantitative survey (Heale and Twycross, 2015). There is also theoretical evidence, that survey methodology is valid for perception research. However, for the assessment of sustainability impact, it only considers the perceptions of those currently using digitalization solutions, although it would be difficult to measure perceptions of those who have not experienced the impact. In terms of reliability of this study, the survey methodology for perception measuring is considered to be reliable, though there could be some reliability issues when it comes to situation where digitalization impact can be discovered differently depending on the scenarios that respondents have faced during their work (Heale and Twycross, 2015). Additionally, the reliability of the study is impacted by the sample of respondents as there is no proven variety in the sense of applying alternative digitalization solutions than the case company solution.

These reliability and validity issues of the study were identified during the study process, and they are to be acknowledged when deriving the results into further absolute conclusions. However, these issues do not undermine the study importance and its suitability for its objectives, as these perceptions can be considered very important for stakeholders considering trying of digitalization solutions and technology developers exploring stakeholder requirements. Eventually the sample size and methodology considered the issues as well as viable, to achieve the highest validity and reliability possible in this framework.

5 Data model

Developing the data model for estimating the realization of GHG emissions was conducted by following the systematic design principles elaborated in chapter 3.3 The process was iterative in its nature and the input from steering group participants was aimed to be taken into an account. Ultimately, the purpose of the information model was to increase knowledge on how the GHG emission impact could be measured with the current technologies available and how the data produced by these technologies should be formatted for the use of stakeholders.

5.1 Case project

The case project that will be used in the modeling and simulation phase of the GHG emission data model development was selected to be a Finnish major construction project Valtatie 3 Hämeenkyrönväylä, which is a highway construction project to enhance the safety and flow of traffic and transportation of the highway (Väylävirasto, 2022). The development phase of the project began in February 2020 and the construction phase in August 2020. During the construction, 10 kilometers of the road will be constructed with 11 bridges and 3 interchanges whereas the cost of the project is 65,35 million euros.

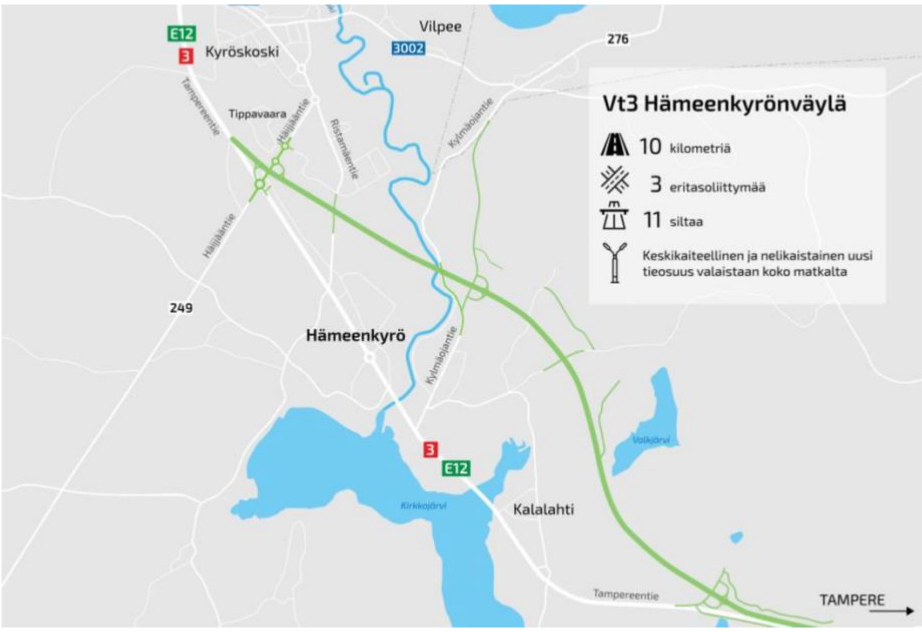

Figure 33. Map of the project Hämeenkyrönväylä (Väylävirasto, 2022).

Figure 33 presents the overall view of the project entity. The case project is estimated to have good source data for modeling and simulating the data model and exploring its data will provide relevant information for iterative development of the model. Furthermore, during the implementation phase of the study, a smaller entity of the case project will be selected to develop the model with accuracy that is adequate for the purpose of this study.

5.2 Requirement allocation

The process of implementation of the data model began by allocating the requirements of the model. As chapter 2.4 presents, the main GHG emission sources of the construction phase of the project were identified. These main sources and the availability of the realized emission data were explored. The data exploration was conducted within the case project presented.

From the case project a certain station space had been selected, where the exploration and allocation of requirements and available data were made. Station space was selected to be between stations 4000-4300 and data exploration began with the machinery data, which according to Karlsson et al (2020, 19-20) generates approximately 32% of the total CO_2e emissions as visualized in chapter 2.4. The requirement of the data was defined to be such, that it may provide a way to calculate CO_2e with the greatest possible accuracy. Firstly, it was discovered that the actual fuel consumption data was not available in the case company's database. However, the exploration revealed that fuel consumption could be calculated through use and drive data that existed in the database.

This calculation method required source values for hourly fuel consumption in working machines for both idling and active working status. As the database provided accurate machine model information, the source value data was retrieved from manufacturer specification sheets for the specific machine models (Caterpillar, 2022). For material transportation machinery, the fuel consumption data was calculated through driven kilometers also considering the effect of the load on the fuel consumption. The source values were then retrieved from manufacturer specification sheets (Lectura GmbH, 2022). Furthermore, to derive the CO_2e from fuel consumption, a conversion factor was needed for propulsion power in the machines, which each had diesel as such. This emission factor of 2,79 kgCO_2e/l was retrieved from IPCC's EFDB where the whole lifecycle effect is pursued to be included in the factor (EFDB, 2020).

For calculating the CO_2e emissions generated from materials, exploration focused on the primary sources described in chapter 2.4: Cement-based products, steel, and asphalt. It was discovered that the category "other materials" includes various emission sources which have no quantifiable data existing in the databases. Also, cement-based products and steel were detected not to have any data available that would provide the opportunity to calculate the used quantity of the material. Eventually, asphalt was the only significant emission source of materials, that currently had applicable data for CO_2e emission calculation. It was discovered that the BIM models contain data that enables the calculation of the area of the asphalt pavement. As-built models were found to provide code 122 break lines in LandXML format, which contained information on the edges of the pavement. This data could have been then formatted further by method of triangulation to provide the needed area of the pavement, which often, as in this case is asphalt.

As the data of BIM models provided the area of the asphalt, to calculate the CO_2e emissions it was required to have a total volume of the used asphalt. Having the area data of the asphalt, thickness data was required for the calculation of the volume. According to Väylävirasto (2018, p. 70-75), in general, in highway projects, the average thickness used as the surface is 140 millimeters. After having the volume calculated, the weight of the asphalt was required to be calculated. SYKE's (2022) CO2data provides a factor of 2500 kg/m^3, the CO_2e emissions of the asphalt could have been calculated by the CO2data conversion factor of 0,048 $kgCO_2e/kg$ for asphalt.

Lastly, as the area of the pavement was provided through the as-built data, it was found to be useful for calculating the CO_2 impact of land-use change. As deforestation and tillage are changing the use of land, their impact could be analyzed through the calculation results. As exact data of removed volume of soil, removed number of trees and their exact emission factor values are lacking, in this case, using the pavement area data was discovered to be the most appropriate method of providing the most accurate quantity of removed square meters of land that operates as a carbon sink. The areas were then converted into comparable CO_2 impact over one year of lost carbon sink via factors for each type of forest in each type of vegetation zone according to Bernal et al (2018, p. 7). For the case project occurring in Finland, a carbon sequestration value of 5 $tCO_2\ ha^{-1}\ year^{-1}$ for conifer forest in the boreal zone was selected.

5.3 Modeling and simulation

During the phase of requirement allocation, iterative modeling was parallelly commenced. Modeling and simulation phases included the construction of the data model and simulating its functionality with Microsoft Excel. The data model was built as a flowchart presenting each information entity, data, and sources of the information whether they are to be retrieved from a database or some external source as constant metadata. The processes of modifying the data were pictured as processes. For the data model, these basic formats of the data model flowchart were defined to be as in Figure 34 and the whole data model flowchart in Appendix 3.

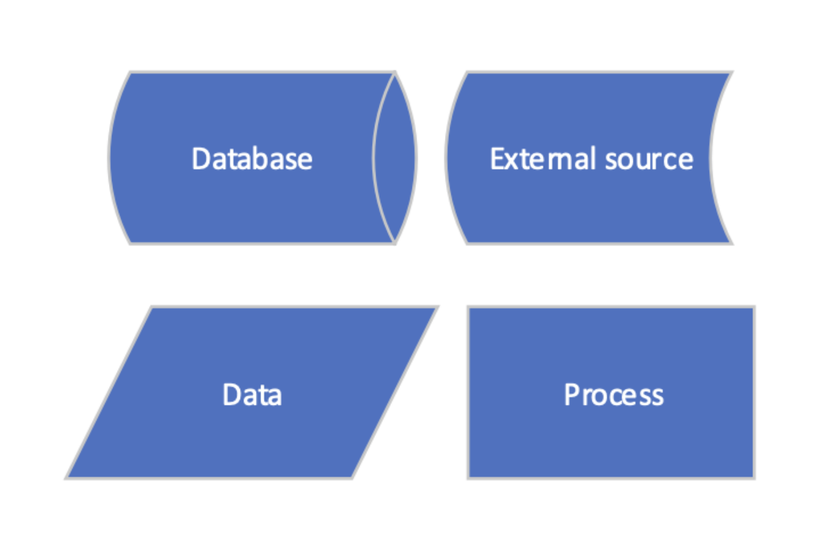

Figure 34. Basic formats of the data model flowchart.

The simulation of the model via Microsoft Excel was conducted and it was used for the iterative development purposes to identify missing data and in the fidelity analysis phase. In the simulation phase, a dashboard for presenting the realized GHG emissions was primarily designed to validate its relevance and usability for stakeholders. Furthermore, the learning outcomes and future development needs could be analyzed through the model and simulation file.

5.4 Fidelity analysis of the data model

As described in the research methodology introduction, the final phase of the data model implementation n this study was to conduct a fidelity analysis, which aims to identify the central deficiencies of the data model when compared to the real-life scenario it should model with the highest possible accuracy. Fidelity analysis eventually provides important knowledge to technology developers of the current state of the data availability and will enable identifying the main opportunities for enhancing technologies measuring the needed data. Fidelity analysis alongside the implemented data model will provide an answer to the RQ2.

As the data model aims to model the emerging CO^2e emissions of a certain phase of a project, it should aim to use the most accurate and verifiable sources of emission data. As in this study's data model, the aim was to identify and model the emission sources which emit the majority of the GHG, the quality and verifiability of the data is the main purpose of the fidelity analysis. Thus, the fidelity analysis will evaluate the emission source specifically the quality of the data.

To begin the analysis with the only material emission source which was identified to have some usable data and was justified to be remarkable, as the Figure 15 adapted from Karlsson et al (2020) presents, was asphalt. To model the emitted CO^2e of asphalt, its volume data and lifecycle impact per unit of volume are required. The quality of the lifecycle impact per unit value can be justified to be precise, as the value can be retrieved from the research-based source of SYKE's (2022) CO2data. The volume data used in the data model was based on pavement area data and average thickness data. The quality of this data can be stated to be valid, as the pavement area data from the Infrakit cloud-services database is very precise and the thickness according to the Väylävirasto (2018) is often standard. The only deficiency that can be identified from this data, is the certainty of the thickness, as it is based on average, not data. Thus, for more precise

CO^2e impact modeling of the asphalt, the exact volume used in the pavement would be required.

For the modeling of working machinery and transportation machinery emissions, the data required contains a volume of the used fuel and the lifecycle impact per unit of the fuel. IPCC's EFDB provides research-based values for the impact per unit, which can be considered good quality (EFDB, 2020). However, as the value may vary not only between fuel sources such as diesel and gasoline, it also may vary between the same source due to for instance producing methods and transportation in the supply chain, thus, to have more precise value for the lifecycle impact per unit of fuel, the origin and supply chain of the fuel should be known. When considering the fuel consumption volume data, the quality of it is in this case mediocre. As there currently was no fuel consumption data available for the data model, the volume data had to be derived from working machinery activity or the distance traveled in the case of transportation machinery and manufacturer consumption information. This data does not consider several factors influencing the fuel consumption of machinery such as load weight, terrain height differences, or driving style. Thus, to achieve a higher stage of accuracy in terms of fuel consumption CO^2e emission modeling, either these factors should be somehow measured, which may not be feasible, or by measuring the fuel consumption through telemetry data, which then automatically has included those factors into the data.

The two major identified deficiencies of the data model are the lack of data from other material-based emission sources outside asphalt, particularly emissions from steel and cement-based products, and the lack of data from land-use change emission impact. In this case study, there was found no data which could have been used to derive the CO^2e emissions of steel or cement-based products, which when correspond to somewhere around 40% of the total emissions of a project, are leaving a major inadequacy to the data model's fidelity (Karlsson et al, 2020). To achieve even some stage of modeling these sources of CO^2e emissions, some volume data would be necessary to be entered into the Infrakit cloud-services database. In the case of land-use change GHG impact, the project pavement area was used as the only factor, which then was multiplied by Bernal et al's (2018) impact value. This method leaves many factors such as excavation depth, actual forest density, and soil differences ignored, which has arguably a great impact on the final model of the CO^2e emission impact. Additionally, as the land-use change impact in its nature is not producing emissions once, but rather decreasing the environment's ability to sequester GHG emissions, there was not found a standardized approach on how long time should the impact be accounted for. Thus, for modeling the CO^2e emissions of infrastructure construction projects, standardized methods not only for estimating the emission impact, which LCA methods produce, should be established more thoroughly but especially for measuring the realized land-use change impact through data.

6 Discussion of the results

The analysis in chapter 4 already includes interpretation and identification of underlying trends impacting the results of the research, this chapter of discussion aims to evaluate the complete study from a more retrospective and holistic perspective. When considering the methodological approach to answer the RQ1, during the study it seemed that having stakeholders strictly from the construction phase was a correct choice. Retrospectively evaluating this indeed provided a selected and well-justified perception from the stakeholders of digitalization’s impact on sustainability. However, what might be missing from the collective perception of stakeholders in the upper management’s insights, when considering the importance of sustainability themes. It was rather surprising, yet quite natural, that environmental sustainability was perceived as the least important theme of sustainability amongst the stakeholders, who mainly consisted of stakeholders responsible for operative management of construction projects, whose primary responsibility is to produce high-quality results with controlled use of budget.

Though this as well impacting the sustainability of projects, hypothetically it was expected that environmental sustainability would have been if not the top priority of stakeholders at least not the fourth. This expectation may derive from the current public talk of stakeholder organizations, which are being very vocal about environmental sustainability being a very high priority for them. However, this statement often is constructed by the top management levels of the stakeholder organizations, whose participation in this survey was minor. But one consideration it may provoke is that if the organization's top-level management and operational-level management have different priorities, are the projects then truly capable of achieving their objectives? When comparing Karlsson et al’s (2020) and Krantz’s (2019) statements about the industry’s urge to enhance and prioritize the measuring, and modeling of environmental impact, the argument of unaligned priorities within organizations might be a sort of obstructive element in the industry’s pursuit.

One suggestion to align these priorities could be to increase the operational management's responsibility for tracking and achieving environmental objectives such as CO^2e emission budgets and judge them as equals with the economic objectives. Furthermore, to enable operative management to track these environmental objectives, it would be recommendable for the organization to use verified and standardized digitalization solutions, where the data could be provided more effortlessly than by over employing operational management of projects. For standardized and verified digitalization solutions to emerge for measuring and modeling these environmental objectives, the industry would be recommended to firstly define common methods for tracking the realized environmental impact such as GHG emissions and furthermore develop digitalization solutions to provide the information to all stakeholders with transparent information flow and processes. This research provided insights and knowledge through the developed data model and its fidelity analysis on how this could be implemented within the industry and the case company. The results and findings of how the carbon dioxide equivalent emissions could be modeled through data were designed to support research made by Krantz (2019) and Karlsson et al (2020), adding value to their findings by providing more practical insight on how the transportation construction industry could implement what they have envisioned. From the case company perspective, it would be recommendable to form a group of stakeholders with whom to develop the first versions of the functionalities that could model the CO^2e emissions of projects at least partially. The first version could be envisioned to include at least the realized emissions of the working machinery and transportation machinery.

When considering the limitations of this study’s approach to assessing the sustainability impact of digitalization through evaluating it within digitalization’s ability to enable organizations to acquire CEEQUAL certification as a proof of their sustainable development work, it is evident that this leaves many aspects of sustainability out of consideration, which digitalization could have impact even CEEQUAL manual not investigating them. However, sustainability and SDGs as well-being such an extensive framework to evaluate the impact within, approach to evaluating the impact through

CEEQUAL appeared to provide concrete information and answers to the research question. This information furthermore could be useful for the industry by acting as evidence for stakeholders who are aiming to achieve their sustainability objectives through the CEEQUAL manuals framework, that applying digitalization solutions such as Infrakit cloud-platform is already in 2022 beneficial for them in the pursuit of achieving CEEQUAL certification. From the case company perspective, it would be recommendable to provide stakeholders using their solutions assistance in achieving CEEQUAL or other sustainability certifications with the help of their solution.

In the beginning of the study, sustainability was defined through the framework of TBL, where SDGs furthermore were dedicated to each of the lines of sustainability. During the study’s analysis phase, it however became more evident, that SDGs cannot be strictly divided to respond to one of the lines of TBL, economic, social, or environmental, but they are rather moving back and forth between these lines, each one of them impacting each other simultaneously. Retrospectively considering, that eventually seems rather natural and inclusive in the framework of sustainability, where the vision of sustainability is to keep things in balance by acknowledging the trade-offs and overlapping nature of things, we as a human impact, that the SDGs are not strictly dedicated and divided between TBL.

7 Summary, Conclusions, and Future Research

This study began by setting up its objective to answer two research questions, RQ1 and RQ2, which were justified by presenting the background, status, and theories of the fields of the infrastructure construction industry, theory of sustainability, current state of digitalization in the industry and central frameworks of sustainability in the industry. The implementation and analysis phases provided interesting insights on the current perspectives of the industry stakeholders, on how digitalization impacts and could impact the future of the infrastructure construction industry's sustainability. Additionally, discoveries in these phases of the study will show the way where future development of digitalization solutions could head.

7.1 Summary and conclusions of the study

Answering to the RQ1 "How is digitalization perceived to impact the infrastructure construction's construction phase's sustainable development in social and environmental aspects?", seems eventually be quite difficult in an exact level due the sustainable development being such a vague concept and point of view may vary the end results of perceptions. However, it evidently can be stated, that the stakeholders of the industry applying digitalization solutions into their processes do find digitalization to have numerous positive impacts on sustainable development of their projects in social and environmental level. Distinctly stakeholders perceive digitalization to enhance the transparency of projects and increase the efficiency of communication amongst stakeholders.

When considering the RQ2 "How can Infrakit cloud-service as a digitalization solution use the emerging data for modeling the environmental sustainability of construction projects, particularly CO^2e emissions?", several discoveries were made, which ultimately were produced as a data model providing current state opportunities and fidelity analysis evaluating the future opportunities of development. The most interesting finding could be stated to be the opportunity of measuring work machinery CO^2e emissions through data emerging in the Infrakit database, which seems to be already a feasible opportunity for development.

Overall, the research identified several interesting trends in stakeholder perceptions about digitalization's ability to enable the sustainable development of infrastructure construction projects. Stakeholders aiming to achieve CEEQUAL certification for their project evidently perceived to receive great assistance from digitalization, especially in terms of categories of "Management" and "Communities and stakeholders". From the survey research results, it was also interpretable, that digitalization in the infrastructure construction industry impacts several SDGs positively. The most significant need for development was identified to be the enablement of tracking and achieving sustainability objectives, especially in terms of providing information to the management about the environmental impacts of the projects. From the data exploration and data model development, various development opportunities for the case company were identified.

This study was limited to considering environmental and social sustainability impacts of digitalization, which furthermore was delimited to be evaluated within the CEEQUAL framework of sustainability. The study furthermore did not take into comparison perceptions of stakeholders not applying digitalization to their operations, nor did it include stakeholders from strategical management levels, who were perceived not to have a concrete perception of digitalization impacts on projects. Additionally, this research had a limitation on considering the construction phase of the projects and in the development of the data model only exploring opportunities on modeling CO^2e emissions of the environmental impacts.

As the overall impact of digitalization was perceived to be relevant already at this stage of solutions available in the markets, this study could have a significant impact on the industry's sustainability, when the key stakeholders of the infrastructure construction industry are becoming more aware of their opportunity to accelerate achieving of their sustainability objectives by applying digitalization solutions. Accelerated adoption of digitalization in the infrastructure construction industry may have a substantial impact on a global scale on the most urgent sustainable development objectives such as the fight against climate change.

7.2 Managerial Implications and Recommendations

From the core identifications further managerial implications and recommendations could be stated to be following. Stakeholders, especially infrastructure asset owners and primary contractors, with ambitious sustainability objectives who are applying digitalization solutions already should collaborate with technology providers to develop solutions which could foster their management of sustainable development. Especially infrastructure asset owners are recommended to pursue this opportunity vigorously, as their objectives often derive from public requirement of sustainability efforts, thus digitalization could provide them an opportunity to achieve their sustainability objectives and prove it alongside. Stakeholders applying for CEEQUAL certification are recommended to discuss and explore digitalization solution providers, who can assist their path into receiving higher scores.

For stakeholders not applying digitalization solutions, but who are ambitious with their sustainability objectives, it is recommended to begin exploring of applying digitalization as an opportunity to achieve their sustainability objectives with higher pace and accuracy. In these cases, it is also a responsibility of institutions which fund the stakeholders to push them into exploring digitalization opportunities in increasing and proving sustainability of their projects, as the institutions with ambitious sustainability objectives are themselves also benefiting from this push. Furthermore, for the infrastructure construction industry to comprehensively become an industry, which promotes sustainability of the humanity, it would be very recommendable, that the stakeholders with highest maturity of digitalization and the most ambitious objectives for sustainable development, would collaborate with digitalization technology providers in acceleration of digitalization adoption. This collaboration in different forms, such as consortiums promoting digitalization, would provide ambitious stakeholders, such as asset owners in Nordics, an opportunity to impact global sustainable development more than they could within their own country or area.

7.3 Future research proposal

When considering the future research opportunities in the field of the sustainable development impact of digitalization in the infrastructure construction industry, it could be coherent and interesting to compare CEEQUAL certification scoring rates between stakeholders who are applying digitalization solutions in the projects and those who are not. Also, it would be a consequent continuation for the scientific community to research digitalization impact on sustainability in the infrastructure construction industry with different frameworks, methods, studying the organizational level impacts, digitalization ability to enhance the processes to achieve sustainability objectives of organizations and obstructive impacts of digitalization. Overall, it would be recommendable to digitalization impact could be researched through concrete impact on each SDG indicator.

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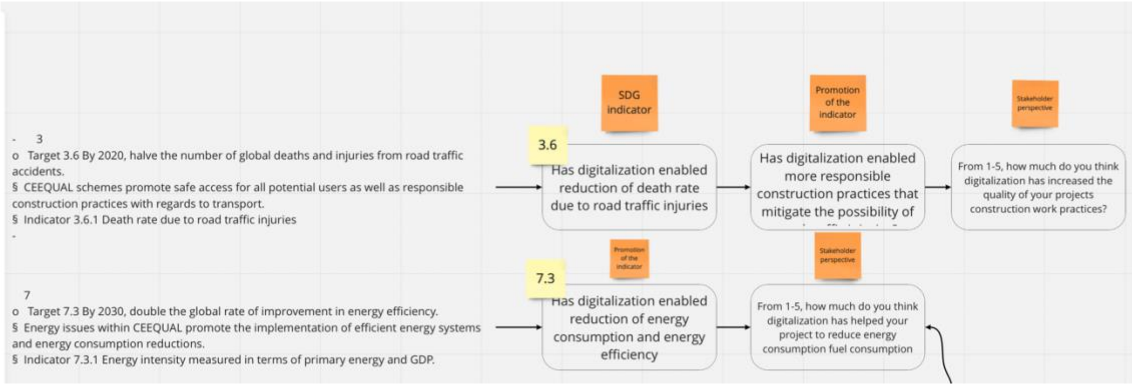
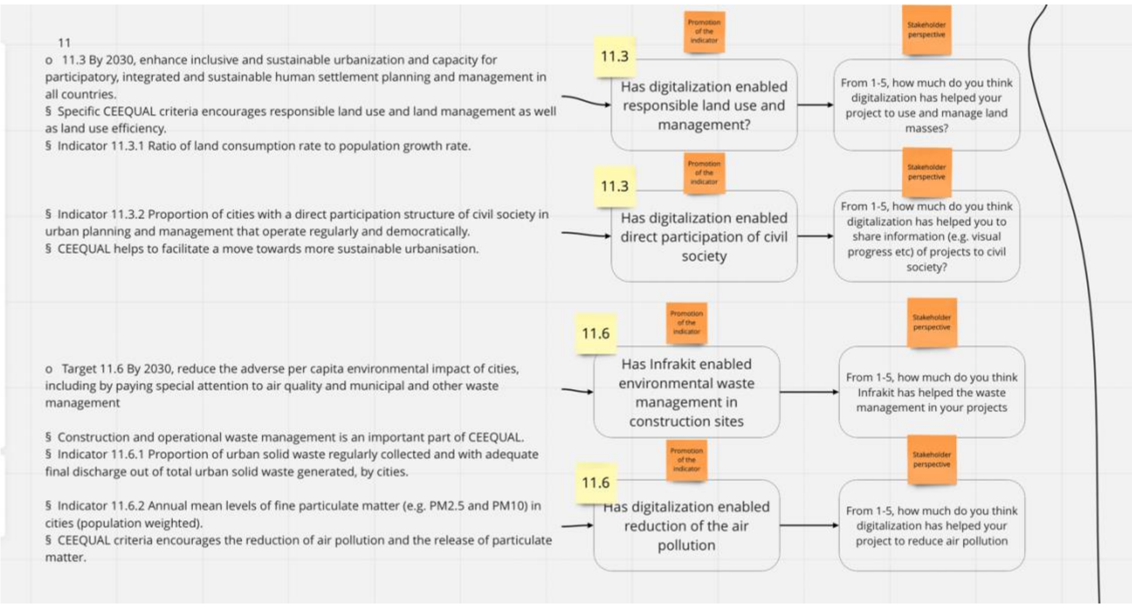
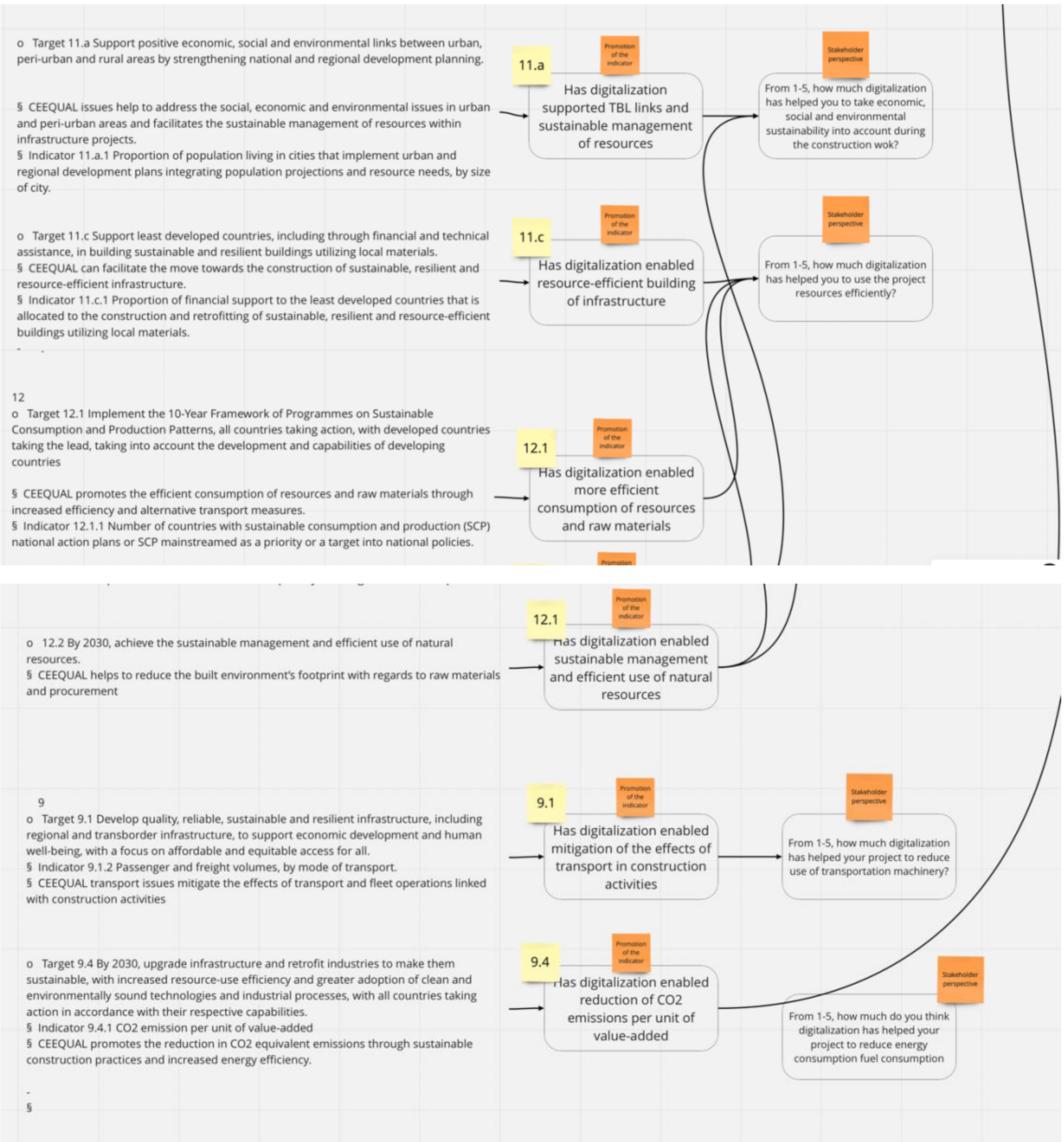
Appendices

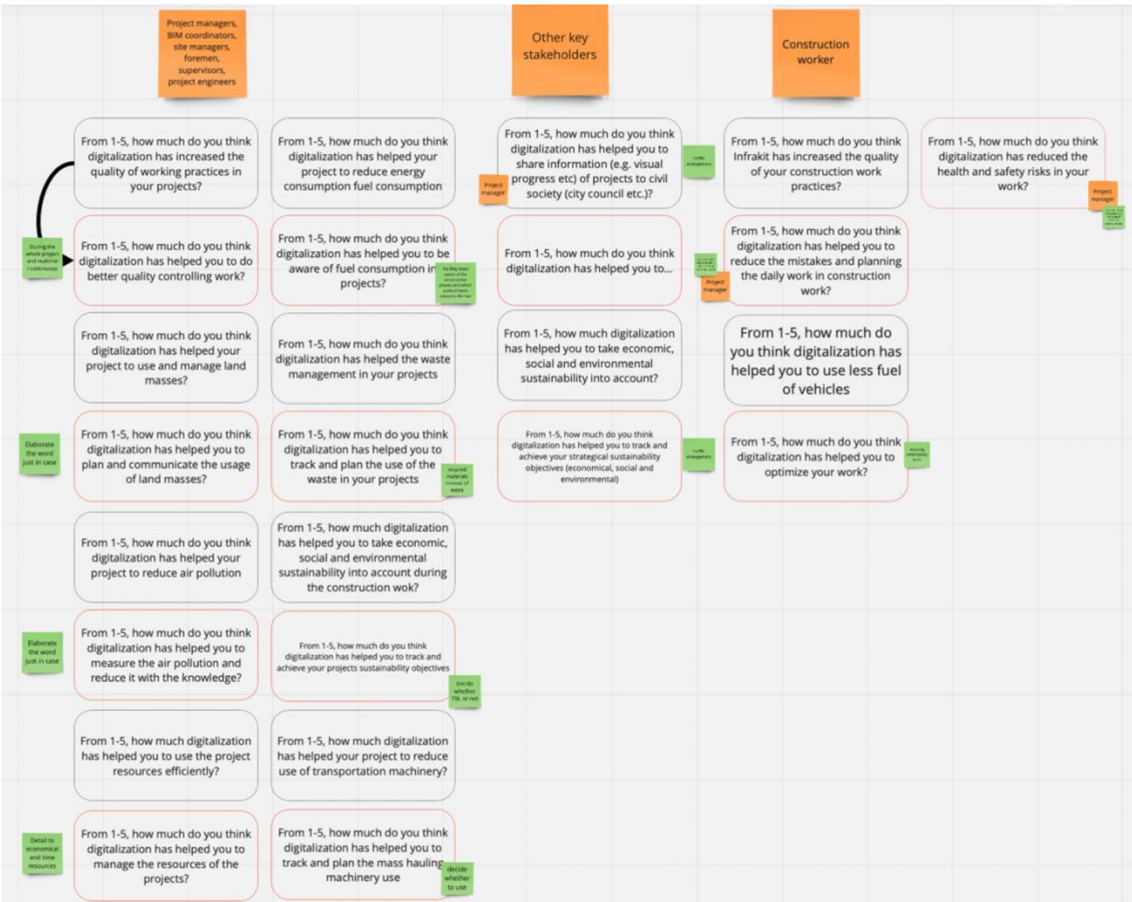
Appendix 1. Question design forming phases 1 and 2



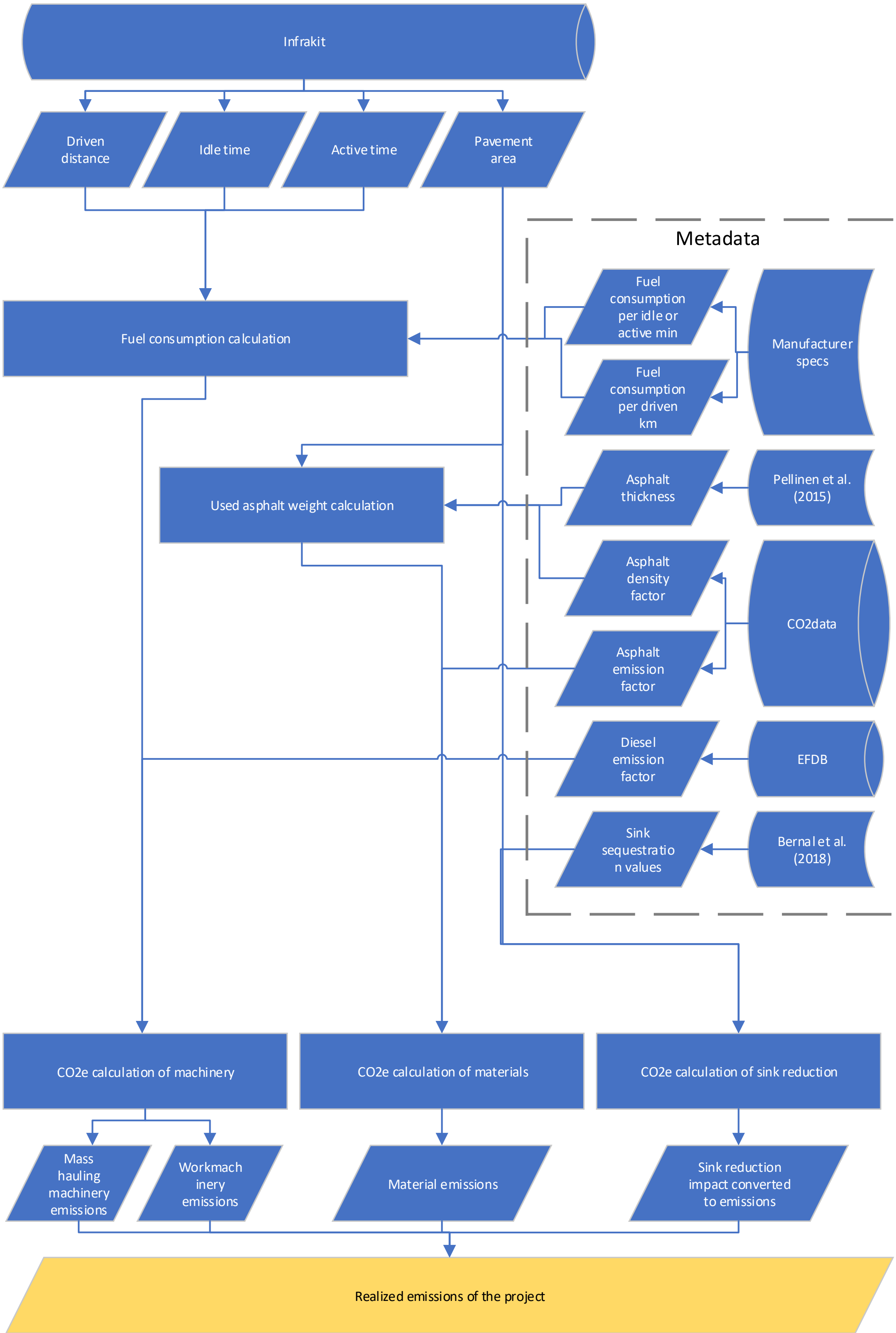



o Target 11.a Support positive economic, social and environmental links between urban, peri-urban and rural areas by strengthening national and regional development planning.
§ CEEQUAL issues help to address the social, economic and environmental issues in urban and peri-urban areas and facilitates the sustainable management of resources within infrastructure projects.
§ Indicator 11.a.1 Proportion of population living in cities that implement urban and regional development plans integrating population projections and resource needs, by size of city.
11.a
Promotion of the indicator
Has digitalization supported TBL links and sustainable management of resources
Stakeholder perspective
From 1-5, how much digitalization has helped you to take economic, social and environmental sustainability into account during the construction wok?
o Target 11.c Support least developed countries, including through financial and technical assistance, in building sustainable and resilient buildings utilizing local materials.
§ CEEQUAL can facilitate the move towards the construction of sustainable, resilient and resource-efficient infrastructure.
§ Indicator 11.c.1 Proportion of financial support to the least developed countries that is allocated to the construction and retrofitting of sustainable, resilient and resource-efficient buildings utilizing local materials.
11.c
Promotion of the indicator
Has digitalization enabled resource-efficient building of infrastructure
Stakeholder perspective
From 1-5, how much digitalization has helped you to use the project resources efficiently?
12
o Target 12.1 Implement the 10-Year Framework of Programmes on Sustainable Consumption and Production Patterns, all countries taking action, with developed countries taking the lead, taking into account the development and capabilities of developing countries
§ CEEQUAL promotes the efficient consumption of resources and raw materials through increased efficiency and alternative transport measures.
§ Indicator 12.1.1 Number of countries with sustainable consumption and production (SCP) national action plans or SCP mainstreamed as a priority or a target into national policies.
12.1
Promotion of the indicator
Has digitalization enabled more efficient consumption of resources and raw materials
o 12.2 By 2030, achieve the sustainable management and efficient use of natural resources.
§ CEEQUAL helps to reduce the built environment's footprint with regards to raw materials and procurement
12.1
Promotion of the indicator
Has digitalization enabled sustainable management and efficient use of natural resources
9
o Target 9.1 Develop quality, reliable, sustainable and resilient infrastructure, including regional and transborder infrastructure, to support economic development and human well-being, with a focus on affordable and equitable access for all.
§ Indicator 9.1.2 Passenger and freight volumes, by mode of transport.
§ CEEQUAL transport issues mitigate the effects of transport and fleet operations linked with construction activities
9.1
Promotion of the indicator
Has digitalization enabled mitigation of the effects of transport in construction activities
Stakeholder perspective
From 1-5, how much digitalization has helped your project to reduce use of transportation machinery?
o Target 9.4 By 2030, upgrade infrastructure and retrofit industries to make them sustainable, with increased resource-use efficiency and greater adoption of clean and environmentally sound technologies and industrial processes, with all countries taking action in accordance with their respective capabilities.
§ Indicator 9.4.1 CO2 emission per unit of value-added
§ CEEQUAL promotes the reduction in CO2 equivalent emissions through sustainable construction practices and increased energy efficiency.
9.4
Promotion of the indicator
Has digitalization enabled reduction of CO2 emissions per unit of value-added
Stakeholder perspective
From 1-5, how much do you think digitalization has helped your project to reduce energy consumption fuel consumption

Appendix 2. Refining the questions to the point of view of stakeholders



Appendix 3. Data model



Appendix 3. Exact survey respondent distribution

First off, indicate which of the following roles in infrastructure construction projects matches you the best:		
Answer Choices	Responses	
Construction site worker / construction site subcontractor	8,93 %	10
Foreman, site manager, supervisor or project manager (either from contra	25,89 %	29
BIM coordinator or project engineer	18,75 %	21
Other contractor organization representative	7,14 %	8
Design consultant	12,50 %	14
Other consultant representative	3,57 %	4
Other infrastructure owner organization representative	7,14 %	8
Some other, please elaborate...	16,07 %	18
	Answered	**112**
	Skipped	**0**

Appendix 4. Stakeholder group 1 questions

Question 2	How much do you think digitalization has helped you to plan and communicate the usage of landmasses?
Question 3	How much do you think digitalization has helped you to measure air pollution and possibly reduce it with knowledge?
Question 4	How much do you think digitalization has helped you to be aware of fuel consumption in projects? (For example, have you been more aware of construction phases and which parts of them are critical for fuel consumption?)
Question 5	How much do you think digitalization has helped you in tracking and planning the use of recycled materials in your projects?
Question 6	How much do you think digitalization has helped you in tracking and planning the mass hauling operations?
Question 7	How much do you think digitalization has helped you to share information (e.g., visual progress) of projects to civil society (city council etc.)?
Question 8	How much do you think digitalization has helped you to communicate daily plans of work and lead the daily construction?
Question 9	How much do you think digitalization has helped you in having a more transparent information flow between all stakeholders and complying with legal arrangements?

Question 10	How much do you think digitalization has reduced the health and safety risks in your projects?
Question 11	How much do you think digitalization has helped you to communicate the risk areas of different work phases?
Question 12	How much do you think digitalization has helped you improving quality control work during projects (e.g., real-time information, continuous control)?
Question 13	How much do you think digitalization has helped you in managing the economical and time resources of the projects?
Question 14	How much do you think digitalization has helped you to track and achieve your projects sustainability objectives? (Economic, social, environmental)

Appendix 5. Stakeholder group 2 questions

Question 2	How much do you think digitalization has helped you to share information (e.g., visual progress etc.) of projects to civil society (city council etc.)?
Question 3	How much do you think digitalization has helped you in having a more transparent information flow between all stakeholders and complying with legal arrangements?
Question 4	How much do you think digitalization has helped you improving quality control work during projects (e.g., real-time information, continuous control)?
Question 5	How much do you think digitalization has helped you in managing the economical and time resources of the projects?
Question 6	How much do you think digitalization has helped you in tracking and planning the use of recycled materials in your projects?
Question 7	How much do you think digitalization has helped you to track and achieve your project's sustainability objectives? (Economic, social, environmental)

Appendix 6. Stakeholder group 3 questions

Question 2	How much do you think digitalization has helped you to reduce the mistakes and plan the daily work in construction work?
Question 3	How much do you think digitalization has reduced the health and safety risks in your work or to be aware of the risks?