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A pre-study

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2022

Document Version:
Publisher's PDF, also known as Version of record

Link to publication

Citation for published version (APA):
Björnsson, I. (2022). *Opportunities and challenges of digitalization and automation in bridge design: A pre-study*. (TVBK; No. 3078). Lund University, Faculty of Engineering, Div. of Structural Engineering.

Total number of authors:
1

Report TVBK-3078

Opportunities and challenges of digitalization and automation in bridge design

A pre-study

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Report TVBK-3078

ISBN 978-91-87993-25-1

ISBN (digital version) 978-91-87993-26-8

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2022

Preface

This report is a summary of the findings from a pre-study[1] funded by the Swedish Transport Administration, Trafikverket. The study was carried out by senior researchers Ivar Björnsson and Oskar Larsson Ivanov at the Division of Structural Engineering, Faculty of Engineering, Lund University during fall 2020 to spring 2021. The report was completed in early 2022 and provides an overview of identified opportunities and challenges of digital transformation in bridge design based on a literature review and feedback from with bridge industry representatives. The content of the report is intended as a basis for future research activities and do not necessarily reflect the opinions of the financing agency.

Ivar Björnsson

Lund, February 2022

[1] BBT Project 2019-023: Pre-study to investigate opportunities and challenges of digitalization and automation in bridge design – highlighting the human contribution to success/failure

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Summary

This report presents the findings from a pre-study concerning the opportunities and challenges of digitalization and automation in bridge design. The project approach is divided into three parts: 1) a short review of the relevant literature, 2) investigations concerning bridge industry perspectives (with focus on bridge consultants), and 3) the identification of future research needs based on parts 1 and 2.

The literature review found that digital transformation is often a desirable goal within different industries in Europe and Sweden with the justification that it could improve productivity. Specific digital technologies which have been identified as providing the most potential specifically in the building sector include the automation of knowledge-based work, the utilization of cloud-based services, internet of things (IoT) as well as mobile internet. When it comes to structural engineering, there is a clear indication that the profession is undergoing a paradigm shift towards a greater reliance on digital tools. Professional societies in both the US (ASCE) and the UK (IStructE) highlight the need for the profession to evolve and both have published insights concerning opportunities, challenges, and future needs. Some specific challenges include the need for broadening expertise as well as reforming and improving education for both students and practicing engineers (continuing profession development). The latter was also highlighted in a recent study in Sweden by af Klintberg (2018).

Bridge industry perspectives were investigated through a small focus-group and questionnaire study, which involved bridge engineering consultants and experts. The results from both highlighted a high interest in and trends toward increased digital transformation and automation in bridge engineering practice today. Some opportunities which were mentioned include the possibility to reduce conservatism and optimize structures considering a variety of criteria, automation of routine work allowing for more time towards other relevant tasks, as well as the adoption of digital platforms and tools for improved communication, coordination, and management. One interesting ongoing trend within companies is the development of in-house digital tools, often viewed as giving a competitive edge. Challenges of digital transformation and automation which were identified often focussed on risks associated with over-reliance and faith in digital tools coupled with the need for adopting suitable design checking procedures considering potentially complex and comprehensive input/output in calculation (FE) software. Another interesting aspect which was discussed concerned the trend of increased specialization within the sector leading to the question of whether there is a need for *'general practitioners'* of structural engineering.

In synthesizing the results from the first two parts of the project, broad future research needs were identified. These include the necessity to investigate further, and in more detail, both positive and negative impacts of ongoing and future digital transformation and automation. To facilitate a more informed way forward, such impacts should be assessed and evaluated in relation to the structural engineering profession, the bridge and construction sector (including all relevant stakeholders), the individual engineer(s), as well as society at large. Some specific relevant future research topics relate to the investigation of professional variability and its implications, the human-machine interface, the transfer of IT models from design and planning to facility management, as well as effective knowledge and experience transfer in modern design practice. The final sections of the report also elaborate briefly on two common digital technologies used today: digital tools for structural design calculations and Building Information Modelling (BIM).

1. Background

The development and application of digital or automated technologies that have affected society in recent decades has had no less of an impact on the structural engineering profession. Some different terms have been associated with the transformation toward digital technologies in the construction engineering sector. In this pre-study, we will focus on digital transformation and automation in bridge engineering, although some parts (e.g. the literature review) will consider these aspects for the structural (or even civil) engineering profession in general.

2. Aim and methodology

The primary aim of the study is to identify possible research opportunities by focusing on identified opportunities and challenges of digitalization and automation in bridge engineering and specifically concerning the task of bridge design. The study is divided into three parts:

PART 1: Review of relevant literature

PART 2: Insight concerning bridge industry perspectives (with focus on bridge consultants)

PART 3: An identification of some future research needs based on parts 1 and 2

The first part is a selective literature review (scoping review) and concerns the state-or-art (and to some extent practice) of digital transformation and automation in 1) the building sector, 2) for structural engineers and, 3) the bridge construction sector specifically. Selected relevant publications are cited to provide an overview and help with developing the second part of this project which centers around the industry perspective (with focus on bridge consultants). A focus group of 6 bridge experts and consultants were contacted, and brainstorming sessions carried out to help identify relevant areas of interest for bridge design in practice which ultimately led to the creation and distribution of a questionnaire. The final part of the project synthesizes the results from the first two parts to provide an overview of opportunities and challenges, forming the basis for potential future research application in the area.

3. Literature review

3.1 Definitions

The general definition of digitization (or digitalization) used in this pre-study is the process of converting information into a digital format; the term digital transformation is sometime used. Automation, on the other hand, is the creation and application of technologies to produce and deliver goods and services with minimal human intervention. Thus, while digitization focusses on *information* and how it is encoded, automation deals with the transformation of a *process* which otherwise requires humans to carry out. This transformation will likely involve digital components or control systems.

Some other related terms, including one cited definition for each, are provided below:

- *Digital engineering:* the advanced computerization of systems engineering practices. (SAIC 2020)

- *Digitalization of AEC*[2]: the transformation of processes, organizational settings, and project delivery methods that need to be coupled with the adoption of digital technologies (Talamo & Bonanomi 2020)

The Swedish terms *digitalisering* and *automatisering* are closely related to the previous definitions.

In this pre-study, focus will be on the structural engineering design and drafting phases of bridge construction. The work carried out by structural engineers and draftsman is in this context knowledge-based (rather than relying on physical work). Considering this, the term *digitalization* encompasses the types of automation which are possible. As such, the review will be focused on digitalization (or digital transformation) without making any specific searches regarding automation.

3.2 Digital transformation trends in the construction sector

There is a world-wide drive towards digitalization. In Sweden, the so-called digitalization strategy (*digitaliseringsstrategi*)[3] outlines the government's aim to be a world leader in the application of digitalization. Likewise, the Swedish Transportation Administration (*Trafikverket*) have planned to increase their efforts towards digital transformation both regarding the benefits it potentially creates for the transportation network (e.g. automated transport) as well as for their organization (TRV 2018). In this section we investigate the general trend of digital transformation and some previous studies outlining its potential with focus on impacts within the construction sector. Thereafter some specific types of digital transformation are highlighted.

Firstly, there are some indications that digital transformation can help improve productivity within various industries. The McKinsey Global Institute (MGI) for business and economic research observed a significant reduction in productivity growth in previous decades. Their report, which included seven countries (US, UK, Sweden, Germany, France, Italy, and Spain), indicates that Sweden, the UK, and the US experienced the largest productivity-growth decline between 2004 and 2014 (Remes et al. 2018a). Their research also determined that there is a positive correlation between productivity growth and digitization while revealing that the construction sector is among the least digitized sectors, especially in Europe. One observation noting is that the construction sector was identified as the main contributor to the decline of productivity specifically for the case of Sweden.

On the other hand, Sweden has been rated relatively high world-wide in terms of their adoption of digital technologies and the economic potential for continuing this trend has been highlighted (McKinsey 2017). Some specific technological trends were identified which can be significant for realizing these economic benefits and thus supporting the aim of further digital transformation:

- **Automation of knowledge-based work** with advanced analyses and digital decision support
- **Advanced robotics** for automation of physical work
- **Autonomous vehicles** to facilitate automation of transportation
- **Mobile internet** for improved information access, communication, and e-commerce
- **Cloud based services**
- **Internet of Things (IoT)**

[2] Architecture, engineering, and construction industry
[3] https://www.regeringen.se/regeringens-politik/digitaliseringsstrategin/

Of the previous trends, primarily automation of knowledge-based work (57%), secondly cloud based services (24%) and thirdly mobile internet (16%) were identified as having the greatest potential towards increased economic benefits within the building sector; the values in the parenthesis indicate the relative contribution from each. Interestingly, advanced robotics were not included for this sector (with greater impacts towards the production industries).

The interest within the Swedish construction industry for digital transformation can also be observed by reviewing the content of some industry and popular science publications in Sweden. As of December 2020, Byggindustrin and NyTeknik have, for instance, published over 100 articles each on the topic of digitalization (Swedish: *digalisering*); most of these were from the previous 3 to 5 years.

3.3 Digital transformation trends within structural engineering

A basic internet search[4] of the phase 'digital transformation of structural engineering' yields nearly 60 million results. Current structural engineering practice is, as with many other sectors, reliant on digital technologies (e.g., the ubiquitous use of Finite Element, FE-, software). There is, however, a general trend towards an even greater reliance on digital tools and workflows in structural engineering practice.

In the UK, for instance, the Institution of Structural Engineers (IStructE) have established a *Structural Futures Committee* to '…consider how structural engineering's approach, skills and knowledge base will need to change in response to an evolving industry.'[5] In May of 2020, the second annual Digital Design and Computation e-conference was held[6]. Topics covered within the conference include computational design, automated processes as well as artificial intelligence (AI). In a previous IStructE workshop, future trends were identified which would potentially have the greatest impact on the structural engineering profession (IStructE 2018):

- **System integration** – need for broadening of expertise; broader collaboration with other professions; focus more on overall building design; go beyond traditional structural engineering
- **Data** – data will provide greater insight into building design and construction; industry needs to be more data and tech driven
- **Nanotechnology & new materials** – invest more in research and development; apply new solutions and innovations in real projects; closer collaboration with scientists and architects
- **Artificial intelligence (AI)** – potential huge impact and can disrupt current ways of working, bringing both opportunity and threat (depending on how profession responds & prepares)
- **Internet of things (IoT)** – learn from other professions to apply this

It should be noted that the first point may be considered a necessary complement to support the other (digitally/technologically oriented) trends. The workshop led to the identification of multiple priority areas for the Institution to consider where the top priority was *the need for a rethink in education of engineers to prepare them for a changing future role*. The institution also provides online training and highlights that 'it has never been more important for structural engineers to be competent in the use of

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[4] Conducted through google.com during early spring 2021

[5] Structural Futures Committee (https://www.istructe.org/get-involved/committees/structural-futures/)

[6] https://www.istructe.org/resources/training/digital-design-and-computation-e-conference-2020/

digital tools and demonstrate an awareness of the potential risks and opportunities digital systems can bring.'[7]

In a similar manner, in the US, the Structural Engineering Institute (SEI) of the American Society of Civil Engineers (ASCE) describe in their *Vision for the future* that 'the profession must fundamentally evolve' (SEI 2015). Key initiatives mentioned include reforming and improving education for both students and practicing engineers (continuing professional education), giving engineers tools to liberate them from limitations of prescriptive code-checking to encourage innovation in design, promoting multi-disciplinary practice, as well as thinking outside the traditional boundaries of structural engineering to identify and apply the most advanced new technologies and science to the practice.

The necessity for further developments in the engineers' role (and how this is supported) has therefore been highlighted on both sides of the Atlantic; in this case exemplified by the work carried out by professional institutions in the UK and US. Institutions such as these serve as a system for certification of professional engineers and provide support in terms of continued training and education. In Sweden, no such institution exists although some have highlighted the need for their establishment in order improve quality, avoid errors and reduces costs (af Klintberg 2018). A survey by af Klintberg (2018) concludes that despite its long-term goals of reduced life-cycle costs and environmental impacts, the Swedish Transport Administration has laid a heavy price pressure on consultant companies, often avoiding the requirement for senior engineering competence. Some presumptive benefits of introducing a certification system for the engineers themselves included continuing education, as well as minimizing the risk of mental fatigue or work overload. Although it is outside the scope of this pre-study to investigate further the benefits of knowledge/skill certification, the possibility for (and access to) continued education and training will help the profession evolve considering ongoing and future digital transformation trends. Currently, there are only a few courses for continuing professional development (CPD) of construction industry practitioners in Sweden, for example, in moisture safety design, concrete construction for workers and engineers, and steel construction engineering.

Another issue highlighted in previous research in Sweden concerns the inherent difficulties associated with desired industry-wide developments, e.g., towards increased sustainability; especially within the infrastructure construction industry (Ekström 2019). This research investigated the need for, and challenges in retaining, a systematic and holistic design approach to enable and effectively support knowledge and experience transfer in the interprofessional interface. Thus, to realize an effective evolution of the structural engineering profession, as well as other industry actors, the complexities, and interrelations inherent to the modern construction industry may pose significant challenges. Embedded within industry practice, and a potential source of additional complexity, are digital tools; e.g. computational software for the analysis and design of structural components (e.g., FEM) and systems, building information modelling (BIM) for draft work and construction planning, etc. This aspect has been mentioned in previous publications including Björnsson et al. (2016), Borthwick et al (2012), and MacLeod (2016) and will be discussed later in Section 5.1.1-5.1.2 of this report.

[7] https://www.istructe.org/resources/digital-engineering/

3.4 (Future) trends in bridge engineering

In the context of this study, it is of relevance to determine which aspects of digital transformation trends are specific to bridge engineering, and specifically in bridge design. Muhaimin et al. (2021) recently presented an exploratory study which identified 30 critical factors may impact the future of bridge design, construction, and operation. The study, which was carried out in the US, involved in-depth interviews with 21 bridge experts (from transportation agencies) as well as a review of published literature and reports on bridges. The factors which were identified as relevant for bridge planning and design are summarized in Table 1.

Table 1. Critical impact factors for the future of bridge planning and design identified in a study by Muhaimin et al. (2021)

CATEGORY	SUBCATEGORY
TECHNOLOGICAL	New Transportation facilities or methods
	Interference between human and traffic
	Adoption of new construction materials or structures
	Adoption of new construction techniques
	Changes in ways of management and communication
ENVIRONMENTAL	Climate change
	Sea level rise
	Change in intensity and frequency of extreme events
	Change in air quality
	Change in soil quality
	Change in water quality
SOCIAL	Changes in aesthetic preferences
	Changes in land use patterns
	Changes in legislation and policies
	Education on new technological knowledge
	Globalization and trade war
	Availability of funding
	Change in construction cost

Of the factors mentioned in Table 1, the adoption of new construction materials such as ultra-high-performance concrete (UHPC), high-performance steel (HPS) and composite materials were near unanimously considered by the interviewees to bring significant impacts to bridges in the future. Interestingly, education on new technological knowledge was considered much less significant. This contrasts with the relative importance given to this aspect by the structural engineering institutions in the US and UK (SEI 2015, IStructE 2018) as well as the relative lack and perceived need for continued professional education of professional engineering in Sweden. The study by Muhaimin et al. (2021), however, only included interviewees from the transportation agencies while consultant and contractor perspectives were not part of the study.

A recent study in Sweden by Leander et al. (2020) investigated opportunities and challenges of digital transformation in relation to management and maintenance of bridges. The study included a questionnaire distributed to industry representatives (mostly consultants) and was supported by interviews with technical experts as well as a literature review. Although focus was on bridge management, the results revealed that modern bridge design and draft work is often digitally supported by Building Information Modelling (BIM). Focus is on the construction phase where cooperation and communication between actors is considered to provide the greatest benefit. The report went on further to highlight the need for integrating information models throughout the life cycle of a bridge and that the current focus on design requires complementary attention being placed on developing suitable management models.

3.5 Academic trend analysis

The introduction of new digital innovations and technologies in industry practice may have some significant lead times until these are sufficiently ripe for wider applications. In this light, a short trend analysis is carried out on some digital technologies based on searches in academic databases. This analysis is confined to the Web of Science (WoS) database and includes six search strings; see Table 2. To confine the results to relevant topics, a filter is placed which confines the search results to topics within the WoS category of "*Engineering Civil*".

Table 2. Number of results (articles) for different search strings in Web of Science (confined to category 'Engineering Civil'), Date: 2020-12-02

Keyword	Record Count*
Computational design	5 531
Building information model	5 131
Artificial intelligence	1 167
Machine learning	1 948
Design automation	692*
Data-driven design	306

* 1 820 if only automation is searched

An historical trend analysis of the three terms with the most search results (*computational design*, *building information model*, and *machine learning*) is provided in Figure 1. All topics show an increased amount of publication over time while *machine learning* appears to be a more recent trend compared with the other two. Their adoption currently within structural or bridge engineering practice was not immediately evident, as will be observed in later sections of this report. However, this may change in the near future.

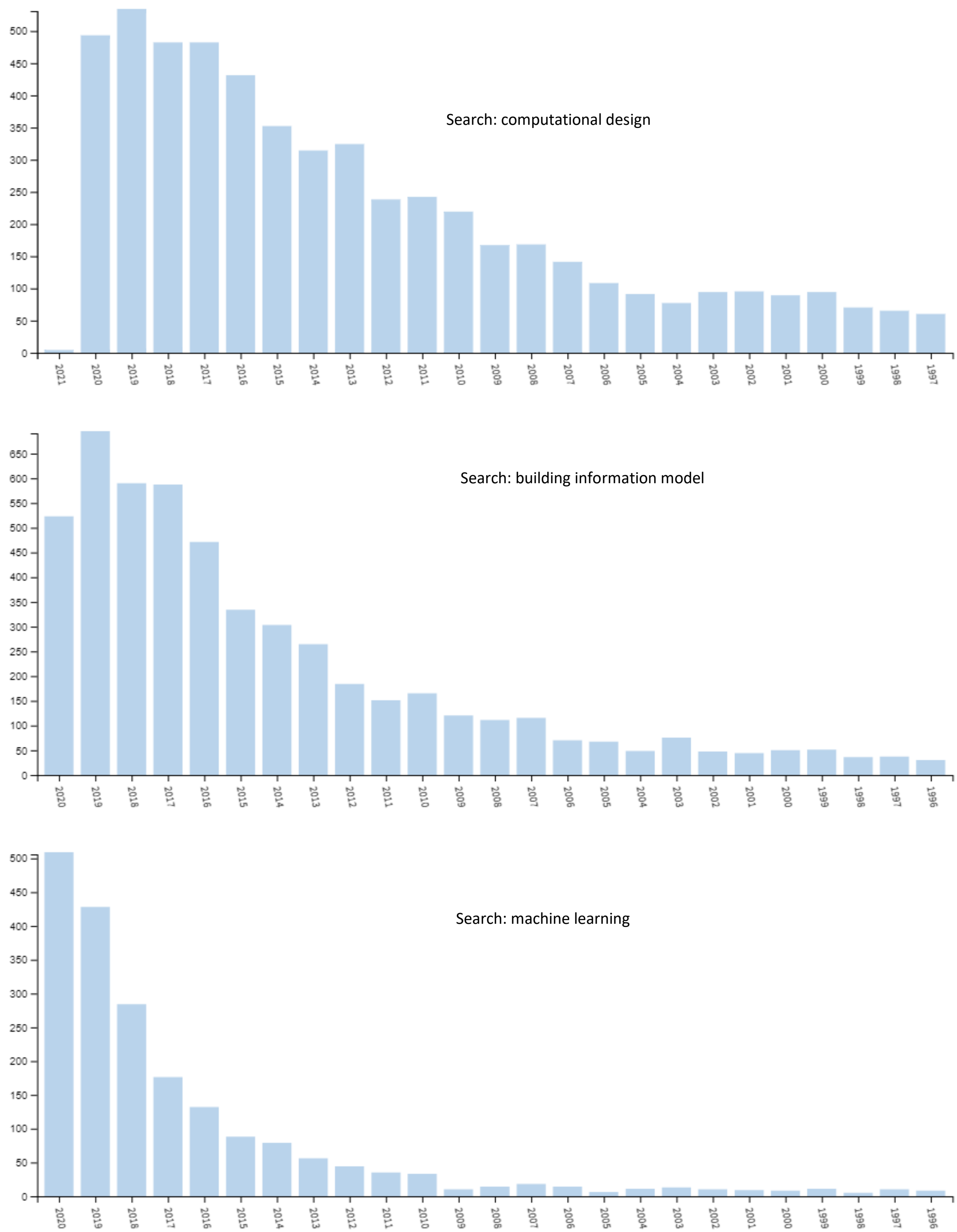

Figure 1. Historical trend analysis in Web of Science for three different search terms 'computational design', 'building information model' and 'machine learning'. Results confined to category: Engineering Civil; Date of search: 2020-12-02.

4. (Bridge) Industry perspectives

4.1 Background

The previous sections highlighted the high relevance of digital transformation trends in the construction sector in general and provided some specific insights concerning these trends and their potential impacts for structural and bridge engineering design. These findings were based on previously published work and will be complemented with a two-part pre-study of the bridge consultancy sector in Sweden. The first part involves a focus group consisting of bridge industry representative while the second part is a questionnaire study. Neither part is intended to provide conclusions concerning industry wide perspectives (e.g., cross sectional analysis) but should are intended to provide some relevant insights as a basis for future research.

4.2 Focus Group

A focus group was created which comprised six experienced bridge experts including 4 bridge engineers and two academics. The first group had between 10 and over 30 years professional experience while the academic members of the group had from 10 to over 50 years experience with relevant research and teaching bridge design and construction. Brainstorming sessions were carried out with each member of the focus group to ascertain their perspectives on the issues considered in this pre-study. This part of the project provided a basis for determining relevant themes and topics used to create the questionnaire (see Section 4.3).

Six individual brainstorming sessions were carried out approximately 2 hours each. As a result of the Covid-19 pandemic it was not possible to have a larger discussion within the entire group in person while some earlier sessions were carried out online. Each brainstorming session included a short presentation in which the project was introduced along with the aims and objectives. Some examples of possible trends were included based on the literature review and previous brainstorming sessions. Thus, information was successively transferred between members of the group. The last part of each session included an open-ended discussion in which the participants were asked to discuss (*based on their own experience and opinions*):

- Their own experience and thoughts on digital transformation and automation in bridge design
- How they have perceived the historical development of the bridge engineers' role
- Examples of opportunities and challenges
- What they perceive the future holds and how the situation can be improved

Upon completion of the project, including results from the questionnaire study, a final feedback session was held in early 2022 with the focus group. The output from the focus group study is provided in the next section.

4.2.1 Focus group output

The participants in the focus group were unanimous in that there is an ongoing paradigm shift in bridge design, that technology is becoming riper for implementation and that digital transformation and automation are common (industry-wide) goals. Driving forces for ongoing developments include both individual industry actors (i.e., consultants or contractors) own initiative for change as well as external requirements placed by relevant authorities (i.e., the transportation administration). The ubiquitous use of 3D structural analysis models as well as BIM models are specific examples of the latter where these are required by the bridge owner.

Concerning the developments of engineers' role considering digital transformation the focus group agreed that the work carried out today is significantly different than in previous decades and highlighted the need for suitable adaptability to technological developments to support these developments. Some highlighted a generational difference within their offices where the younger generation is perceived to be more tech savvy and in general have a different, more positive, outlook on technology adoption while becoming more reliant on digital tools than previous generations. Specific aspects which were mentioned included the ubiquitous use and widespread reliance on finite element (FE) software for design and/or verification and building information modeling (BIM) for draft work. Another issue which was mentioned concerned an overall reduction in productivity coupled with an increase in costs. The prior can be indirectly supported by the McKinsey study in section 3.2 while increased material expenditure and construction costs have been mentioned by others active within the bridge engineering sector in Sweden (see, e.g., Lövquist A et al 2021). In fact, the Swedish National Audit Office, NAO, (*Riksrevisionen*) recently published a governmentally sanctioned report identifying a significant cost increase in Swedish infrastructure projects from planning until completion (RIR 2021).

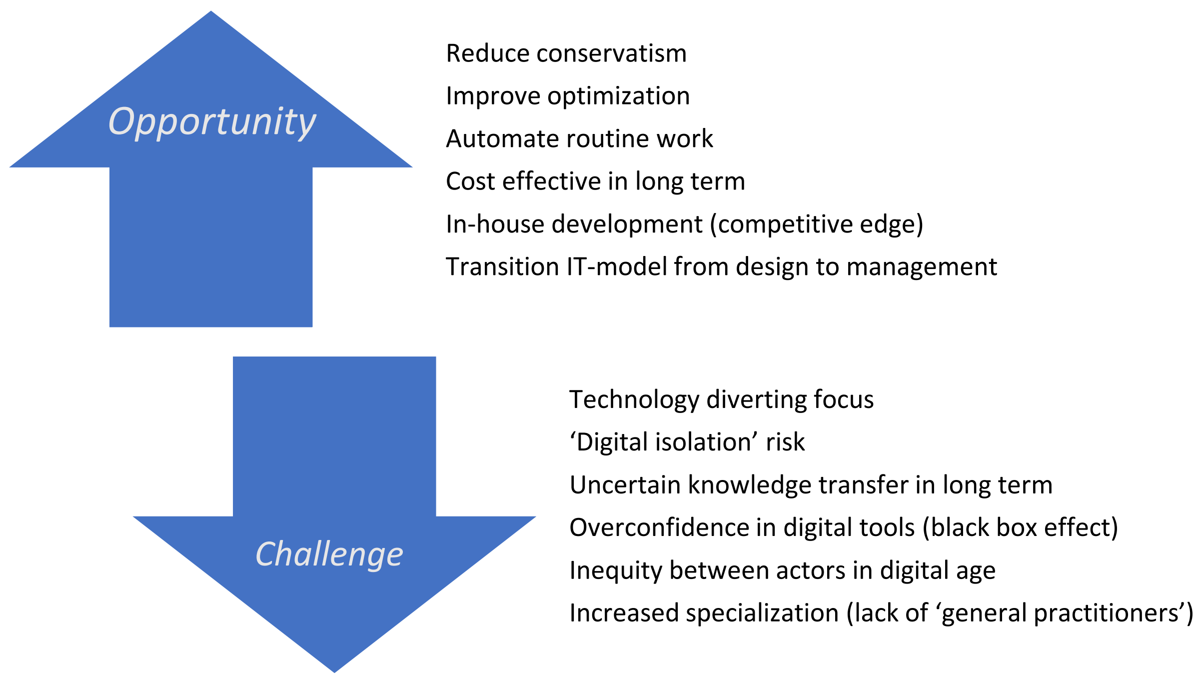

Figure 2. A summary of the opportunities and challenges associated with digital transformation and automation in bridge design based on conclusions from the focus group

When asked specifically about opportunities and challenges with digitalization and automation in bridge design, the focus group provided several topics based on their own experiences; see Figure 2. Opportunities with the adoption of digital models and technologies include reduced conservatism and improved optimization (e.g., of material expenditure) while routine work could be automated. Specific applications included the use of parametric design approaches for automating draft work (BIM) and automated digital routines for dealing with complex output form computational software (FE-models). Although, as previously mentioned, there were some concerns about increased design and building costs there was also optimism concerning long-term benefits in terms of increased cost-effectiveness in the future. Another interesting aspect which was mentioned by all the bridge consultants concerned in-house developments of digital tools and technologies. In fact, one of the members of the focus group indicate thar their firm had developed their own comprehensive software for bridge design which has given them a competitive edge in their field over the past few decades. Finally, one member of the group highlighted the opportunity of harmonizing bridge design practice with facility management.

Challenges associated with digital transformation and automation in bridge design includes a general concern of technological aspects diverting focus from other vital tasks. The group stated that a significantly large proportion of work conducted at their offices was required towards the use of digital tools. One mentioned the risk of *digital isolation* in which necessary social interactions (with, e.g., contractors or clients) may be negatively impacted when personnel were mostly working digitally and isolated at their workstation. In addition, there were some concerns of how effectively knowledge and experience could be transferred from senior to junior staff considering current (digitally focused) work protocols and specifically related to conceptual design decisions and design checking. The use of computation models and tools is ubiquitous, and the group agreed that there is a tendency for some to rely on results from software without adequate reflection and checking (i.e., black box effect). On the other hand, most indicated these models were often based on and compared with previous 'tried-and-tested' solutions (i.e., previous bridges) and that this helps prevent potential gross human errors.

A general challenge which was mentioned concerned the issue of *digital inequity* between industry actors. One mentioned that it has become easy to require work by sending an e-mail while the amount of work this demand entails may not be adequately considered leading to added and perhaps unnecessary workload and pressure. A possible indirect consequence of this is an increased proneness towards human error, i.e., more stress and less time creates (latent) conditions conducive to human error. Finally, one interesting aspect which was identified during one of the brainstorming sessions concerned the trend of increased specialization of industry actors. This may be advantageous in many ways (e.g., improved sub-optimization) but may have long-term implications if it comes at the cost of general and holistic knowledge. To use a medical analogy, is there a future need for bridge '*general practitioners'* to complement the various bridge *specialists*? Specialized knowledge is important an overall conceptual understanding for how structure can be designed and built is essential especially for attaining a global optimization of overall conceptual design solutions.

4.3 Questionnaire

Based on the input from the focus group, a questionnaire was created and distributed to bridge industry contact persons during spring 2021. The distribution was carried out through e-mail where each recipient was asked to forward the questionnaire link to other colleagues and contacts; the response rate could thus not be determined. The questionnaire, which can be found in Appendix 1, contained 32 questions thereof 14 being open-ended questions. The results are categorized and presented in text, graphically, and in some cases using word clouds; the latter is useful in visualizing results from the open-ended questions. In total, 13 responses to the questionnaire were received. An overview of the results from the questionnaire are provided in the sections that follow.

4.3.1 Professional background & experience with digital tools (Q1-Q16)

Of the 13 that responded, 10 worked as bridge consultants, two were from academia and one worked for the bridge owners/managers. In terms of the professional roles at the company, most (8) were bridge designers (*konstruktör*) while some were technical experts or specialists (2) or had other roles (3) including researchers or BIM-responsible. The total experience for the respondents (within their current professional role) is provided in Figure 3.

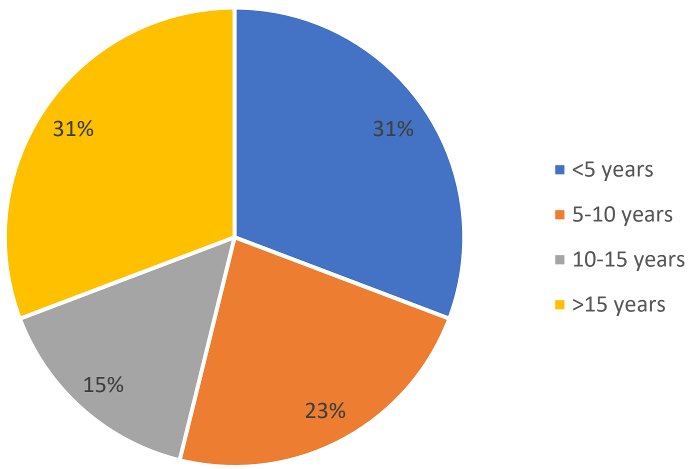

Figure 3. Experience of 13 respondents to questionnaire

It was clear from the results that most of the respondents spent a significant amount of time working with digital tools (not including e-mails or administrative tasks). In fact, 8 (62%) stated that more than 2/3rd of their time at work was done with the aid of digital tools while only 3 (23%) stated this as being less than a 1/3rd of their time. Interestingly, when the question was formulated the other way around (i.e., how much work time is spent without digital tools) then the results were slightly different although the trend was the same. In addition, only 2 (15%) of the respondents spend more than a 1/3rd of their time with administrative tasks while 9 (75%) stated that they spend less than 1/3 of their time communicating with colleagues (internal or external). Thus, the average respondent is a bridge designer with about 10 years work experience where current work is done mostly with the aid of digital tools.

4.3.2 Opportunities/challenges with digital transformation (Q17 & Q27)

A summary of the cited opportunities and challenges mentioned by the respondents is provided in Table 3. In general, the respondents provided longer responses concerning the latter with most focusing on the engineers' role and (potentially negative) development considering the ubiquitous reliance on digital software (specifically calculation software). However, the respondents also highlighted several opportunities. For instance, it was stated that digital transformation and automation could facilitate a greater optimization of structures while considering multiple design criteria simultaneously. In this way, human and material resources would be saved leading to positive economic and sustainability impacts. Parametric design and drafting were also specifically mentioned as promising methods, which are used to some extent already now. Another opportunity was related to increased use of digital platforms for more effective knowledge sharing, document exchange, as well as for coordination and management of projects. Finally, the respondents stated that automation of routine work (e.g., concerning standard solutions) was positive and could allow for more time spent towards other relevant work tasks.

Table 3. A summary of cited opportunities and challenges with digital transformation and automation in bridge design (these are listed in no particular order)

Opportunities	Challenges
Optimization	Over-reliance and faith in digital tools
Parametric design & drafting	"Black-box" effect
Digital platforms (knowledge, documents, etc)	Greater need for adapted design checking
Digital coordination & management	Reduced competences of future engineers
Automation of routine work	High initial investment (time/money)
More time for other relevant tasks	Digital technologies divert focus

There were also several challenges mentioned. Most (9 of 69%) of the respondents stated concerns with calculation software including the 'black-box' effect in which the user is less aware of the inner workings of the software. The respondents further highlight the need for adapted design checking to root out potential errors and reduce the risk of overreliance on the software and the results. An issue raised concerning the latter is that it may be more difficult for the engineer (especially those with less experience) to retain a holistic understanding of the structure and how it behaves. Some even went further to highlight the risk of negative impacts to engineering competences, i.e., future engineers may be less competent because of reliance on digital tools. Other issues which were highlighted include a high initial investment, both in terms of time and money, for adopting new digital technologies. However, it was also stated that this investment would likely be justified and result in improvements in the long term.

As an aid for visualizing the questionnaire results for these questions, words clouds were also created (in Swedish); see Figure 4 and Figure 5. The word clouds included the following filters to retain only the relevant words:

- Irrelevant words such as *finns*, *detta* and *eller* (in English: exists, this and or)
- Words with fewer than 5 characters were removed (except for some keywords including FEM & BIM)
- Prominent words from the questions themselves which may be repeated in the response were also removed, e.g. *digitalisering, automatisering*, etc (in English: digital transformation, automatization)

Figure 4. Word clouds for questions Q17 concerning what the respondents perceive as opportunities associated with digital tools and automation. The red words (most common) translate to: use, structure, design, management, organize.

Figure 5. Word clouds for questions Q27 concerning what the respondents perceive as challenges and risks associated with digital tools and automation. The red words (most common) translate to: calculations, black (box), result, tool, bigger.

4.3.3 Observed digital trends, in-house digital tool developments, parametric design & driving forces for digital transformations (Q18-22 & Q25)

Observed digital trends included automation of digital calculations and specifically the input and/or output from FE-software. In addition, the general ambition of automating routing tasks was mentioned, where the previous example would fall within such a category. The application of parametric design for both FE-, BIM or other 3D models (e.g., Grasshopper) were also stated as ongoing trends. There were also some who mentioned further incorporation and consideration of sustainability aspects using digital tools. Finally, the increased use of digital tools for communication and working from home were also highlighted. This final trend is not localized to the bridge or even structural engineering sector but could be seen as a general result of the Covid-19 pandemic; a fact that was also mentioned by a few of the respondents. Figure 6 shows a word cloud visualizing these results.

The second pair of questions concerning in-house digital tool development and parametric design could be seen as examples of possible digital trends. For the former, 10 (77%) of the respondent stated that digital tools had been developed and adopted at their own company. Consistent with the previous results, most of the respondents mention such tools in relation to the input and/or output to/from finite element (FE-) software while some mention draft work (CAD/BIM). Concerning parametric design, 9 (69%) said that they had some experience with this while respondents usually highlight the application of this approach in connection with either structural design calculations (e.g., FE-modelling and output) or for draft work (CAD/BIM).

Figure 6. Word cloud for questions Q18 concerning digital trends observed by respondents at their own company. The red words (most common) translate to: development, communication, calculations, better, parametric.

Finally, most (8 or 62%) indicated that digital transformation at their company was internally driven while some requirements from the clients and external actors were also highlighted and indicated by some (3 or 23%) identify this as being the primary driving force. The latter was also specified in the previous questions concerning trends where it was mentioned the use of BIM has become more common because of requirements from the Swedish Transportation Administration (*Trafikverket*).

4.3.4 Verification of output from calculation software, communication of results & knowledge transfer (Q23, Q26, & Q29)

One of the of the challenges highlighted by the respondents in a previous question concerned the verification of input and output of calculation software. A common response from the questionnaire in this regard was the use of complementary simplified calculations either by hand or with the use of simpler software such as, e.g., Mathcad or Excel. About 5 or 38% of the respondents explicitly state that hand-calculations are used. It was also specified that design checks were done by the engineer using the software (i.e., self-checking) while checking (e.g., by a colleague) was also mentioned. The word *independent* was sometimes included although it could not be concluded that its omission indicates a lack of independent checking. Automated, or half-automated, checking procedures, were also mentioned by a few of the respondents although this appeared to be less common. Another verification approach which was mentioned concerned a comparison with previous projects. Figure 7 shows the word cloud for this question.

Figure 7. Word cloud for question Q23 concerning how the output from digital calculation tools are verified (quality control measures). The red words translate to: output, control(led), independent

Concerning the communication of results from digital tools to others within or outside the company there were a variety of answers which touched upon some aspects of the question. Some of the respondents mention internal communications between colleagues while others mention distribution via pdf or through various online databases. Still others indicated that the question was too broad, irrelevant or that they were not sure.

Respondents stated that knowledge transfer was carried out through both formal and informal settings. These included seminars, (digital) meetings, networking activities, cooperation, discussions, as well as demonstrations. Most perceive that the knowledge transfer with their company works well for them, or at least few indicated otherwise.

4.3.5 Reliance on existing bridge solutions (Q24)

A significant portion of the respondents (7 or 53%) indicated that most of the new bridges designed are conceptually based on previous experiences, e.g., with older bridges that have been designed previously. Concerning the same questions, 5 (or 38%) did not respond at all, stated that they were unsure, or indicated that the question was irrelevant for their specific role at the company. Only one of the respondents stated that only half of the bridges were designed in this way.

4.3.6 Quality of existing digital tools, historical perspective, & impacts on the work process (Q28, Q30-31)

Concerning the quality of the digital tools used, approximately half of the comments were positive while half were negative. For the former, little additional commentary was provided. However, negative comments highlighted potential improvements including the need to fix bugs, improve the presentation of results, and provide more flexibility. One issue that was mentioned was the advantage of being able to provide text (script) based input; a feature which may not always be possible.

The results from the questionnaire indicated that, for those with longer experience, there is a significant development towards increased digitalization in their work. For the less experienced respondents (<10 years), little or no change was noted. Responses to the final question concerning how digital tools have impacted the work process were mixed. Most (7 or 54%)) highlight both positive and negative developments, two indicated that the work is more effective today, and two provided only negative comments; the remaining two respondents were unsure. Positive comments were not always elaborated although one respondent indicated that there was a general higher quality of the structures made today compared with past decades. Negative comments were more elaborated and related to reduced competences of today’s bridge engineers, disproportionate time spent with digital tools, as well as complex and overly comprehensive design codes.

5. Conclusions – synthesis of results

The output from the literature review, the focus group and the questionnaire all indicate a high interest in and trends toward increased digitalization and automation. Several opportunities and challenges were also identified although the study indicates current focus within the bridge design in Sweden is on digital tools for design calculations and drafting. On the other hand, it was also clear that there is a drive for increased digital transformation and the adoption of more digital technologies with some current efforts geared towards in-house development of digital tools. Specific examples include automatic handling of input/output from FE-software and parametric design applications for drafting work. Although it is unclear exactly how these types of transformations are impacting the bridge engineering sector, there is a broad acceptance that these types of changes are and will continue to happen. Furthermore, digitalization and automation have, according to industry inputs in this study, led to improvements including reduced conservatism, freeing up time from routine work, as well as making it easier to communicate digitally (especially in light of the Covid-19 pandemic). On the other hand, several concerns were raised concerning the impacts these developments are and will continue to have. In fact, many of the concerns related to the human factor and the risk for gross human errors in light of a high dependency on digital technologies and tools. Overall, it is necessary to investigate further, and in more detail, both positive and negative impacts of ongoing and future digital transformation and automation. To facilitate a more informed way forward, such impacts should be assessed and evaluated in relation to the structural engineering profession, the bridge and construction sector (including all relevant stakeholders), the individual engineer(s), as well as society at large.

5.1 Ideas for future research & the way forward

As a summary of the findings from this pre-study, a list of broad research topics considered relevant for future study has been prepared by the author of this report, see below.

- More in-depth investigations and analyses of previous and ongoing digital transformation activities within the bridge construction sector (focusing on different actors and phases of the construction processes) and exactly what (quantifiable) impact these have had (both positive and negative).
- Professional variability considering modern design approaches and control systems – the human-machine interface and how to effectively avoid human error considering an increased reliance on digital tools?
- Facilitating the transfer of IT models (e.g., BIM models) from design to facility management – how can this be done in an efficient and meaningful way to streamline the digital workflow and, e.g., improve maintenance planning?
- The (digital) interface between Architecture, Engineering, and Construction (AEC) actors – complexities, communication, cooperation, and other relevant aspects. How have and are these evolving and what are the consequences for specific infrastructure projects?
- The adoption of state-of-the-art digital technologies considering a (commonly) traditional building sector – what are the challenges and how can these be effectively overcome without losing focus on the end goal of delivering safe and functional structures? Focus can be on different actors and phases of the construction process.

- Effective knowledge and experience transfer considering a digital work environment – how does this currently work (within divisions, companies, the industry, academia, etc) and how can it be improved to avoid e.g., loss of tacit (unspoken) knowledge?
- Future needs for the structural and bridge engineering profession and what this means in terms of engineering education needs (both at universities and continued professional development) – what must the future engineer know and do (different knowledge types and tasks can be considered)? (One specific question could concern the need for a *general practitioner* of structural engineering to offset a possible over-saturation of specialists)
- The influence of extensive and complex design codes in combination with more complex and comprehensive design calculations – what are the impacts and how can this be improved?

The previous list is based on a synthesis of the results from the focus group, the questionnaire, as well as critical reflection by the primary author of the study. It is not exhaustive, and each point requires further elaboration and development before they can be presented formally as part of future research applications. It should also be noted that no general investigation has been undertaken to determine the current state-of-the-art concerning each of these topics (apart from what has already been presented in this report). However, to provide some insights, two topics, which recurred in discussions with the focus group as well as in the questionnaire, will be further elaborated upon in the sub-sections that follow. These specifically concern the use of digital tools for structural design calculations and BIM in construction projects.

5.1.1 Computational digital tools

Currently in practice, computational digital tools used for structural and bridge engineering essentially concern the use of the Finite Element Method (FEM) implemented in FE-software. This method has its roots in the aeronautics industry around the 1950s (Kurrer 2008). Nowadays, engineers can solve numerically complex structural configurations and account for non-linear material and geometric behavior using FEM; thus, potentially reducing design conservatism in comparison with simpler methods solvable by hand. The speed with which these calculations take place and the sophistication of the FE-models themselves have also developed quite significantly in recent decades.

This study and other publications have indicated, however, an awareness from within the (bridge and structural) engineering community of the potential risks associated with improper use of digital tools (Björnsson et al. 2016, Borthwick et al 2012, MacLeod 2016). Both the American Society of Civil Engineers (ASCE) in the US and IStructE in the UK had, as early as 1997, prepared reports and guidelines for the proper use of computers for engineering calculations (Brown 2006). Previous structural failures which are often cited as associated with errors in computer-based calculations include the sinking of the Sleipner Platform in 1991 (Jakobsen & Rosendahl 1994, Selby et al. 1997) and collapse of the Hartford City Center roof in 1978 (Martin & Delatte 2001). The more recent collapse of the Perkolo Bridge in Norway has also been attributed to the improper interpretation of computer-based structural calculations (Bell et al. 2016, Björnsson et al. 2016). Björnsson et al. (2016) highlighted the following questions in relation to the failure of this timber truss bridge (which included over 1200 pages of design calculations):

- Are high levels of modeling sophistication warranted for relatively simple and well understood structures?

- Are high degrees of complexity associated with the design calculation possible error-promoting sources?

Advanced computational structural modeling has allowed engineers to design and build structures which could not have been realized in the past, e.g., thin-shelled structures with complex geometries. However, the output of a model is only as good as the provided input and, to ensure that no errors were made, it is vital that the engineer understand and verify the results (Borthwick et al. 2012). Checks based on simplified hand calculations, founded on a basic conceptual understanding of structural performance, as well as a healthy dose of critical reflection are essential for reducing the risk of errors (MacLeod 2016, Björnsson et al. 2018). One specific issue which should be highlighted concerns that of precision vs. accuracy (or suitability). The significance and impact of overly precise assessments containing erroneous assumptions or inputs is illustrated in Figure 8. A simplified model may vaguely capture the behavior of a structure, as the left target indicates, while an advanced model may provide more precise (and less varied) results which, if incorrect, will still be off the mark as indicated by the right target. Another highly relevant issue concerns the high variability of engineering performance observed in practice and the potential negative impacts this may have to structural safety and function (Fröderberg & Thelandersson 2015). A qualitative study of experienced engineers (ave. 20 years work experience) by Klasson et al. (2018) revealed a significant variation in terms of the assumptions made when designing slender roof structures; in some cases, these assumptions were found to yield unstable roof design solutions. An interesting future research concerns obtaining a better understanding of this (professional) variability, specifically in relation to software usage. Furthermore, it is on high relevance to investigate the impacts that this has and can have in terms of the performance and safety of the designed structures.

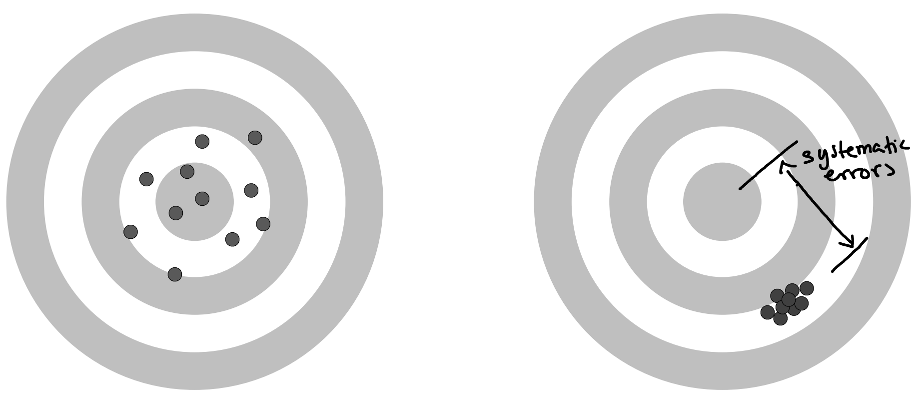

Figure 8. A vaguely accurate or precisely wrong model; wrong in this light indicates errors in the model assumptions or input (adapted from Reason 1990).

5.1.2 Building Information Modelling (BIM)

The drive towards digital transformation within the construction industry (at least in Sweden) is often associated with the adoption of Building Information Models (BIM). BIM combines object oriented three-dimensional (3D) models; information can be added to the physical dimensions to consider time (4D), cost (5D), sustainability (6D), facilities management (7D), and so on (Eastman et al. 2011). The information in the model intends to support the needs during the complete life cycle of the building. Information is stored as attributes to database objects representing the building and all its parts from different aspects. A key concept in BIM is interoperability, i.e., the possibility of information exchange between different actors, software, and technical platforms (Smith and Tardif 2009). The question of common exchangeable information is not a new one but has been in focus since the mid 40's and addressed through the development of common building classification and specification systems.

According to the focus group, the use of BIM in the Swedish housing industry has become widespread while this development has not had the same impact for the bridge sector. However, the Swedish Transport Administration have a BIM strategy in place for facilitating the adoption of BIM in infrastructure projects and in all project and operational phases (TRV 2017). In fact, for projects procured as of 2015 they have made BIM a requirement[8]. A non-profit organization, BIM Alliance, was formed in Sweden in 2014 which 'promotes implementation, management and development of open standards, processes, methods and tools, aiming towards the best possible IT tools and open standards that are utilized to stimulate effective processes within the built environment.'[9] The organization currently has ca 180 companies and organizations representing real estate owners, architects, technical consultants, contractors, building material suppliers and software companies.

BIM is by no means a new technology, having been introduced already within academia in the 1970s (Eastman et al. 1974). Thus, its adoption in the construction industry, especially in the case of bridges, has had a significant lead time. Research in Finland identified 23 key challenges of implementing BIM in the construction industry and realizing its potential (Tulenheimo 2015). It was concluded that successful BIM technology implementation requires consideration of the complexity of BIM requirements, customers, social aspects, company's own organization, information, and communications technologies. Merchbrock et al (2015) characterized BIM practice as often being 'messy' and characterized by a large degree of unnecessary rework and workarounds – or steps taken by practitioners faced with inadequate resources. Such workarounds are often necessary but may negatively impact quality in construction design. Some other challenges for wider BIM adoptions include:

- The lack of systematic legal and contractual systems; Arshad et al. (2019) identified 14 significant legal risks and formalized mitigation strategies within a proposed contractual framework for design-bid-build projects
- Inadequate relevant knowledge and expertise was round to be a primary root risk category for risk paths in BIM adoption based on a study in China (Zhao et al. 2018). Other categories included technological issues, poor information sharing and collaboration and liability for data input.
- The need for semantic interoperability was shared by the BIM Strategist at the Swedish Transport Administration in an interview with the European Commission (Axelsson 2020). The STA have the aim of implementing BIM across the whole lifecycle and identified the challenge of transferring information in the asset management phase.

Concerning BIM and risk, other researcher have indicated the potential for BIM to reduce risks in construction projects as well as incorporating risk management approaches within BIM (see, e.g., Björnsson et al 2018). Research and publications concerning potential risks with the (mis)use of BIM or other possible negative impacts are, to the author's knowledge, decidedly lacking.

[8] Byggnadsinformationsmodellering (BIM) – Trafikverket: https://www.trafikverket.se/for-dig-i-branschen/teknik/byggnadsinformationsmodellering-bim/

[9] About BIM Alliance Sweden - BIM Alliance: https://www.bimalliance.se/om-oss/in-english/

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[10] SAIC provides governmental services and information technology support and are US based

Appendix 1 – Questionnaire (in Swedish)

Introductory text

Denna enkät syftar till att få en bild av möjligheter och utmaningar med ökande digitalisering inom brodimensionering och byggnation. De flesta av frågorna är öppna frågor, enkäten beräknas ta ca 10-20 minuter att genomföra. Med ökande digitalisering menas i detta fall den ökning och förändring som skett inom byggbranschen gällande projektering, där digitala beräkningar och modellering mer och mer ersatt andra typer av metoder. Ökad digitalisering omfattar även ökad automatisering, både av projektering och av andra arbetsuppgifter, molnbaserade tjänster, ökad tillgång till mobilt internet och möjligheter till att utnyttja VR (virtual reality), AR (augmented reality), samt AI (artificiell intelligens). Den pågående globala Corona-pandemin har ytterligare bidragit till en ökande digitalisering, med en mycket snabb utveckling. Projektet som denna enkät är en del av är en förstudie som ska utvärdera möjliga strategier för hur broingenjörers roll kan stärkas i den moderna projekteringsprocessen för att reducera fel och förbättrad prestanda, relaterat till den ökande digitaliseringen. Projektet finansieras av Trafikverket/BBT och genomförs av seniorforskare vid Avdelningen för Konstruktionsteknik, Lunds Tekniska Högskola. Resultaten från projektet kommer att ligga till grund för en större, mer djupgående, forskningsansökan i samma ämne, ditt bidrag via denna enkät är därför mycket uppskattat. Tack på förhand

Ivar Björnsson och Oskar Larsson Ivanov Konstruktionsteknik, Lunds Tekniska Högskola

Questions

Table 4. Questionnaire questions

NR.	FRÅGA	TYP
'Q1'	'Vilken typ av företag/organisation arbetar du på? - Brokonsult'	Ja/Nej
'Q2'	'Vilken typ av företag/organisation arbetar du på? - Entreprenör'	Ja/Nej
'Q3'	'Vilken typ av företag/organisation arbetar du på? - Beställare/broägare'	Ja/Nej
'Q4'	'Vilken typ av företag/organisation arbetar du på? - Programutvecklare'	Ja/Nej
'Q5'	'Vilken typ av företag/organisation arbetar du på? - Annat'	Ja/Nej
'Q6'	'Vilken typ av företag/organisation arbetar du på? - Om annat:'	Ja/Nej
'Q7'	'Vilken yrkesroll har du?'	Fritext
'Q8'	'Hur länge har du arbetat i din nuvarande yrkesroll? - Mindre än 5 år'	Ja/Nej
'Q9'	'Hur länge har du arbetat i din nuvarande yrkesroll? - 5 - 10 år'	Ja/Nej
'Q10'	'Hur länge har du arbetat i din nuvarande yrkesroll? - 10 - 15 år'	Ja/Nej
'Q11'	'Hur länge har du arbetat i din nuvarande yrkesroll? - Mer än 15 år'	Ja/Nej
'Q12'	'Hur länge har du arbetat i din nuvarande yrkesroll? - Kommentar'	Ja/Nej
'Q13'	'Hur stor del av din arbetstid spenderar du med digitala verktyg? Det kan vara verktyg för beräkning, modellering men även för planering av arbete. Räkna inte med administrativa uppgifter eller t.ex. att svara på e-post.'	Fritext
'Q14'	'Hur stor del av din arbetstid spenderar du på arbetsuppgifter som inte omfattar digitala verktyg? Det kan till exempel vara handberäkningar, genomläsning av regelverk, etc.'	Fritext
'Q15'	'Hur stor del av din arbetstid lägger du på administration? Det kan vara uppgifter som t.ex. att ladda upp handlingar i olika plattformar, införa metadata, organisera och administrera möten etc.'	Fritext

'Q16'	'Hur stor del av din tid spenderar du med kommunikation med andra, kollegor eller beställare/entreprenör?'	Fritext
'Q17'	'Vad ser du för möjligheter med digitalisering/automatisering inom ditt arbete? Det kan exempelvis omfatta automatisering av kunskapsarbete, molntjänster, IoT (Internet of Things), mobilt internet, men kan även vara annat.'	Fritext
'Q18'	'Vilka digitala trender har förekommit på de företag du arbetat på? Se föregående fråga för exempel'	Fritext
'Q19'	'Har ni på det företag du arbetar på nu egna interna digitala verktyg som skapats för olika ändamål? Det som avses är verktyg (mjukvara) för t.ex. beräkning, databashantering, BIM, administrativa verktyg m.m. som är framtagna inom företaget men som inte kan köpas på marknaden.'	Ja/Nej
'Q20'	'Har ni på det företag du arbetar på nu egna interna digitala verktyg som skapats för olika ändamål? Det som avses är verktyg (mjukvara) för t.ex. beräkning, databashantering, BIM, administrativa verktyg m.m. som är framtagna inom företaget men som inte kan köpas på marknaden. - Om ja, till vad används dessa verktyg?'	Fritext
'Q21'	'Har du erfarenheter av parametrisk design? (t.ex. inom ritningsframställan, BIM, beräkningsverktyg)'	Ja/Nej
'Q22'	'Har du erfarenheter av parametrisk design? (t.ex. inom ritningsframställan, BIM, beräkningsverktyg) - Kommentar'	Fritext
'Q23'	'Hur hanteras och kontrolleras utdata från digitala beräkningar? Ange gärna i hur stor del dessa kontrolleras genom automatisering respektive för hand'	Fritext
'Q24'	'Bygger er konceptuella design på helt nytt eller baserar ni den på tidigare broar? I hur stor del?'	Fritext
'Q25'	'Genomförs satsningar på ökad digitalisering på eget initiativ, ser ni att ert företag vill digitalisera eller är det krav och efterfrågan från omgivningen, t.ex. myndigheter och beställare, som styr?'	Fritext
'Q26'	'Hur kommuniceras resultat från digitala verktyg till andra personer inom företaget eller andra aktörer inom byggbranschen?'	Fritext
'Q27'	'Vad ser du för utmaningar och risker med digitalisering/automatisering för ditt arbete?'	Fritext
'Q28'	'Hur upplever du att kvaliteten är på de digitala verktyg som du huvudsakligen använder i ditt arbete? Om det finns bristande kvalitet, vilken typ av problem uppkommer?'	Fritext
'Q29'	'Hur arbetar ni med kunskapsöverföring? Känner du att du i din roll kan få/överföra kunskap från dina kollegor på ett tillfredsställande sätt?'	Fritext
'Q30'	'Hur har din användning av digitala verktyg utvecklats under åren som du har arbetat inom branschen?'	Fritext
'Q31'	'Upplever du att de digitala verktygen har effektiviserat arbetsprocessen? Är ni mer effektiva idag än för 10 respektive 20 år sedan?'	Fritext
'Q32'	'Övriga kommentarer?'	Fritext