



Technical Report

Construction Automation and Robotics in Infrastructure

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Summary

In Sweden, as in many other countries, the construction and infrastructure sector are of large and growing importance for the economy and society. For instance, the construction industry's turnover equals 11% of the Swedish gross domestic product (GDP) (Byggföretagen 2021), and the Swedish Transport Administration plans to invest SEK 799 billion during the period 2022-2033 (Regeringen 2021). At the same time, the cost of infrastructure projects has increased more than the consumer price index (CPI) (Trafikverket (2021)), partly due to a poorer development of the productivity compared to other industries. An improved productivity and efficiency in the transport infrastructure and construction industry is therefore necessary. One way to increase productivity, improve the occupational health and safety, and sustainability is through automation and digitalization of the construction industry.

The aim of the present report has been to identify ongoing initiatives and existing research trends in construction automation with a focus on civil engineering, both nationally and internationally; and to identify potentials and challenges that exist for the development of construction automation. Furthermore, the prerequisites for the implementation of automation in the construction industry have been studied. The research questions were studied through a literature study and two thematic days on the subject.

The results from the literature study shows that a clear increasing trend exists, both nationally and internationally, in automation, digitization and robotisation in the construction industry. The same trend can also be seen in civil engineering for roads, bridges, tunnels, as well as in the mining industry.

With the mining industry as a role model, construction companies, universities, suppliers and clients together with small and medium-sized enterprises (SMEs) should come together to develop a common vision and a strategic roadmap to enforce automation and digitization of the construction industry. A development of both technical, organizational and financial structures is required, where an attractive business ecosystem can be developed, enabling the upscaling of construction automation. Interdisciplinary collaborations, test-beds at an early stage, competence development, new financing infrastructure and a common vision are crucial to create conditions for construction automation.

Keywords: construction automation, robotics, infrastructure, lifecycle

Sammanfattning

I Sverige, och även i många andra länder, är byggindustrin och transportinfrastrukturen av stor och växande betydelse för samhället och ekonomin. Byggindustrin omsätter 11% av svensk bruttonationalprodukt (BNP) (Byggföretagen 2021) och Trafikverket planerar att investera 799 miljarder kronor under perioden 2022-2033 (Regeringen 2021). Samtidigt har kostnaden för infrastruktur-projekt ökat mer än konsumentprisindex (KPI) (Trafikverket 2021). En möjlig orsak till denna ökning är en sämre utveckling av produktiviteten jämfört med andra branscher. En förbättrad produktivitet och effektivitet inom transportinfrastrukturen och byggbranschen är därför nödvändig. En sätt att öka produktiviteten och även förbättra arbetsmiljön samt hållbarheten är genom en automatisering och digitalisering av byggbranschen.

Syftet med föreliggande rapport har varit att identifiera pågående initiativ och existerande forskningstrender inom byggautomation med fokus på anläggningsbyggande, både nationellt och internationellt; samt vilka potentialer och utmaningar som existerar för en utveckling av byggautomation. Vidare har förutsättningarna för implementering av automation inom byggindustrin studerats. Forskningsfrågorna studerades genom en litteraturstudie samt genom anordnande av två temadagar.

Den utförda litteraturstudien visar på en tydligt ökande trend, både nationellt och internationellt, inom automatisering, digitalisering och robotisering inom byggbranschen. Samma trend kan också ses inom anläggningsbyggande för vägar, broar, tunnlar samt inom gruvindustrin.

Med gruvindustrin som förebild bör byggbolag, universitet, leverantörer och beställare tillsammans med små och medelstora företag (SMEs) samlas för att ta fram en gemensam vision och en strategisk färdplan för att driva igenom en automatisering och digitalisering av branschen. En utveckling av både tekniska, organisatoriska och finansiella strukturer krävs, där utvecklingen av ett attraktivt affärsekosystem som möjliggör uppskalning av byggautomation kan genomföras. Tvärvetenskapliga samarbeten, testbäddar i tidigt skede, kompetensutveckling, ny finansieringsinfrastruktur och en gemensam vision för ökad säkerhet, högre produktivitet och lägre klimatpåverkan är avgörande för att skapa förutsättningar för byggautomation.

Nyckelord: byggautomation, robotik, infrastruktur, livscykelperspektiv

Preface

This study constitutes a part of the project National Network for Automated Construction. The overall aim of the project is to coordinate the different research initiatives within the construction sector in Sweden to obtain increased national collaboration, exchange in knowledge within the field of automated construction and create conditions to set up test-beds for automated construction within the field of infrastructure engineering.

The project has been financed by the strategic research program Smart Built Environment and the Swedish construction industry's development fund, SBUF. The working group of the project consists of the authors. A reference group has assisted the project with valuable comments during the work consisting of: Lars Albinsson, Maestro; Tommy Ellison, Besab; Robert Larsson, Cementa; and Hans Alenius, Digital Route. In addition, a steering group has assisted the project with valuable comments concerning the work and initiation of the National Network for automated construction consisting of: Pontus Gruhs, Trafikverket, Ronny Andersson, Cementa; Mats Emborg, LTU; Jan Hillgård, JAHIL AB; Nils Rydén, Peab; Lars Redtzler, Byggföretagen; Johan Silfwerbrand, KTH; Joakim Jeppsson and Ulf Håkansson, Skanska; Thomas Nolte, Mälardalens University; Christina Claeson-Jonsson, NCC and Torbjörn Glad, JM.

Speakers and participants in the thematic days on automated construction held in May 2021 are also gratefully acknowledged.

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Contents

1. Introduction	1
1.1. Background.....	1
1.2. Aim.....	2
1.3. Report outline	3
1.4. Definitions	3
2. Methodology	7
2.1. Literature review	7
2.2. Activities in Sweden.....	8
2.3. Thematic days.....	9
3. Literature review.....	11
3.1. Automation in construction.....	11
3.1.1. Geographic focus	11
3.1.2. Publication sources	12
3.1.3. Research areas.....	13
3.1.4. Historical developments	15
3.1.5. Current topics.....	16
3.1.6. Benefits and challenges	17
3.1.7. Future steps	19
3.2. Automation in infrastructure	19
3.2.1. Highways.....	21
3.2.2. Bridges	27
3.2.3. Tunneling.....	33
3.2.4. Mining.....	40
3.3. Summary	48
4. Activities in Sweden.....	51
4.1. Introduction.....	51
4.2. Early work	51
4.3. Current work	54
4.3.1. Academia	54
4.3.2. Industry.....	55
4.3.3. Financiers and strategic innovation programs	58
4.4. Future trends	61
5. Thematic Days	65
5.1. Introduction.....	65
5.2. Thematic day 1: Technology	66

5.2.1. Automation in mining	66
5.2.2. Automation in construction	68
5.2.3. Automation in robotics	70
5.3. Thematic day 2: Organization and business models	72
5.3.1. Implementation requirements	72
5.3.2. The role of the client	74
5.3.3. Business models	75
6. Discussion	77
6.1. Current initiatives and trends	77
6.2. Potentials and challenges	80
6.3. Requirements for implementation	84
6.4. Business, project and ecosystem implications	86
7. Conclusions	89
References	91

1. Introduction

1.1. Background

The total investments in the Swedish construction industry, that is investments in real estate and infrastructure, amounted the year 2020 to 546 billion SEK (Byggföretagen 2021), which constitute approximately 11% of the Swedish gross domestic product (GDP). According to the Swedish government's proposal for the transport infrastructure 2022-2033, it is proposed that the total investments in the transport infrastructure sector during this ten-year period shall amount to 799 Billion SEK (Regeringen 2021). The proposal is based on the report "Proposal for national plan for the transport infrastructure 2022-2033 by the Swedish Transport Administration (Trafikverket 2021). Approximately 80% of the planned investments are allocated to railway projects, and 15% of the investments are allocated to road projects. The investments include both the construction of new, and the maintenance of existing, infrastructure. For example, 104 billion SEK is allocated for the new high speed railway main lines.

With those large investments being planned in the infrastructure sector in the coming decade, it is important that design, construction and maintenance are being performed efficiently. However, according to Trafikverket (2021) the costs in larger planned infrastructure projects have increased more than the consumer price index (CPI). For example, the projects not yet started have increased with more than 50%, compared to the previous national plan for the years 2018-2029. There are several reasons for this increase, but one possible reason according to Trafikanalys (2021) may be a lower productivity development in the transportation infrastructure sector compared to other sectors in the Swedish industry. This is supported by Albinsson (2019) which, based on data from SCB, states that the costs in the construction industry during the last twenty years have increased eight times the CPI.

Thus, it is clear that an increased productivity and effectiveness within the transportation infrastructure is needed. This can save the society large

amounts of money, reduce the use of natural resources and the emissions of carbon dioxide, and strengthen the competitiveness of the Swedish construction industry. According to the climate policy framework, Sweden shall have zero net emissions of greenhouse gases by the end of 2045 (Regeringen 2020). If this is to be possible, a transformation of the construction industry is needed towards more efficient design, construction and maintenance.

Today, a rapid development is occurring within the areas of digitalisation, robotics, artificial intelligence and sensors. This enables the construction of single unique elements or modules to be manufactured in a more automated way. Uncomfortable or dangerous tasks can be replaced with production by robots. A striking example is the ongoing development of a robot for automated construction of reinforcement cages by Skanska in collaboration with Mälardalen University (SBUF 2022), which has the potential to significantly increase productivity for this type of construction activity. At the same time, the uncomfortable working postures that tying rebar constitutes, disappear. The development of autonomous systems may also enable future development of almost fully automated construction sites with real-time updating of the construction progress and new possibilities for more efficient maintenance. Additive manufacturing in combination with the use of new types of materials also opens up for new production methods and new exotic designs. With these techniques, it is the author's belief that increased productivity and more efficient design, construction and maintenance can be achieved – a belief also shared with the Swedish Transport administration who judge that there exists a potential to increase productivity by implementing new techniques within digitalisation, automation and electrification (Trafikverket 2021).

1.2. Aim

This report aims to answer the following three main research questions:

- 1) What are the current initiatives and existing research trends in the field of construction automation with a focus on infrastructure, both from an international and a national, Swedish, perspective?
- 2) What are the potentials and the challenges in construction automation and robotics?

- 3) What is needed for large-scale implementation of automation and robotic solutions in the industry?

1.3. Report outline

The report starts in chapter 2 with a description of the methodology used. Thereafter, in chapter 3, the results from the literature review are presented, with focus on the current status, trends and future possibilities, followed by examples in the infrastructure sector (highways, bridges, tunnels and mines). In chapter 4, a review of ongoing activities within automated construction in Sweden are presented. Chapter 5 discusses the findings from the two thematic days arranged within the project on construction automation. The results are discussed in chapter 6, with focus on existing trends, potentials, and challenges in construction automation, and what is needed for large-scale implementation in the industry. Conclusions and recommendations for future work are presented in chapter 7.

1.4. Definitions

According to Howe (1998), the main difference between manufacturing in the construction industry, and manufacturing in other types of industries, is that the architecture in the construction industry as a rule is unique. This results in a need for the production of single, one of a kind, components – a need that constitutes one of the main challenges in the implementation of automated construction.

Construction automation includes the use of automation systems, i.e. some sort of robotic system. To understand the area of construction automation, it can be separated into two main categories: (i) on-site construction robots, and (ii) robots used in a prefabrication production process where the product is moved or transported to the construction site. There are also examples of prefabrication on-site as setup.

Already during the 1980's, 150 different types of automated systems or robots were developed in Japan for the construction industry (Åhman 2013). Åhman (2013) categorized them in the following four categories: (i) framework, (ii) post handling, (iii) inspection, and (iv) maintenance. The categories mentioned by Åhman (2013) are all examples of single task robots. Many of whom are constraint to a work cell. A work cell is a place where a

robot is permitted to work – often sealed off for human interaction or intervention due to the risk of injuries. However, a construction site often consists of a large area, which implies that on-site robots need to move around on the site. This put requirements on on-site robots to be aware of their surroundings, and to be able to communicate with each other in order to perform all the on-site decisions needed to complete the construction. Today, these issues imply restrictions of what on-site construction robots are able to do.

The following notion for different generations of robots were introduced by Moravec (2000) to describe the evolution of robot technology in the near future, with a division of the generations with respect to their intelligence and intellectual capacity: (i) generation zero, used to describe earlier developments in robot technology, (ii) first generation robots that has an autonomy and intellectual capacity that is comparable to that of a lizard (available: 2010), (iii) second generation robots that are capable of learning and their intelligence is comparable to that of a mouse (available: 2020), (iv) third generation robots that shall be comparable to that of a monkey (available 2030), and (v) fourth generation robot's with an intelligence that shall be comparable to that of human beings (available: 2040).

Bock et al. (2012) made an extensive categorisation of the use of more advanced construction automation technologies, including exoskeletal and humanoids in the construction industry, see Figure 1. They categorized the working environment with respect to two different aspects, as structured to more and more unstructured and the use of human interaction and with the use of more and more “Ambient intelligence”. They concluded that there would be different generations of robots with different amount of intelligence. Bock & Linner (2015) furthermore categorized the development into five different areas: (i) robot-oriented design (design and management tools for using automation and robotics in construction), (ii) robotic industrialization (automation and robotics for customized component, module, and building prefabrication), (iii) construction robots (elementary technologies and single-task construction robots), (iv) site automation (automated/ robotic on-site factories), and (v) ambient robotics (technologies for maintenance, assistance, and service).

Exoskeletons and Humanoid Robots in Construction		Ambient intelligence				
		Human interaction				
		Element Technology	Sub Systems	Total Systems	Autonomous Systems	Disrupted Systems
<div> <div>Structured environment</div> <div>Unstructured environment</div> </div>	Mining, dam, Tunneling, Road construction	Generation 0 robots				
	Stationary industry (Component, prefab)					
	On-site construction	Generation 1 robots				
	Facility Management					
	Services in built environment (Building to City Scale)	Generation 2 robots				

Figure 1. Categorization of development areas for exoskeletons and humanoid robots in construction (Recreated from Bock et al. 2012)

The categorization by Moravec (2000) are mainly categorizing the automation of more and more complex tasks, and the categorization by Bock et al. (2012) and Bock & Linner (2015) focus on the construction phase rather than the whole construction process and did not address for example logistics or transportation as part of the problem. However, Howe (1998) concluded that a top-down view is needed to understand the changes in the design process that has to be included, and implies that the design process needs to be made aware of the limitation of the manufacturing method. Bock (1988) proposed “Robot-Oriented Design, ROD” as a way of designing for the use of robotic assembly. In addition, NASA has been defining “Design guidelines for automatic assembly in outer space” (Dwivedi et al. 1989). This shows that design for manufacturability or design for automation needs to be used and included in construction automation. Howe (1998) further concludes that the impact from construction automation is on the whole process. In order to fully implement and fully assimilate the benefits from automated construction, a new logistics chain has to be arranged including: design for robotic construction, logistics, transportation, and material handling. Thus, it can be concluded that the whole chain has to be digitalized and automatized to fully get the benefits out of digitising, automating, and robotizing of the construction industry.

In this report, *Construction Automation* is defined as automation of a single task construction robot to more advanced automated tasks operated in

an automated system made up by single task construction robots (STCR) or other automated systems, guided or controlled by an overall automated, or AI operated, control or supervision function; the definition includes design, the construction process and maintenance together with the overall logistic chain – with the overall aim to reduce the amount of input from a human operator in order to obtain higher productivity and a safer work environment and reduce human induced errors.

1.5. Limitations

The literature study in chapter 3 is based on peer-reviewed articles from the Scopus database only. While this ensures a manageable scope and a high quality of references, it excludes other publications and conference articles which may be relevant from an industry perspective. To address this limitation, the review of ongoing activities within automated construction in Sweden in chapter 4 is also based on other relevant sources such as conference proceedings and research reports, etc.

The report focuses on the applications of construction automation in an infrastructure context. Automated housing construction is not included.

In addition, the examples of automated construction are limited to the description of relevant techniques used in a Swedish context (e.g. only the drill and blast method in tunneling), even if other techniques are used elsewhere in the world.

Furthermore, even though the aspects of the industry discussions are to a large extent overlapping with literature findings, they represent a Swedish perspective and may differ from other countries.

2. Methodology

To answer the three research questions stated in chapter 1.2, a methodology which included three main activities was chosen: (i) a systematic literature review in the Scopus database on automated construction with particular focus on infrastructure, (ii) an identification of ongoing research and existing research centers in academia and industry in Sweden combined with a supplementary literature review to identify published research in Sweden not covered by the review in the Scopus database, and (iii) thematic days where participants from industry and academia presented ongoing research and discussed challenges for implementation of automated construction in Sweden. In the following sub-chapters, a more detailed description of the methodology for each activity is given.

2.1. Literature review

The literature review in the Scopus database highlights key areas and research patterns in the field of automation in construction, with a particular focus on selected infrastructure areas. A visualization of the steps followed for the literature review is shown in Figure 2.

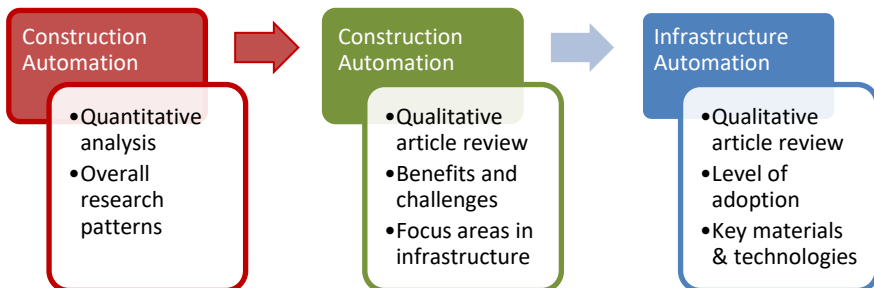


Figure 2. Structure of the literature review performed in the Scopus database

All analyses performed for the literature review were based on search results retrieved from the Scopus database in November 2020. Scopus is one of the major scientific databases spanning different scientific fields and contains, in comparison to Web of Science, more articles from recent years, which was considered important in the rather new field of construction automation as stated by Aghaei Chadegani et al. (2013) and Hosseini et al. (2018). All searches were limited to scientific journal articles and only English results were considered.

At first, the more general subject of construction automation is analyzed. A bibliometric approach was adopted to get an overview of trends in the construction automation research in terms of dominating keywords, journals and geographic regions. The search focused on publications with search words “Construction Automation” in their titles, abstracts or keywords and yielded a total of 140 articles of which 129 articles were thematically related. Results are presented using Bibliometrix for R, a literature review package for visualizing bibliometric clusters and networks (Aria & Cuccurullo 2017).

Based on these findings, key areas in the field of infrastructure automation were chosen with a focus on highways, bridges and tunnels. Table 1 presents the keyword combinations (connected by AND, e.g. automation AND construction AND highway) used for filtering relevant research contributions in Scopus.

Table 1. Keyword search results

Search keywords in Scopus	Highway	Bridge	Tunnel
Automation AND Construction	64	75	71
Robotics AND Construction	29	38	29
Additive Manufacturing AND Construction	0	9	0
Control System AND Construction	98	0	94
Operation AND Automation	124	139	61

2.2. Activities in Sweden

Identification of existing research groups in academia and industry were identified. The largest universities in Sweden were included, together with those where the project group knew that research on construction automation

is performed. The following universities were included: Chalmers University of Technology, Lund University – Faculty of Engineering (LTH), KTH Royal Institute of Technology (KTH), Luleå University of Technology (LTU), Linköping University and Mälardalen University.

A supplementary literature review was performed for identification of performed and ongoing research within the Swedish construction companies and research institutes. This supplementary literature review focused on research reports published by the Swedish construction industry's organization for research and development (SBUF), the Swedish rock engineering research foundation (BeFo) and the strategic innovation programs Smart Built Environment and InfraSweden2030. In addition, general searches on the web and personal communication with construction companies were performed.

2.3. Thematic days

Two thematic days were held in May 2021, where the technical possibilities and barriers as well as business models to enable commercially viable use cases were discussed. The thematic days were organized and moderated by the project group of the National Network for Construction Automation with speakers and attendees from the fields of both construction, mining and robotics:

1) Thematic day 1: The technical perspective

The first thematic day focused on understanding the current and future technical application areas of automated construction.

Topic	Speakers
<i>Automation in Mining</i>	Peter Burman (Boliden) Jenny Greberg (LTU)
<i>Automation in Construction</i>	Ulf Håkansson (Skanska) Lars Pettersson (Skanska)
<i>Automation in Robotics</i>	Robert Andersson (LTH) Helena Eriksson (Cognibotics)

2) Thematic day 2: The organizational & economic perspective

The focus of the second thematic day was on organizational and economic conditions that are necessary for enabling implementation of automated construction. Lars Albinsson was invited as moderator.

Topic

*What is required for
implementation?*

The role of the client

Business models

Speakers

Susanne Nelleman Ek (BIM Alliance)

Lars Albinsson (Maestro)

Bernt Henrikssen (Automation Region)

Samuel Holmström (Lundqvist Trävaru)

Professor Kent Eriksson (KTH)

3. Literature review

3.1. Automation in construction

The following section presents the geographical and topical patterns identified in the bibliometric analysis using the Bibliometrix package in R as well as a literature review of key articles in construction automation.

3.1.1. Geographic focus

As visualized in Figure 3, the most productive countries in the field of construction automation based on the number of published articles in the Scopus database are (note that the number of articles are counted based on authors, resulting in more than 140 articles as mentioned in section 2.2):

- **USA** (151 authors) and **Canada** (30) in America
- **South Korea** (87), **China** (22) and **Japan** (13) in Asia
- **Australia** (17) as well as
- **UK** (26), **Spain** (13) and **Switzerland** (13) in Europe.

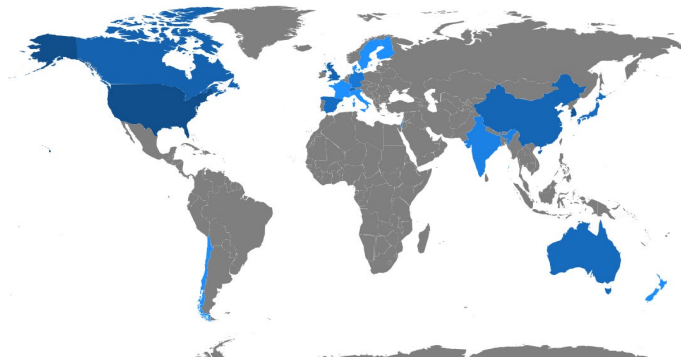


Figure 3. Most productive countries¹

¹ with respect to author frequency for search term “Construction Automation”

In particular, a majority of research efforts on construction automation are linked to the following institutions listed in Table 2.

Table 2. Leading research institutions working with construction automation

Country	Institutions
<i>USA</i>	North Carolina State University, Georgia Tech, Stanford University
<i>Canada</i>	University of Alberta, University of Waterloo
<i>South Korea</i>	Korea University, Hanyang University, Inha University, Yonsei University, Chung-Ang University
<i>China</i>	Tsinghua University, Ningbo University
<i>Japan</i>	Osaka University, Keio University
<i>Australia</i>	UT Sydney, Western Sydney University
<i>UK</i>	Loughborough University, University of Central Lancashire
<i>Spain</i>	University Carlos III Madrid
<i>Switzerland</i>	ETH Zurich
<i>Germany</i>	RWTH Aachen, Technical University Munich

Ranked by article citations, the USA (775 total citations/ 20.95 average article citations), UK (566/141.5), Korea (460/18.4), Canada (74/24.67), China (62/8.86), Germany (40/40) and Switzerland (24/12) are leading.

3.1.2. Publication sources

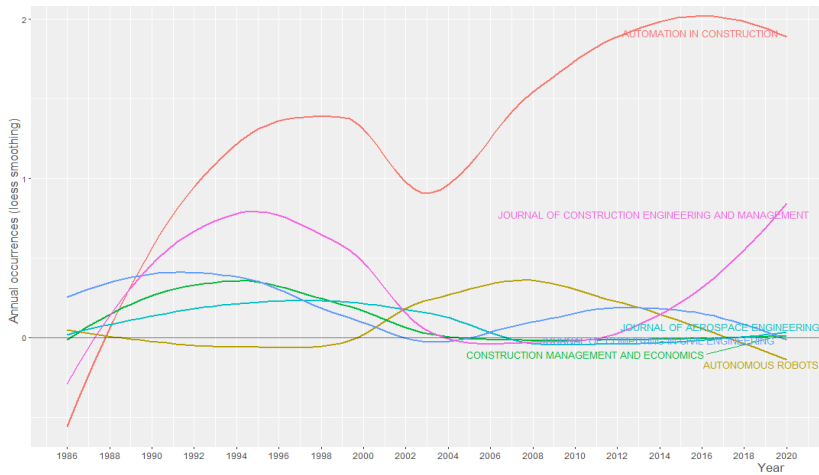
As for the sources, the by far most popular journal is “Automation in Construction”, followed by the “Journal of Construction Engineering and Management” and the “Journal of Computing in Civil Engineering”.

Table 3 visualizes the total number of articles per journal, whereas the annual growth of each source is shown in Figure 4.

Table 3. Most relevant sources ²

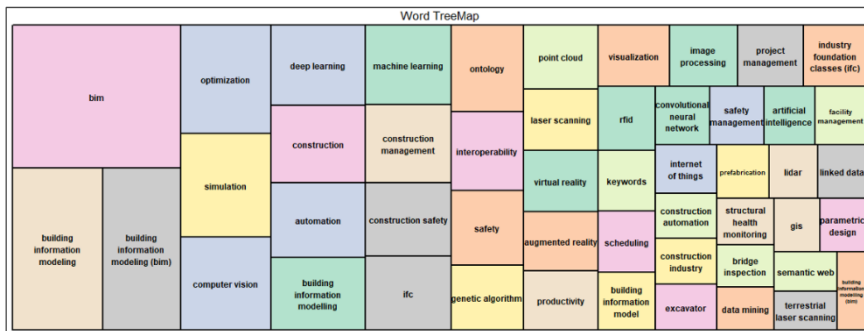
Journal	Articles
Automation in Construction	45
Journal of Construction Engineering and Management	11
Journal of Computing in Civil Engineering	7
Computer-Aided Civil and Infrastructure Engineering	4
Construction Management and Economics	4
Autonomous Robots	3

² Ranked by No. of Documents

Figure 4. Source growth – Construction automation ³

3.1.3. Research areas

Dominant topics in the leading journal “Automation in Construction” are the use of Building Information Modelling as well as applications for artificial intelligence and deep learning from design to construction management and maintenance. Less notably, the rise of concepts related to safety and sustainability can also be recognized as shown in Figure 5.

Figure 5. Journal topics – “Automation in Construction”⁴

³ Annual Occurrence

⁴ Based on Author Keywords

Looking into clusters within the analyzed articles from the Scopus database, the most frequent keywords shown in Figure 6 give an impression of the prevailing research focus. It should be noted that the dominance of “construction” and “automation” can be attributed to these words being the main search terms. However, all other keywords give a good overview of typical links and focus areas related to construction automation.

These keywords can be structured in a thematic map (Figure 7) based on their centrality and density (Aria & Cuccurullo 2017). This visualization indicates, which clusters appear in the majority of research articles as an underlying common denominator (high density) and which are centered around a very specific cluster (high centrality).

Here, the groups in the lower-right quadrant such as cost effectiveness, architectural design and construction equipment constitute “basic” themes where a lot of research has been performed on a broad spectrum. In contrast, for instance excavation and project management are considered more specialized themes in the area of construction automation. Last but not least, 3D printing and the respective keywords are positioned as an emerging topic in the selected papers. There are of course many subthemes that are not visualized here within the overarching clusters. A more detailed investigation is needed to look into each of them individually.

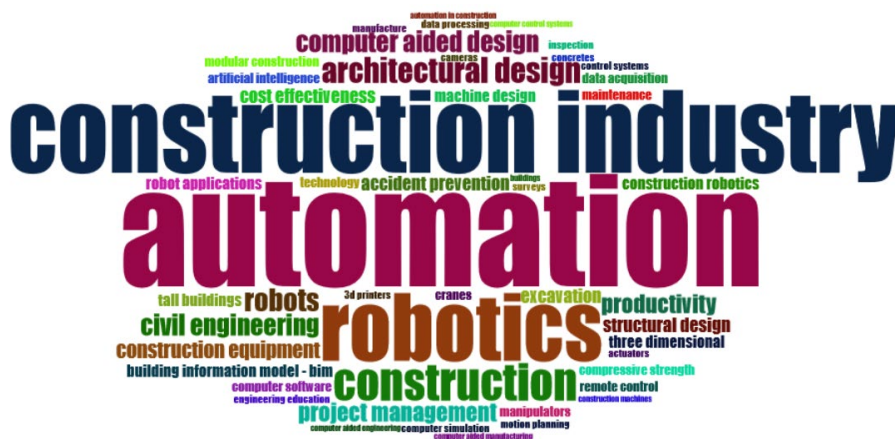


Figure 6. Word map – Construction automation

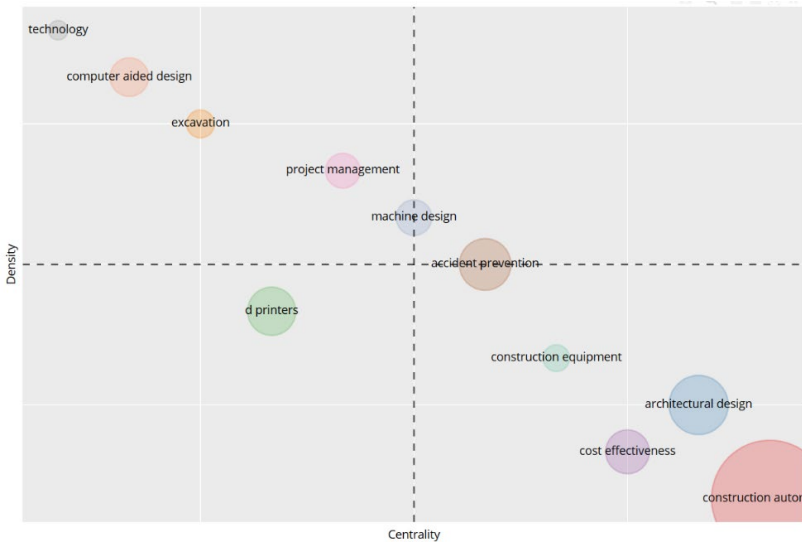


Figure 7. Thematic map – Construction automation

3.1.4. Historical developments

Bock (2015) describes the adoption of technology in the construction industry as S-shaped to describe the growth in construction automation, starting with early innovations in the field of conventional construction between 1970 and 2010, before turning into a disruptive growth phase of automated construction after 2010, leading to performance improvements and a more mature and wider implementation across the sector.

A major underlying driver of these improvements has been the rapid development of computer hardware and software, which allowed for advances in e.g. “robotic control, sensing, localization, mapping and planning” (Kim et al. 2015). Son et al. (2010) found that the initial research focus had been on the construction phase (76%) at the expense of planning (7%) and operation (10%).

Dominant topics included construction management systems as well as sensors and sensing for on-site management in addition to control and automation systems for construction robots. To a lesser extent, the use of design assistance tools in the planning phase or monitoring and inspection systems in the operation phase are covered. The same paper also showed that research efforts, while being mostly conducted by academia, are often uncoordinated with the industry and hence call for a more collaborative

approach among R&D instances (academia, research institutes, private sector and government) to accelerate innovation.

In Sweden, Åhman (2013) outlined the developments in the field throughout the last three decades. According to him, the first project mapping was performed in 1987/88 with the intention to identify the possibilities of using robotics in construction. At that point, Japan, USA and France among a few other countries were considered leading, with the first robots actually being tested on site in Japan. From 1989-1995, a pilot project to develop prototypes in Sweden was initiated. While robots had been used in factory environments for a longer time, the research in this project was focused on how to adapt the technology in the highly unpredictable, heterogeneous outdoor surroundings on a construction site and ensure its flexibility as well as safety of the workers.

Upon successfully testing prototypes for concrete grinding and cleaning in the laboratory and at a construction site in Gothenburg with a network of national actors, the perspective was opened up to the international stage.

Sweden, together with representatives from USA, Japan, France, UK and Israel founded the International Association for Automation and Robotics in Construction (IAARC) in 1985, later forming a main body of the International Symposium on Automation and Robotics in Construction (ISARC), founded the year before by researchers in the USA. The major objective with this work was and still is to collect information on advancements in the field and spread this knowledge through different media and events around the world.

In addition, the 1990s and early 2000s saw several use case explorations backed by higher standardization, more sophisticated CAD-software and early BIM tools. Nonetheless, global financial crises, the difficulty of aligning design practices and automated construction as well as the lack of scalability of those very unique projects led to an overall lower engagement in the field, and the discontinuation of some ventures. In the years since 2010, however, the interest in the field has gained a significant momentum - as described by Bock with the S-curve – notable for instance through a growing number of participants in the ISARC symposiums and larger R&D investments in several countries that result in increasingly scalable solutions.

3.1.5. Current topics

Kim et al. (2015) list practical applications that have benefited from recent advancements in software and hardware, such as surveying processes and

quality controls (faster checking of construction accuracy, prevention of collateral damages, automated image/model mapping and improved equipment calibration), especially in civil excavation, tunneling and infrastructure monitoring. Improved communication between platforms and the use of RFID-tracking also allow for better project control and quality. In addition, risk and safety management as well as sustainability innovation, e.g. through Life Cycle Analysis tools, also progress in the light of a higher level of automation.

This is backed by Kim et al. (2020), who performed a keyword network analysis that showed a high research interest in the use of modeling and simulation for better building performances as well as a focus on hardware for real-time monitoring of construction equipment and sites. In contrast, less interest was detected for the development of cost and information management systems.

In terms of technologies, real-time sensing (e.g. proximity detection, material tracking and structural behavior monitoring) and simulation techniques received the most attention recently. Connected to these findings and in line with the results of the bibliometric overview of this report, Aghimien et al. (2019) further point towards upcoming topics like the applications of machine learning and digitalization.

Recognizing those recent advancements, Gharbia et al. (2020) propose to open the perspective from the discussion of single construction activities (e.g. additive manufacturing, automated installation, assembly or bricklaying) towards an integrated robotized construction site including innovative materials, improved robotic hardware and streamlined construction workflows.

3.1.6. Benefits and challenges

Higher level of automation is often associated with improved productivity and better workplace safety. In addition, an enhanced communication and collaboration between stakeholders, as well as the potential to increase market shares, are expected, as found by Chen et al. (2018).

Pan et al. (2018) summarize the expectations as such that by linking the operational and strategic decision-making through technology, automation and robotics will lead to more sustainable construction and management of buildings and infrastructure in terms of both economic factors, environmental and social factors.

However, even if the potential of automation and robotics for the construction sector is widely recognized, industry actors are still held back by a variety of barriers to their integration into existing workflows and practices. According to Chen et al. (2018), the most common challenges are a lack of maturity of the use of information, interoperability constraints, insufficient corporate budget allocation, a lack of economic competition and a lot of insecurities surrounding information security and contractual responsibility aspects.

Davila Delgado et al. (2019) grouped the challenges identified in literature and industry surveys into four categories: (i) contractor-side economic factors, (ii) client-side economic factors, (iii) technical and work-culture factors, and (iv) weak business case factors. As many contractors are SMEs, they often lack the financial stability to take on the high initial capital investments in automation solutions. The client side on the other hand, often public instances in the case of infrastructure, is dominated by a “lowest price” tendering approach in combination with short-term budgeting, which often hinders the use of more costly, innovative solutions. The paper further state that there is a substantial discussion about the need for a client-driven, mandatory use of BIM (as seen in e.g. the UK) and the associated disruptive forces to the industry in comparison to voluntary collaboration programs (like in Sweden). In terms of technical and work-culture factors, common barriers are technical difficulties and the high complexity and uniqueness of construction tasks that limit the usability and flexibility of robots and automated solutions.

Another major concern is the alignment of human-machine interaction. In order for unmanned ground vehicles (UGVs) to be adopted on a larger scale, Czarnowski et al. (2018) conclude that both better human machine interfaces for easier machine operations as well as a higher level of autonomy (including the independent ability of sensing, analyzing, communicating, decision-making and execution) will be needed.

As for the business side, Davila Delgado et al. (2019) point out that there is a lack of detailed cost/benefit analyses that go beyond time saving calculations by including e.g., costs for installation, maintenance, training and energy as well as health considerations. Additionally, market dynamics and absorption potentials have not been investigated; hence, making it difficult to calculate viable business cases in the field of robotic-enabled construction.

3.1.7. Future steps

Chen et al. (2018) suggest that in order for automation and robotics to advance further, several prerequisites need to be fulfilled. These include the reengineering of processes and organizational structures, an increased scale of adoption, continuous project performance assessments, as well as the development of standard data schemes, building information protocols and appropriate legal contracts. A larger scale of adoption combined with precise, digital tools will enable “BIM-based mass customization”, i.e. customized yet economically viable solutions for construction projects which are typically unique in nature (Chen et al. 2018).

Thematic fields for those advancements to be realized in infrastructure production are, according to Bock (2015), for instance automated road construction, tunneling, bridge construction, (de-)construction of dams and power plants, mining and container ports. Automated building construction focuses on housing production, construction in space, sea, desert, etc., or automated building maintenance. In addition, closely related fields are also seeing a rise in automation and robotics innovation, e.g. transportation systems (cars, public transport, air travel, etc.), household devices, farming and food production as well as town management (smart grids, traffic control, infrastructure inspection, supply management of water, gas, goods, etc.).

3.2. Automation in infrastructure

Not only in building construction, but also in infrastructure, the focus is increasingly shifting towards automation potentials. Early studies of use cases for robotics in highway construction were e.g. performed in the 1980s by Moavenzadeh (1985) and Najafi & Naik (1989).

“Today an extraordinary confluence of new technologies and a large and stable market for construction can bring about a revolution in the U. S. industry. The decay of the U. S. infrastructure - highways, mass-transit systems, ports, water mains, sewers, and other public works - will provide a market for new construction. Computers, robotics, and advanced materials stand ready to be used, especially in labor-intensive repair and maintenance.”

(Moavenzadeh 1985) – p. 32

Looking into current research about applications of automation and robotics in infrastructure, many of the aforementioned topics present in general construction research investigates specific infrastructure cases. As an example, Costin et al. (2018) mention the use of Building Information Modelling, which – though not initially intended for infrastructure use – has been implemented successfully in several transportation projects across the world, often driven by public actors as the largest client group.

In addition, Figure 8 shows that keywords related to urban planning (e.g. smart city, disaster management and infrastructure management) are appearing frequently in research and so do maintenance-related keywords like monitoring, Internet of Things (IoT), remote sensing and automated machine control. Last but not least, sustainability appears to be a major driver of the developments in automation efforts.

As for the sources, the most common journal in the field of infrastructure automation is once again “Automation in Construction”, followed by “Computer-Aided Civil and Infrastructure Engineering”, “Remote Sensing” and “IEEE Access”, see Figure 9.

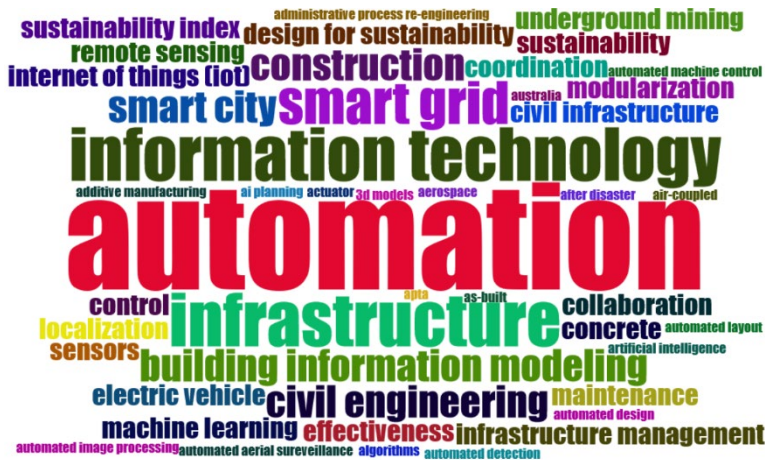


Figure 8. Word map – Infrastructure automation⁵

⁵ Based on Author Keywords

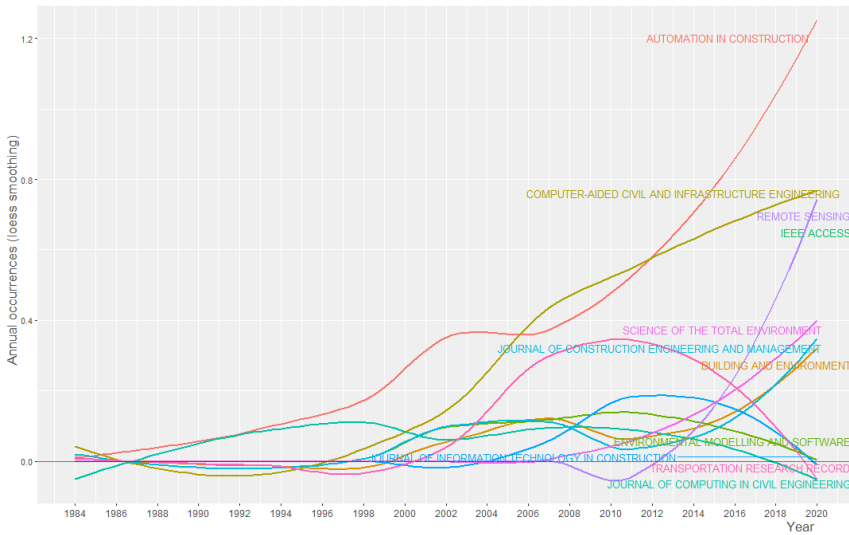


Figure 9. Source growth – Infrastructure automation⁶

While significant advancements have been made in infrastructure automation as stated by e.g. Costin et al. (2018), their full potential remains to be realized. Kuenzel et al. (2016) highlight that many tasks still rely on human decisions and are hence prone to errors and inefficiencies.

To take a closer look at the impact of automation and robotics in infrastructure, the following sections highlight research patterns and key areas with regards to highways, bridges and tunnels as well as the mining industry. Use cases and trends in the design, construction and maintenance phases are presented.

3.2.1. Highways

The use of automation and robotics in the context of highways shall support the resource-efficient design, construction and maintenance of safe, resilient roads. In the short run, construction logistics and material efficiency at adequate costs and time are to be achieved; while upon completion of the works, high levels of driver safety and longevity at low maintenance efforts need to be ensured. This has to be seen in the broader context of intelligent highway systems for smooth traffic flows, in particular in conjunction with, and response to, advances in the fields of autonomous transport vehicles and smart cities.

⁶ Search Keywords in Scopus: “Automation AND Construction AND Infrastructure”

Planning and Design

In the overall design process, future traffic demand forecasts, as well as the analysis of the prevailing geology along the prospective route, needs to be taken into account to ensure smooth traffic flows and adequate road layouts. Based on this, the design process includes for instances the conception of highway intersections and interchanges, the geometric alignment and design, pavement materials choices and the structural design of pavement thickness. Additionally, the design of a site-specific drainage system is crucial for surface water management and erosion control.

Beyond the provision of a dry, crack-free road, safety considerations are also reflected for instance in the calculation of smooth transitions, road banks in curves and grade steepness adequate for the reaction capabilities of human drivers in relation to the intended driving speed. In the geometric design, cut/fill-operations should be minimized and/or performed locally to ensure sustainability in terms of short soil transportation routes and efficient material use. Common ways to reflect those considerations are for instance the visualization in cross sections showing the local balance of cut and fill work as well as mass-haul-diagrams showing the volume balance over the project length. For each design scenario, cost and schedule impacts need to be monitored and evaluated as the basis for decision-making in political planning and the following execution. Other factors to be considered include the impact on e.g. air quality, wild life, water systems, pedestrians and cyclists, and the surrounding built environment.

Automation in the phase of design and planning of highway constructions, often linked to the aforementioned use of BIM, allows for scenario analyses and the optimization of resource usage, waste prevention, and impact minimization as listed above. Kim et al. (2014) describe one such example for scenario analyses in the context of cut and fill calculations, cost estimations and scheduling, which all have a major impact on the project results. In their work, process automation in highway alignment design is enabled by object-oriented visual models using IFC standards, whose standardized output data for costs and quantities in earthworks, as well as pavement and roadworks, facilitates the selection in design comparisons. GIS data integration can further improve the planning process.

Zanen et al. (2013) explore another important field of automation in this phase, namely the planning of sequences and workflows. Using a set of rules and codes in 4D construction planning enables the project team to generate and visualize various schedule alternatives and their respective spatial impacts, both for the internal communication as well as for the general public affected by road construction projects. This connects to Shah (2014), who showed that using 4D schedules linked to the design models also provides more flexible responses to design changes and enables an algorithm-based generation of location-based earthwork schedules as well as the optimization of resource allocations based on e.g. productivity rates and supply chain information. Automating those processes hence assists in resources planning, the identification of time-space congestion, activity monitoring in the construction phase and stakeholder communication.

In the larger context of smart cities, Toh et al. (2020) discuss a number of attributes that in the future will allow smart roads to interact with their environment, and hence further increase safety and the generation of renewable energy. Recent advances in this field include for instance smart intersections, roads that detect traffic violations and produce sounds (“musical roads”, for both entertainment, hazard warning and speed control), roads with wireless digital traffic signs, weigh-in-motion systems for truck load controls, electrified roads for charging electric vehicles, fast emergency rescue structures and roads that store or produce energy, e.g. from solar energy.

Looking further into the future, Khoury et al. (2019) shed a light on the impact of a fully automated vehicle fleet on the geometric design of roads. In their research, parameters such as the stopping sight distance, decision sight distance and vertical curve designs are adjusted to the scenario without human drivers, for whose capabilities and limitations roads are currently designed. Compared to traditional roads, significant economic and environmental improvements are expected in an autonomous scenario.

Construction

Building on the information from the design phase, project management aspects as well as excavation and compaction works are crucial parts of the construction phase to ensure high-quality construction results and the longevity of the roads.

A road consists of different layers (also called lifts), including the wearing or surface course typically made of concrete or asphalt, structural support layers (aggregate base course and sub base course), and the natural sub grade. Depending on the traffic predictions, the lower layers may also be treated with cement, asphalt or lime for additional load support, frost susceptibility and as a moisture barrier between the base and surface layers.

During road constructions, at first cut and fill operations are performed to shape the landscape for the designed road geometry. As part of this process, dump trucks place the excavated or additional soil in roughly the correct location along the road path. Subsequently, this soil is moved into consistent layers by a bulldozer or motor grader. The soil itself is however not strong enough to bear the load of vehicles and will settle over time. To avoid damage and deterioration in the use phase, maximum density calculations are performed for optimal compaction estimation before a compactor compacts each lift during construction. During the course of the works, the soil density is tested regularly. Tests results are then compared with maximum density values from lab settings. The iterative process is approved once the measurement results are close to the benchmark, otherwise more compaction is performed. The whole compaction process causes road constructions to take long time, but is crucial for road longevity and needs to be carried out properly to avoid expensive reworks. Often, it is however still performed in a rather manual way with punctual testing and compaction heavily depending on the experience of the human operators.

To overcome the reliance on manual processes and monitor progress in long-distance road projects, Goger & Bisenberger (2020) highlight an increasing automation in the use and networking of heavy machines, both autonomously and in interaction with humans, and the efficient combination of digital models with sensors and visual data of as-built conditions as a focus of research activities in this phase.

A project that successfully adopted artificial intelligence, machine learning and decision theory for the road construction process is the Smart Site project in Germany, described by Kuenzel et al. (2016). Based on digital planning models, it establishes an autonomously controlled information exchange among construction machines, between the environment and the construction machine, and between the construction management and the construction machine to eliminate or reduce human errors and increase precision. An important example is the case of compaction works, which is

one of the most crucial steps as faults in this phase are irreversibly connected with high costs for re-building road segments. In the Smart Site project, the use of real-time sensor input to the machine control systems prevents the compactors from over-compacting, thus increasing the pavement's longevity over the life cycle and allowing the construction management to re-allocate resources to other decisions and tasks. Ultimately, the goal in this project part is to develop a fully automated asphalt compactor.

In the field of lift-thickness control during pavement construction, Liu et al. (2016) focused on a real-time monitoring system by integrating robotic total stations, inclinometers, laser-ranging sensors and wireless communication technology. This allowed for previously unproductive, inaccurate punctual checks to be transformed into millimeter-accurate monitoring across the entire pavement surface.

Upon completion of the layering and compaction works, concrete surface grinding is performed to remove road surface irregularities. Traditionally, the grinding process is linked to hazardous working conditions (e.g. due to dust, noise and the handling of heavy equipment) with an outcome quality highly dependent on the skills of the operator. Moon et al. (2017) addressed this gap by prototyping a remotely-controlled machine to improve both safety and performance in a semi-automated setting.

To exploit the possibilities of automation from a project management perspective, Perkinson et al. (2010) propose an implementation framework for the integrated use of GPS and communication technology in total job-site management. Based on a survey showing sub-optimal levels of GPS usage by heavy contractors due to a lack of suitable ICT infrastructure and understanding for data collection and interpretation, they identify required technological and organizational changes as well as their perceived costs and benefits. While GPS, by itself or combined with the use of other sensors like ultra-wideband (UWB), radio frequency identification (RFID) or barcodes, provides important progress data, it does not directly represent physical progress on site. This issue was addressed by Vick & Brilakis (2018), who developed a structure to automatically detect road design layers in digital as-built point cloud data for efficient progress monitoring.

Maintenance

Despite accurate design and construction, traffic, rain, snow and sunlight will cause deterioration of the surface pavement during the life span of roads. To detect cracks early and seal them efficiently before they become larger potholes, and hence a major safety risk, is therefore in the focus of road maintenance works. Water shall be prevented from entering the sub-surface layers, as it gets trapped below the pavement, making the respective area softer and hence vulnerable to traffic loads. Left untreated, the water gets pressed out whenever a tire hits the surface. It simultaneously removes some soil of the lower lifts, which in turn additionally weakens the roads structure and causes the pavement to break off and crumble eventually – a problem that is particularly visible in cold climate, where the water freezes below the surface and then melts during spring. Once detected, the lost soil and pavement needs to be replaced, before the surface is sealed from further intrusion of water. This operation requires high precision to avoid the creation of new openings at the edges of the sealing, where water can easily enter again.

Next to cracks and potholes, road operations also deal with for instance winter maintenance as well as the control of strips and traffic signs. Overall, the maintenance strategies are mostly chosen depending on cost, material and climate factors. Given the mere scale of road networks, automation can support maintenance works and significantly cut its costs both in detection and repairment of irregularities.

Out of 25 road maintenance activities, Osmani et al. (1996) identified “base removal and replacement, crack and joint sealing, leveling or overlays, pothole repairs, strip and spot seal, seal coat, ditch maintenance, traffic assistance, and paint and bead striping to be the most conceptually feasible ones for automation based on economic and qualitative factors.

In a review study about automated defect detection, assessment and repair, Radopoulou & Brilakis (2016) grouped existing research efforts in the field of maintenance automation in three method categories: vision data based methods, spatial data based methods and vehicle dynamic sensor data. Common implementation barriers identified in a comparison of the different solutions are high investment costs (especially for sensors and specialized vehicles to obtain spatial data), system complexity and limited functionality

of the individual tools. There is currently no holistic approach to the automation of road defect detection.

In terms of individual solutions, Feng et al. (2005) explored the use of a machine vision system to find pavement cracks for a robotic crack sealing machine. Based on camera images of the robot's workspace, cracks are identified for sealing and robot pathways are planned accordingly for a high degree of process automation. A similar setting is presented by Leonardi et al. (2019), who tested unmanned aerial vehicles (UAVs) to monitor pavement conditions and detect distress on (un-)paved surfaces based on 3D mapping data. In addition, Zhang & Ge (2012) tested an approach to the automated maintenance of pavement markings. Instead of relying on human expert interpretation, digital image processing techniques were used to identify geometric deformity as well as the percentages of remaining marking material and retained retroreflectivity, two main criteria of marking performance for safe roads.

In Sweden, research projects in the field of road maintenance have recently focused on the data-driven, dynamic design of road maintenance strategies, in particular on winter maintenance. For instance, one internationally acclaimed project, performed by Svevia in three parts from 2016-2020 and led by Bäckström (2018), aims to automate the route planning of maintenance works. By monitoring the road conditions and local weather, and using this information to optimize driving routes, the operator gets directly updated instructions in the vehicle's navigation system. Future work aims to additionally include the level of remaining salt in the model for more accurate results and measures.

3.2.2. Bridges

Bridges constitute important structures to enable transportations and connect societies. The first bridges were constructed by natural materials available at the construction site such as rock and timber, and it was mainly in the last 150-200 years that steel and concrete started to be used in bridge construction (Johansen & Nilsson 2006). In Sweden, The Swedish Transport Administration manages approximately 21 000 bridges, of which 17 000 are traffic bridges and 4 000 are railway bridges (Trafikverket 2022).

As urbanisation and densification of our cities and societies proceed, our need of transport infrastructure increases, not at least the need for new bridges. For example, the new technical demands on our planned high-speed

railways in Sweden imply an increased share of bridges and tunnels – the high speed that is needed to attract travellers from the flight demands straighter railway tracks and admits fewer alternative adaptations to the landscape (SOU 2009). This is illustrated by the fact that for the first part of the new high-speed railway between Järna and Linköping, approximately 200 new bridges and 30 tunnels are planned. At the same time, the building of this transport infrastructure results in significant environmental impacts, both in the form of air pollution and CO₂ emissions. There is therefore much to gain in terms of reduced costs and environmental impact if the construction of the new transport infrastructure could be built more efficient.

Design and Planning

Today, the most common bridge type in Sweden is the concrete slab frame bridge, which consists of a simple square shaped reinforced concrete frame structure kept in place by the prevailing earth pressure on the sides. This type of bridge mainly works when the length of the bridge span is short. Another common type of bridge is the reinforced concrete slab bridge, which consists of a reinforced concrete slab casted on a number of columns/piers. Since the bearing capacity of the concrete slab is limited, this type of bridge is mainly suitable for shorter spans. If longer bridges of this type is needed, more columns/piers are added. When higher bearing capacity or longer spans are needed, the beam bridge can be used. It consists of reinforced concrete or steel beams with a slab on top of the beams.

Just like other construction projects, the traditional delivery of bridge structures is characterised by a fragmented information transfer from early design to fabrication, assembly and operation processes (Chen & Shirolé 2006). Chen & Shirolé (2006) conclude that in order to accelerate the delivery of bridges, an information-centric approach to planning, design construction, operation and maintenance should be utilized by using a uniform language for electronic communication of the bridges life-cycle information.

A more automated construction of bridges requires a design that is adapted for this. Automation fuels the need for new materials, extensive performance testing, updated design guidelines and adjusted assembly processes. This concerns both the automation of traditional design processes as well as the design for new fabrication methods like additive manufacturing.

A recently completed example of an entirely digital bridge project is the Randselva bridge in Norway, which – being fully BIM-based – was constructed without any paper drawings (Vieira et al. 2022). Having high quality digital models does not only improve collaborative workflows, but is also the basis for robotic tasks such as rebar installation automation and any other robotic assembly task. Moreover, the use of information models allows for scenario analyses and model evaluation for lifecycle impact assessment at an early project stage. For instance, the most feasible construction method can be chosen using advanced computational models that balance different factors like site conditions, traffic, durability, damage costs, environmental impact etc. to find the safest and most economic strategy (Pan 2008).

Construction

Commonly used modern bridge construction methods include full-span and pre-cast launching method, advancing shoring method, balanced cantilever method, incremental launching method, and precast segmental method (Pan 2008). Depending on the method, the steel or concrete beams can be lifted in place or ejected into place during construction, saving time for shutting down potential traffic under the bridge. Sweden longest bridge, the Öland Bridge, is a famous example of a typical beam bridge. If very long spans are needed, suspension bridges or cable-stayed bridges can be used even if they are not so frequently used in Sweden. The main span for the Öresund Bridge is a famous example of such a bridge in Sweden, see Figure 10, while the High Coast Bridge is a striking example of a suspension bridge.

Automation in the construction of bridges can concern both on-site and off-site fabrication. For instance, the use of additive manufacturing (AM) in the construction industry also opens up new possibilities for the construction of bridges. A technology already in use in other sectors, wire and arc additive manufacturing (WAAM), are now started to gain attention in the construction industry. Gardner et al. (2020) reports of the world first 3D-printed metal footbridge. The footbridge has an overall length of 12.5 m, a span of 10.5 m and an average width of 2.5 m. The bridge was printed using a six-axis ABB



Figure 10. The Öresund bridge (@ Nick-D, CC-BY 4.0, <https://creativecommons.org/licenses/by/4.0>)

industrial robot, fitted with a MIG welding machine controlled using developed software. The overall mass of the bridge was 7.8 ton, of which approximately 4.6 ton was printed. To determine the printed material stress-strain characteristics a series of tensile material tests were performed on coupons cut from printed plates of the same material as that in the bridge, which was compared against machined coupons. Three different directions against the printed layers were tested, 0° , 45° and 90° . The results showed an inherent material anisotropy due to the internal microstructure of the printed material, where for example the Young's modulus tested in the 0° and 90° directions were 25% lower than for stainless steel, while the Young's modulus in the 45° direction exhibited a significantly higher value. Similar characteristics could also be seen for the 0.2% proof stress, the 1% proof stress and the ultimate tensile stress. This clearly shows that the printed as-built materials are influenced by the variability of the geometry of the tested coupons and the derived material properties needs to be considered as effective material properties. Gardner et al. (2020) also tested the compressive structural response of key components of the bridge by means of stub column testing. Among other things, comparisons were made between the measured ultimate axial load and the resistance prediction according to

EN 1993-1-4 based on mean measured properties. The results showed that the “stockier” sections were generally on the safe side due to strain hardening, which is not accounted for in the EC3 calculations, while the resistance for the slenderer sections were overpredicted by the design calculations. According to Gardner et al. (2020), these results primarily reflect the greater geometric variability associated with the WAMM-sections, and highlight the need for design guidelines that are specific to this type of manufacturing.

Opportunities that come with the use of metal additive manufacturing include, but are not limited to, geometric flexibility, the optimization of material properties, customization and reduced construction time. In contrast, the costs are generally higher at current stage (though depending on the project basis) and manufacturing processes cannot be easily changed due to the prevailing lack of standards and manufacturing guidelines. In addition, new digital workflows are needed including changes in the design methodology (Buchanan & Gardner 2019).

Salet et al. (2018) report on the design of a 3D printed concrete bridge by testing, which was the first of its kind (pre-stressed, fused de-positioning modelling printed) worldwide to be put into service in the Netherlands. Other applications of automation in the construction of bridges can also include the robotic assembly of rebars on site for the concrete structures such as piers or bridge decks. Skanska together with Robotdalen present a proof-of-concept for an automated fabrication process for rebar cages (Momeni et al. 2022) that e.g. can be used in bridge construction. The overall process scheme for the fabrication are illustrated in Figure 11.

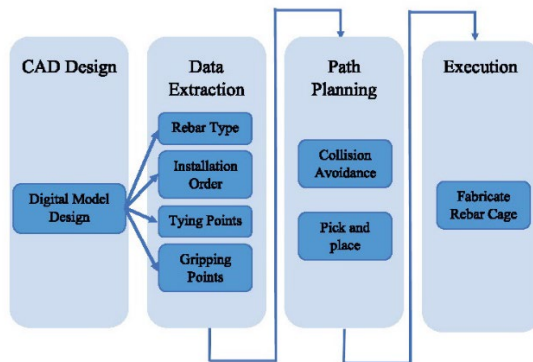


Figure 11. Overall process scheme for automated fabrication of rebar cages (© Momeni et al. (2022) CC-BY 4.0, <https://creativecommons.org/licenses/by/4.0>)

The intention is to pre-fabricate these cages off-site and then lift them into their permanent positions before pouring the concrete. The main benefits according to Momeni et al. (2022) is the overall increased efficiency and productivity together with the reduction of hard work and wear of the workers. The solution utilized three industrial robots mounted on a gantry system. In their work, they present how to transfer data from a 3D BIM model to corresponding models in the robot simulation program CoppeliaSim, together with path planning algorithms for transporting and tying the rebars, see Figure 12. However, according to (Momeni et al. 2022) several challenges remains to be solved; future work will include, (i) automatic generation of the required data, (ii) dealing with the deviations of the robot, gantry and the rebars from their theoretical geometry, (iii) investigating the possibility of modifying the digital model and considering the addition of a stable frame so that the rebars are fixed in the final position.

This type of off-site manufacturing possibilities also allow for the prefabrication of large bridge components and the use of robots for tasks like welding of steel.

Combined with the use of self-compacting concrete and 3D printing technologies, bridge pillars can be built with minimal waste and a high degree of standardization. A pilot-study was performed by Silfwerbrand (2022) in

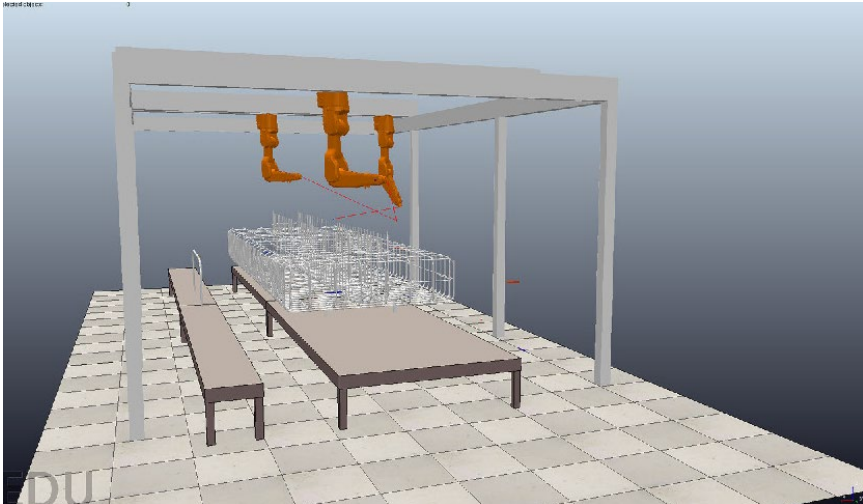


Figure 12. Simulation of automated fabrication of rebar cages in Coppelia SIM (© Momeni et al. (2022) CC-BY 4.0, <https://creativecommons.org/licenses/by/4.0>)

collaboration with the company ConcretePrint for efficient fabrication of bridge pillars. In their work, 3D-printing was successfully used for the fabrication of the mold with a height of 2.4 m. The mold was thereafter filled with self-compacting concrete. According to Silfwerbrand (2022), this type of interaction pillars can provide the architects with new design alternatives and can increase the productivity.

Inspection and Maintenance

With an increasing age of existing bridges, the need for a more efficient management and maintenance of the structures will also increase in the future. A major focus is thereby placed on structural health monitoring and predictive maintenance supported by automation instead of manual inspections at fixed intervals. Considering that the traffic loads, volumes and speeds on railway networks have increased throughout the last years and are likely to continue to do so in the future, many bridges are subjected to loads they originally were not designed for. Since not all bridges can be replaced at once and the existing ones form a core part of the transportation network, it is very important to assess their conditions and maximal capacities. For example, Leander et al. (2009) implemented an extensive monitoring program for the Söderström bridge in Stockholm to detect fatigue cracks and spot deviations compared to the remaining service life from design calculations.

Automation can support the structural health monitoring and allow to realize time savings, cost efficiency and the prevention of hazardous conditions due to poor structural conditions and reactive measures. For instance, Neves et al. (2017) propose the use of machine learning for damage detection and the definition of thresholds in the fatigue assessment procedure. In addition, a proactive maintenance decision-making approach is presented by Neves et al. (2019) using the Bayesian Theorem to identify optimal structural health monitoring (SHM) and maintenance decisions in the context of different scenarios for event probabilities and associated maintenance costs.

3.2.3. Tunneling

Underground construction is one of the most challenging applications for construction equipment that must be able to work under specific conditions

with limited space and large volumes of material to remove. For tunnel development, it is usually the speed of advancement that is crucial, giving high importance to utilization of machinery and labor (Schunnesson 2009). Modern tunneling techniques and equipment have various benefits such as production control, improvement in tunnel profile, characterization of the surrounding rock mass etc. (Schunnesson 2009).

This section is limited to describing automation advances for the tunnelling industry using the drill and blast method, which is the most common tunnel excavation method in Sweden. Although the limitation is set to drill and blast, it is worth to mention that the automation level and advances are high for the tunnel boring machines (TBM), which is commonly used for tunnelling projects worldwide. TBMs are highly advanced and automated machines that perform all stages of a tunnel construction in one round.

Design and Planning

Designing a tunnel bears numerous challenges. For example, the design of shallow tunnels under cities must take special care of parameters such as ground vibrations and possible ground settlements due to the presence of infrastructure at the surface and in the vicinity of the tunnels (Massinas 2019). Such tunnels are mostly constructed in soils or weak rocks with a thin layer of overburden that increases the risk of collapse and high deformations at the surface. This implies that the urban infrastructure overlying the tunnels may be subjected to negative impacts if suitable measures are not taken at the design phase of these tunnels (Massinas 2019). On the other hand, high overburden and complex geological conditions for deep tunnels can adversely affect the stability of the tunnels (Massinas 2019). Therefore, the design and planning of any tunnelling project should be carried out carefully. It requires the interdependent participation of different disciplines including geology, geotechnical engineering, excavation technology, design of the supporting structural elements, contract principles, etc. (ITA 1988). Although, people from different disciplines contribute with their specific knowledge, the final design of the tunnel should be the result of the integrated cooperation of all these disciplines (ITA 1988). Only then, the project can be developed and completed as a whole, rather than an addition of the separate efforts by different experts (ITA 1988).

The planning of a tunnel includes many variables which need to be considered such as tunnel shape, road types and vehicle sizes, traffic capacity, geotechnical investigations, environmental and community issues, operational issues, sustainability, ground water control, tunnel drainage, cost analysis, risk analysis and management. Similarly, the design of a tunnel investigates different design standards or parameters. These parameters include maximum grades, horizontal and vertical curves, sight and braking distance requirements, travel clearance, cross section elements, travel lanes and shoulders, emergency walkways, drainage requirements, ventilation and lighting requirements, and traffic control requirements.

Automated drill plans can be created through different design tools. Modern drill support software typically includes all design data (tunnel lines, sections, tunnel profiles, planned rock reinforcement etc.) (Schunnesson 2009). Schunnesson (2009) further describes that the navigation tools, e.g., laser lines can be used to connect the designed drill plans to the accurate position in the tunnel. Furthermore, Sorge (2019) describes how Building Information Modelling (BIM) was adopted as a tool for design and information sharing for the Brenner Base tunnel project which connects Austria and Italy through a 55 km long straight tunnel. BIM describes any infrastructure project in terms of 3D representations of constituent elements, which can incorporate further information about the other properties of the project (Kontothanasis 2019).

Application of BIM in tunnelling projects will allow to realize tunnel designs which are ideal for existing site conditions as well as fulfilment of socioeconomic and environmental requirements (Kontothanasis 2019). Geotechnical investigations, which lay down the basis for the design of tunnels, can also be automated to different extents. For example, site reconnaissance, topographic surveys, hydrographical surveys, utility surveys, identification of underground structures and obstacles, geological mapping, groundwater investigations, seismic surveys, probing and pilot tunnels can be performed using automated operations. Similarly automated clash analysis can be performed to identify any discrepancies for different tunnel designs and shapes.

Construction

Tunnels are constructed using either the conventional drill and blast method or mechanical excavation. The drill and blast technique is still the most common method to construct tunnels in underground mining operations, while mechanical excavation using TBMs, road headers, etc., is becoming more popular in infrastructure related projects. Yet, the drill and blast method is often the only workable method for constructing short or large cross section tunnels, caverns, and shafts. The drill and blast method also has the flexibility to adapt to variable profiles, compared to a TBM that always gives a circular cross section. This flexibility is especially important for road tunnels, where a circular cross section could result in a lot of over-break compared to the actual cross section required. In the Nordic countries, tunnels are often constructed in solid, hard crystalline rocks which makes the drill and blast method efficient and economical (Jennemyr 2019).

The principal elements of a drill and blast cycle include: drilling, blasting, debris clearance or mucking, and ground support installation (King 1996). Drilling is carried out either using a single machine or a jumbo depending upon the project. After that, the drilled holes are charged with explosives and blasted. The broken material is removed or mucked out and finally the support is installed as required to stabilize the opening. In poor rock mass quality or in areas with poor rock cover, pre-support using pipe umbrella systems are used to stabilize the rock during excavation, see Figure 13.



Figure 13. Drilling at Johannelund, Bypass Stockholm. Note the pipe umbrella system installed as pre-support (Photo Fredrik Johansson with permission)

There can be other operations as well in a drill and blast cycle like surveying to ensure the correct alignment and geometry of the tunnel, and face ventilation to remove dust, toxic gases and fumes produced due to the blasting of the explosives (King 1996).

The unit operation in a drill and blast cycle that have the highest degree of automation is the drilling operation. Different levels of automation, from fully automated systems to simpler tools used for operator support, are being used for drilling of a tunnel round. The created drill plans from the design tools are being used for the fully automated drilling systems (Schunnesson 2009). One of the advantages with automated drilling is the consistency between rounds and the control of the contours. Manual drilling is dependent on the experience and skill of the operator and makes it more difficult to keep a correct alignment between the holes (Schunnesson 2009). It is further described that the impact on blasting, with e.g. additional explosives or varying burdens between holes, are substantial for manual drilling. The use of the automated Rod Adding System (RAS) has not only increased the speed of drilling but also has increased the safety of the operation (Jennemyr 2019).

In the past, drilled holes were loaded with explosives manually that makes the operation slow and unsafe. However, the use of explosive charging trucks for bulk explosives is becoming more common allowing some degree of automation. The Robotics and Autonomous Systems group at CSIRO developed a prototype system for blast hole charging automation and successfully demonstrated the system in 2001 (CSIRO 2002). The system is documented in detail in Bonchis et al. (2014). The explosive manufacturing company, Orica, and the mining equipment manufacturing company, Epiroc, together developed and unveiled a prototype system for semi-automated explosives charging in November 2020 and regarded it as first-of-its-kind for commercial purposes. The system will be under trial during 2021 before it is available commercially (Orica 2020).

Mucking or debris clearance is mostly done using wheel loaders and trucks. However, conveyor belts are another development from central Europe for mucking in long tunnels (Jennemyr 2019). Some degree of automation is also reported at the support installation stage of the tunnel construction. For example, an automated equipment was introduced by the contractor specific to the tunnel lining of the Paghuashan tunnel (Lin et al. 2006). The use of robots and UAVs for surveying purposes is getting widespread acceptance as well.

A large difference between the tunnel industry and the mining industry regarding automation level are the fact that tunnelling projects are usually short-term projects using contractors. The benefit of buying, installing and using an automation system could be more limited than e.g. in a mine, where the production areas are used for a much longer time. Recent trends go towards automation of the installation of rock support, where different methods are being tested and evaluated. The processes of scaling, application of shotcrete, installation of tunnel lining, etc., have all huge potential for automation and there are tests being carried out in these fields. The automation level in the drilling stage is already quite high as compared to other stages. However, there is still research needed in the automation of the explosive charging phase. Material loading and excavation have already been automated or semi-automated in the mining industry and can be applied to tunnelling projects as well. 3D printing is another technique which can be applied to tunnel construction for prefabrication of tunnel lining elements, etc. (Kontothanasis 2019).

Inspection and Maintenance

One of the challenges with an existing infrastructure, such as a tunnel, is the inspection and maintenance. Tunnels have for example increased both in size and in length and will continue to do so in the future. Also, tunnels constructed a long time ago are still in use and require inspections and maintenance, since deteriorating factors such as age, change in use, increased loading, environmental factors, etc., influence the conditions of the tunnel. Inspections are made to analyse whether the support in the tunnel, which has been operational for some time, are still safe or not (Jardón 2014, Leonidas & Xu 2018). Inspections also help to forecast the remaining functional life of the tunnels (Leonidas & Xu 2018). Today, inspections are typically performed by experienced workers. However, the trend is shifting towards the use of robotic tunnel inspections to increase productivity, quality and repetitiveness (Jardón 2014). Research on how automated inspections and maintenance can be considered already in the design phase are also being performed. One example is described by Jardón (2014), who describes how rails can be installed along the tunnel for robot attachment to enable different types of fully automated inspections.

English (2016) describes all the required inspection and maintenance works in roadway tunnels in the Tunnel Operations, Maintenance, Inspection and Evaluation (TOMIE) manual. Human-based tunnel inspections have many challenges associated with them. For example, workers health and safety issues, high costs and labour intensive, accuracy issues due to limited time, hindrance to tunnel operation etc. make the inspection process less efficient (Victores et al. 2011, Cipolla 2015). By automating the inspection processes, the overall operational productivity and accuracy can be increased (Balaguer 2000, Balaguer & Abderrahim 2008). There are numerous factors which are investigated during these inspections. The most common tunnel defects searched for during inspections include cracking in the tunnel perimeter, scaling of concrete or shotcrete support layers, efflorescence, and water leakage that can severely affect the iron or steel structures inside the tunnels (Park et al. 2006). Mostly, Non-Destructive Inspection (NDI) methods are used instead of destructive ones to avoid any negative impact on the tunnel structures (Leonidas & Xu 2018). These methods include visual, strength based, sonic and ultrasonic, magnetic, electrical, thermography, radar, radiography and endoscopy methods (Jardón 2014).

There are a number of ongoing work related to the field of automated inspection and maintenance of tunnels. Most of these works focus on robotic inspection of the tunnels, see for example Victores et al. (2011), Menendez et al. (2018), Leonidas & Xu (2018), Cipolla (2015), Balaguer (2009), and Balaguer (2017). To improve safety and get objective results from an inspection in an efficient way, research and tests are being performed using robotic systems for inspections (Jardón 2014). Jardón (2014) has reviewed a number of projects and research papers showing the use of robotics in the field. Several projects and methods used and tested for inspecting the wall linings using robotics are described. It is also mentioned that the inspections of the tunnels with reduced dimensions can be performed using small tele-operated mobile robots. Ventilation shafts and water tunnels are also tested in various projects using automated inspection techniques. Automated cleaning of tunnels has been tested and performed using e.g., mechanized cleaning trucks (Jardón 2014). Another example is Sánchez-Rodríguez et al. (2018), who applied laser scanning technique to automate the detection of anomalies in railway tunnels.

The main drawback of most robotic systems is that they are tele-operated. The next step in automation development is towards a fully automated tunnel

inspection (Jardón 2014). That, however, requires that the problems related to manual inspections procedures are solved. Two projects where these issues were studied were the TunConstruct project (Balaguer 2009, Victores et al. 2011) and the ROBINSPECT project (Loupos et al. 2014).

The inspection and maintenance part of tunnels have greater potential for automation because of a less complex nature of the operations as compared to design, planning and construction of tunnels. In addition, the technical service life is much longer compared to the construction phase. In addition, the equipment and machines are producing a lot of machine data that can be used for automated anomaly detection and failure predictions (Tichý et al. 2021). A drill rig, for example, produces a large amount of data that can be retrieved using an automatic data transfer system. The data can be used to analyse the condition of the equipment for diagnosing problems and evaluating the consequences and maintenance measures. Compared to the area of automation for maintenance, the area of inspection is lagging behind and could be an area for future research.

3.2.4. Mining

Mining is not a one stage process. It involves a series of processes including exploration, planning and design, development, production, and reclamation. Every stage has its own level of technological advancements. The harsh mining environments make it challenging to keep the technology and automation at the same level as other industrial sectors (ABB 2021). Due to the high consumption of minerals, mining is reaching greater depths. This requires special attention in the design and automating processes due to high ground stress levels (NRC 2002).

Technological advancements in automation, digitization and electrification are impacting the mining sector rapidly (Bliss 2018). Some of the technologies that are having major impact include drones, automated drilling, smart sensors, and autonomous vehicles (Bliss 2018). The adoption of automation for modernizing mining operations is worldwide (Black et al. 2018). The primary reason for this adoption is to find new ways for increased production rate, reduced operational and production cost, extended mine life, and improved workplace safety (ABB 2021). Increasing efforts and research projects are being carried out across the world for increasing the level of automation in the mining industry (Noone 2020). As per the estimates of the World Economic Forum, autonomous machines will be quite common by

2025 (Bliss 2018). Developments in artificial intelligence, machine learning, and industrial Internet of Things (IoT) can possibly save approximately \$373 billion by 2025 (ABB 2021).

Design and Planning

This section mainly focusses on mine planning and the design phase of the mine life. However, the 1st stage, i.e. the exploration stage, is also discussed to some extent. Any mining project starts from exploration, which includes the search for minerals and defining the size and shape of a deposit as accurately as possible (Hartman & Mutmanský 2002). Currently, exploration is mainly based on technologies such as tomographic imaging, magnetic and seismic surveys, remote sensing, diamond drilling etc. (NRC 2002). Bringing automation to mineral exploration is a relatively new phenomenon with possible widespread application (Walker 2019). The mineral exploration company, Goldspot Discoveries Inc., is using artificial intelligence and machine learning to find new gold deposits in Canada (Walker 2019). Recently, one of the largest gold mining companies, Goldcorp, started collaboration with one of the world's largest computer companies, IBM, to search for new exploration targets at Red Lake mine (Topf 2017).

Mine planning and design is becoming more and more software based in recent times. Mine planning involves the conceptual and feasibility studies where the software-based designs help to select the best scenarios for maximizing the profitability of the project (Hustrulid 2013). Modern mine planning involves the use of the latest computational methods for optimizing large scale scenario-based problems (Davis 2008). The use of artificial intelligence and machine learning can improve this scenario-based optimization. The flow of information from mine plans to operational mining automation systems and their integration is crucial for the sustainability and profitability of the mining operation (Burger 2006).

As automation in exploration is in its earlier stages, there is huge automation potential in this phase of a mine's life. This can be at either operational assistance level for decision support, or at fully functional level where equipment can perform and locate minerals by itself. Artificial intelligence (AI), machine learning (ML), internet of things (IoT), and big data analytics can help to:

- collect and analyse more robust thermodynamic and kinetic geochemical data,
- build new deposit models with fewer environmental issues after mining,
- build better geohydrological models,
- construct more accurate mineral maps,
- perform better geophysical surveys,
- perform unmanned aerial and ground-based topographic surveys,
- perform low-cost seismic surveys,
- better interpret hyperspectral data, and
- apply autonomous drilling technologies.

Similarly, use of AI, ML, IoT and big data analytics are increasingly being used in software development for mine planning and design. Scheduling of different activities and resource planning can be automated and optimized using the above-mentioned techniques. A closer relationship between end-users and software developers will result in high quality, functionality and ensure the future of mine planning software. AI can also be used to automate the planning and coordination of ore transport vehicles (Pecora 2020).

Construction

Mine development includes all the work carried out before the mineral is taken out. It involves preliminary paperwork, building the required infrastructure, excavating openings to reach the mineral deposit in case of underground mining, and the removal of overburden for surface mining operations (Hartman & Mutmanský 2002). The production stage involves the exploitation of the mineral deposit itself (Hartman & Mutmanský 2002). The infrastructure development is almost similar to other construction industries like buildings or roads, etc. The development of openings for underground mining operations is similar to tunnelling with a key difference of duration of the project. Mining operations are longer than tunnelling projects and can afford higher level of automation for the operation. Major operations that have been focussed on in the past for automation in mining include rock drilling, material handling and communication systems.

Epiroc built the Rig Control System (RCS) platform in the 1990s and has been using it as a core for an onboard automation solution for surface drill rigs (Epiroc 2021a). Sandvik has also made great progress in terms of drilling

automation. For example, the intelligent drill rig with the innovative AutoMine® software (Sandvik 2021). Today, the drilling systems can be equipped with an automated rod handling system (RHS), automated pick up of drill rods after drilling, COP Logic to help the drill rig overcome changing ground conditions, semi-automatic positioning of rig feed, hole navigation system (HNS), auto feed fold, and auto level (Epiroc 2021a). A semi-automatic explosives delivery system has been developed for Epiroc's boomer M2 integrated with Orica's explosives technology (Epiroc, 2020). Boliden, one of the largest mining companies in Sweden, is in the process of upgrading all its drilling machines to autonomous level at Aitik and Kevitsa mines (Burman 2021). The main advantages of automating a drilling operation includes increased productivity, improved accuracy of the operation, and removal of workers from harsh and dangerous conditions, especially in underground mines.

Material handling and haulage systems in mining have transformed from manual, animal driven carriages to large-scale trucks and more recently, autonomous vehicles. Automation can be seen in both the surface mining operations and in underground mining operations. Automation of earth moving machines is commonly focussed in small steps as automating the whole process is quite difficult (Dadhich et al. 2016). Roberts et al. (2002) suggested a five-step approach to automate such machines including manual, in-sight, tele-remote, assisted tele-remote, and fully autonomous operation. Automation of Load-Haul-Dump (LHD) machines, which are used for underground material excavation and transport, has been a research interest from the mid 1980s. Many systems have been tested around the world, but most mines have not frequently used autonomous LHDs. However, recently it is becoming more accepted and used due to e.g. safety reasons, the possibility to load after blasting and the potential to increase productivity.

CSIRO (2004) reported successful development of an LHD automation system based on reactive navigation and opportunistic localisation principals that was later launched as MINEGEM by Caterpillar. Marshall (2008) reported the successful development of a robust auto-tramming technology that he claimed was fast and reliable. This technology did not require any installation of fixed infrastructure. The hardware as well as user interfaces of Scooptram® automation system by Epiroc were documented by Atlas Copco (2009). A majority of the research has focussed on semi-automation instead of fully automated LHD because of the flexibility of the operation (Gustafson

2011). Recently, Epiroc and Combitech jointly came up with a solution for traffic management of autonomous LHDs in underground mines (International Mining 2020). The solution is named Epiroc Scooptram Automation Total, which has a Traffic Management System (TMS) as well as a Fleet Management System (FMS). TMS helps the LHD machines to interact and share roads and other common facilities to avoid collisions or jamming events. FMS helps to automate resource management and assignment without operator interference (International Mining 2020). The different levels of automation according to Epiroc (2021b) can be seen in Figure 14.

One of the major difficulties in automating an underground mining operation is the navigation system in narrow, harsh, and dark environments (Dragt et al. 2005). Surface mining trucks use both radar and Light Detection and Ranging (LiDAR) devices for sensing nearby objects. These devices together with high-precision Global Positioning System (GPS) help to create a clear picture of potential obstacles, location, and speed of the machine (Morell 2017). However, GPS navigation systems, being only useful for surface navigation, is not appropriate for underground mining vehicles (Dragt et al. 2005). Therefore, different navigation systems have been developed and tested for this purpose (Gustafson 2011). Gustafson (2011) described dead reckoning as a system to measure the vehicle's motion and determine its position. Another method is inertial navigation systems

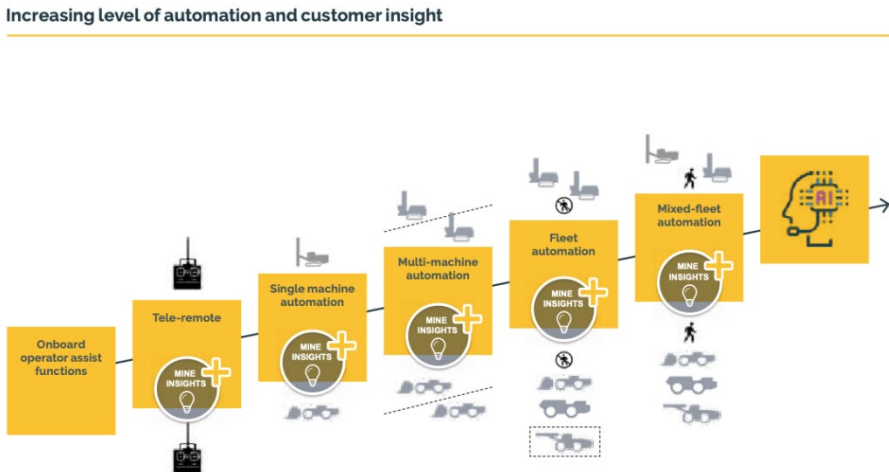


Figure 14. Different levels of automation according to Epiroc (Source Epiroc with permission)

that measures accelerations to determine the state of motion (Dragt et al. 2005). However, the huge price of the system does not favour its application in autonomous vehicles. Different researchers have applied artificial beacons, absolute navigation schemes, reactive navigation, neural networks, sensors, and fail-safe systems for automating LHD operations (Dragt et al. 2005). Neumann (2014) used LiDAR sensors coupled with tilting mechanism to construct accurate 3D maps around the vehicles. Kamijo & Yanlei (2015) proposed a simultaneous localization and mapping algorithm based on Kalman filter or particle filtering techniques to improve the accuracy of constructing maps. Ruiz-del-Solar et al. (2016) documented a robust semi-autonomous navigation system based on laser scanners, inertial measurement unit, and cameras. However, such solutions often need infrastructure and may offer drawbacks like installation and maintenance costs, etc. along with accuracy issues (Rowduru 2019). More recently, a collaboration of Mining Systems Laboratory, Canada; Örebro University's Centre for Applied Autonomous Sensor Systems, Sweden; and Epiroc, Sweden came up with a newer technology for LHD vehicles. This technology is called auto-tunable robotic loading (ATRL), which enables the automated LHDs to feel its surroundings rather than seeing it. This solution allows the machine to work in dust and darkness as it is not using camera technology (Anyadike 2017).

Currently, wireless communications i.e., Wi-Fi, 4G/LTE and 5G internet technologies, are being explored more and more to overcome the limitations of the past navigation systems. Wi-Fi communications had connectivity problems that were reduced by 4G/LTE private wireless network and 5G will further boost the machine automation significantly (Wordsworth 2021). Ericsson is testing 5G technology to automate Boliden's drill rigs that can enhance up to 40% of machine productivity (Ericsson 2018). Works of Ralston et al. (2014), Ralston et al. (2015), Ralston et al. (2017), Peng et al. (2019), and Bolož & Biały (2020) documented the automation level in longwall mining used for excavating coal.

An important unit operation that must be considered for automation is mine ventilation if a human-free working environment is desired. Production of dust, gasses, heat, radiations, etc. during development and operation of any mine cause different potential hazards. Automation for regulating the mine ventilation through automated ventilation doors, fans and control panels has been studied in the past. Witrant (2008) presented a novel approach for

wireless automation of mine ventilation control based on distributed sensing capabilities. Levin (2017) described the theoretical, as well as the technological, grounds of the automated ventilation control system and its execution. Different aspect of mine ventilation like airflow measurements, monitoring gas concentrations, air pressure measurements and communications have been automated to varying degree (Accutron 2021).

The harsh and remote mining environment always presents challenges to the mine automation. 5G technology is one of the modern fields making its way into mine automation. It can help to overcome the latency or delay issues in connectivity for improved navigation (Wordsworth 2021). Areas like optimal bucket trajectory for excavators, dynamic modelling and navigation have been addressed regarding automation quite extensively. However, they still need improvements (Dadhich et al. 2016). One of the areas regarding automation of excavators that needs more attention is bucket-rock interaction as it is different for different grades of rock (Marshall 2008). There is ongoing research and development work on development of an industrial IoT architecture that can bring all the individual mining systems to one platform and bridge the exchange of data in the mining environment. This can be possible by bringing together different technologies like OT/IT applications, business applications, IoT devices, big data, and cloud & edge computing (Aziz et al. 2020). Improvements in sensors, big data analytics, automatic ore-grade analysis, automatic fragmentation analysis, autonomous blasting, etc. are some other potential areas that will be explored extensively in the future to make mining more autonomous. Automated installation of ventilation accessories as well as ground support also needs to be focussed on to make the working face human-free.

Inspection and Maintenance

Harsh and dangerous work environment has been an inherent property of mining operations. Therefore, regular inspection and maintenance of different unit operations are very important for a safer mining operation. Inspections are mostly carried out to check the level of stresses, installed supports, water influx, and level of toxic gases in the mine. Autonomous Mobile Robots (AMRs) are gaining widespread application in mining industry as inspection tools (Association for Advancing Automation 2019). LiDAR technology is combined with mobile robots to get the most out of 3D

and high-resolution data (Association for Advancing Automation 2019). AMRs can be used to inspect old, abandoned mines which can be very dangerous for human-based inspections (Association for Advancing Automation 2019). Qadri (2021) documented an IoT based robotic scanning and inspection system for inspecting mine environment including carbon monoxide, humidity, and temperature monitoring. LKAB, one of the high-tech mining companies in the world, started using the robotic dog Spot® for increasing safety and efficiency of the inspection of damaged areas of the mine (LKAB 2020). Szrek et al. (2020) proposed a prototype of inspection robots for maintenance of belt conveyors in underground mines. Companies such as Percepto, Airbotics and Scott offer such robotic solutions that can fully automate mine inspections and gather high-resolution data. Another important factor to consider is the maintenance of automated mining machinery. The key challenges in this maintenance include the safety of maintenance personnel, generation of big data, and integration of automation system (Hoseinie 2015). ControlNet has been used for an integrated mining automation system by Chen (2007). Hoseinie (2015) recommended intelligent Reliability Centered Maintenance (iRCM) and eMaintenance methods for improving maintenance of automated mining machinery.

Automation in mine closure and reclamation stage is rarely documented and carries a huge potential for future studies. More et al. (2020) documented the potential methods for mine water management, which include artificial intelligence, drones, wireless sensor networks, radio frequency identification (RFID) and near field communication (NFC), and internet of mine water. Automation of maintenance of automation systems will be an interesting future prospect as well.

Although semi or fully autonomous equipment can increase the mine productivity and improve safety conditions, they can present new hazards as well. Some of the key challenges that are unique to automation of mining equipment include the variable operating conditions because of geology, challenging work environment with dust, noise, darkness, etc.; specialized design to meet safety standards; and more demanding maintenance plans for proper functioning (NRC 2002).

3.3. Summary

The trends are clear, internationally there are an increasing trend in research and development in the areas of automation, digitalization and robotics in the construction industry. Internationally, leading countries are USA, United Kingdom, South Korea, Canada, China, Germany and Switzerland with research ongoing in both universities and companies. The same trend can also be seen in the area of automation for infrastructure such as tunnels, highways, and bridges for design, construction, inspection and maintenance.

The use of BIM has increased the possibilities for automation and more efficient design and planning. By using BIM, 4D schedules linked to the design models can provides more flexible responses to design changes and enables an algorithm-based generation of, for example, location-based earthwork in highway construction schedules as well as the optimization of resource allocations based on e.g. productivity rates and supply chain information. Data in the BIM model can continuously be supplemented and updated, with data taken by drones and other stationary scanning equipment if needed for adequate planning and design, and for monitoring of the progress during construction, and during operation for the service life of the structure.

An accurate digital model is a prerequisite for automation and robotic construction. For highway construction, several examples of autonomous vehicles for excavation, compaction, and asphalt spreading and compaction are currently being developed. For bridges, additive manufacturing has been tested with success for automated construction of steel bridges and concrete pillars. Automatic fabrication of rebar cages using robots are also currently under development, which can be used as on-site factories for modular production. Within mining, Sweden is one of the leaders and drives automation in the industry. In the last decades, mining operations have evolved from remotely controlled to more autonomous self-driving technology. The technology developed in the mines can be used in tunnel construction with similar conditions.

Also, it can be concluded that inspection and maintenance is tedious work to a large extent performed by humans. As described above, automation within these areas have started. Several examples using different types of sensor technology, combined with IoT and cloud technology have been used

for automation of monitoring and inspections. In the area of maintenance, however, the progress of automation has not reached as far as for inspections.

4. Activities in Sweden

4.1. Introduction

According to a statement by Sven-Arne Paulsson at Automation Region the year 2009, Sweden has an extremely strong position within automation, with a market share of approximately 10% of the global market (Paulsson 2009). He further states that two thirds of the automation industry is situated in the region Mälardalen. A more recent report issued by PiiA, Automation Region and Blue Institute, specifies that the Swedish IndTech industry, which includes both operational production technology (OT) and information technology (IT), has a global market share of 3% (Larsson 2021). Compared to the size of the Swedish economy in relation to the global, the Swedish IndTech industry is six to seven times larger than comparable countries like Germany, France and Great Britain.

Large Swedish corporations like ABB, Ericsson, Saab Combitec, Volvo and Scania are working towards automation, autonomous systems, self-driving and robotization within their different disciplines. With this background Sweden should have a unique possibility to produce automation and robots for the construction industry.

Below, an overview of the early and recent research work performed within the area of construction automation in Sweden is presented together with current trends. Since the work performed with construction automation in Sweden is limited both housing and infrastructure is included in this chapter. The aim is to give an overview of construction automation in Sweden and does not intend to give a complete coverage.

4.2. Early work

One of the pioneer work within the area of automation in the Swedish construction industry was a pre-study by Tarandi et al. (1988). In their study, they motivate the need for robots in the construction industry due to the

following reasons: decreasing productivity in the construction sector compared to other industry sectors, dangerous and unhealthy work tasks, difficulties finding qualified labor, and that the Swedish export in the construction industry needs to be improved, especially in the competitive environment that exists globally.

Tarandi et al. (1988) also made a mapping on the application of robots internationally within the construction industry. Based on this mapping they conclude that most robots are in an initial stage and mainly prototype exists. Furthermore, they concluded that CAD-drawings will be the most important information carrier in the future. In addition, they predicted that at the future work site there will exist a number of different robots performing different tasks in specific on site-factories. A pilot-project was also proposed, consisting of a mobile robot for smoothing and grinding concrete floors.

During the period 1987-1998, the work with the development of a mobile robot for smoothing and grinding concrete floors was continued by Pär Åhman. A summary of the work has been presented in the report "Robots in the construction industry – use and opportunities" (Åhman 2013). In the report, a historical outlook on the use of robots in the construction industry internationally was presented, partly based on the work by Tarandi et al. (1988), together with the development of a fully automatic prototype machine for smoothing and grinding concrete floor as well as cleaning. The starting point for the work was the use of advanced technology to create better working conditions, safer production, better quality and higher production.

In early work performed by Johansson & Åhman (1992), it was concluded that a total change and automation of the construction industry was far away, but single tasks could be automated and that will gradually change the industry from low technology usage to higher. This transformation leads to better working conditions and to easier recruitment. It was concluded that continued research was needed, together with collection of new knowledge, education and maybe a new category of construction workers.

In a conference paper, Rahm (1988) lists some examples of robots used at Swedish construction sites. The following rather broad definition for robots with an increasing level of complexity was used:

1. *"Manual Manipulators - which perform fixed or pre-determined work sequences. These includes remote controlled machines which are sometimes called low level robots, as they often constitute a*

preliminary stage to fully developed robots, but often offered at sales as robots.

2. *Playback robots - which repeat fixed instructions.*
3. *Numerically controlled robots - which perform works or duties through numerically recorded information or data.*
4. *Intelligent robots - which perform given works or duties by using "their own experience".*

The list by Rahm included the following examples: (1) Tunnel drilling technique with a FORO drilling machine developed by Atlas Copco (today that part of Atals Copco is called Epiroc), (2) BROOK, a remote controlled robot developed by Atlas Copco (today the company Brook) for demolishing concrete and other concrete structures, (3) DEMEC 520, a remote controlled robot for demolishing purposes developed by Diamantex AB, (4) HANDY CRUSHER, a remote controlled hydraulic cutting or shearing tool used mainly for quiet, dust and vibration free demolition of concrete walls, (5) LARVEN, a remote controlled hand-driven load carrier which could work in narrow spaces and minimizes the risks for broken backs and squeeze injuries, (7) LASER CONTROLLED ROTO MACHINE, developed by ABV and Chalmers Industri Teknik to avoid heavy and stressful operations of concreting slabs, (7) ELECTROLUX EUROCLEAN CLEANER ROBOT AXV-01, which was a battery driven vacuum cleaner that navigated with the help of ultra-sound sensors, working three to four times quicker than a person, and (8) AUTOMATIC MIXER developed by BELAB and ABS used for mixing mortar for bricklaying. The aggregates and water was automatically mixed to a pre-determined mortar consistency.

Rahm (1988) concluded that there were few robots utilized in the Swedish construction industry even though a broad definition was used. Possible reasons for that were, according to Rahm (1988), a small market and the number of repetitions of working operations are limited. At the same time construction sites are dynamic environments that evolves during construction, and weather conditions often change over the construction time. Rahm (1988) points out that there are also economic concerns, mainly concerning profitability but also social problems when laborers are reorganized and new work operations are being introduced.

A plastering robot for walls and ceilings was developed at Luleå University of Technology by Forsberg et al. (1995). The robot had a spray gun attached

to a mobile robot base with three wheels, and the robot was equipped with two range cameras as sensors. A spinoff company, MoRoCo, was founded based on the work with the plastering robot.

4.3. Current work

4.3.1. Academia

At the present time, there are several ongoing initiatives in academia which, in some way, focus on digitalization and construction automation located at different universities:

- Lund University, Faculty of Engineering, formed the Centre for Construction Robotics with the aim to develop, adapt, demonstrate and test solutions for construction automation. The centre has collaboration with 15 partners representing material suppliers, architects, contractors, robot companies, system integrators, researchers, clients, property managers, and investment companies.
- KTH Royal Institute of Technology has formed the Centre for Construction Efficiency and work, for example, with 3D printing of concrete in collaboration with ConcretePrint. In collaboration with the cross-disciplinary research centre Digital Futures at KTH, the project “Towards Safe Smart Construction: Algorithms, Digital Twins and Infrastructures” started in 2022 in collaboration with Skanska and Ericsson.
- Luleå University of Technology has the last decade performed extensive research on mine automation in close collaboration with e.g. Boliden and LKAB. During the years 2017 to 2020, they performed research in the EU financed project SIMS – Sustainable Intelligent Mining Systems. Partners in the project where, among others, Epiroc, Boliden, Ericsson, LKAB, Mobilaris, and RWTH Aachen University. Today, LTU is heavily involved in the EU financed NEXGEN-SIMS project
- Mälardalen University in collaboration with Robotdalen perform research within industrial robotics, which also includes construction automation. One example is the research project in collaboration with Skanska for construction of reinforcement cages using robots (Relefors 2021).

- Linköping University performs research in the strategic Smart Built Environment project “Digital Transformation av Byggplatser”, which ends in December 2023. The project is a continuation of the project “Uppkopplad byggplats”, which was performed during the years 2017 to 2021. These projects want to reach sustainable efficiency of the construction sites through digitalization.
- Chalmers has created the consortium Digital Twin Cities consisting of 29 stakeholders with the base at Chalmers. Research is performed in eight areas that covers the needs to develop large-scale digital twins with the goal to use digital technology in new ways for urban planning, design, architecture and digital construction.

4.3.2. Industry

Many companies in the Swedish IndTech and construction area are world leading within their field. Below is list of examples in alphabetic order of Swedish companies who have, or are, working with construction automation (mines included):

- **Aquajet** 1988 developed hydro demolition robots used for concrete removal. It was a remotely controlled robot, and Aquajet was acquired by the company Brokk and is today a subsidiary of Brokk.
- **Build-r** developed a robot to mount sheet material on inner walls. The robot system consists of an industrial robot arm on a self-driving platform. The company had collaboration with NCC, ABB and Robotdalen in Eskilstuna. Build-r did not prevail the initial startup sequence.
- **ConcretePrint** creates large scale 3D-printers for concrete 3D-printing. The company started 2015 and has since then created a 3D-printable concrete, and among other things printed a small cottage (Attefallshus) of 24 m². ConcretePrint collaborates with researchers from KTH.
- **Epiroc** is a world leading company in developing and building equipments for mining and tunneling, which include drill rigs, products such as the Rig Control System (RCS) platform and the automated rod handling system (RHS), and the Epiroc Scooptram Automation Total for traffic and fleet management.

- **Husqvarna** is a longtime producer of STCR robots for mowing grass. In 2021, Husqvarna released a fully autonomous lawnmower without electronic fence for safeguarding aimed for commercial use. Husqvarna also produce remotely controlled robots for demolition, compacting dirt, and floor grinding, etc.
- **NCC** has made two strategic ventures the last 15 years, the building system Komplett and the mobile app Looprocks. Komplett was a building system for prefabrication of concrete walls in large building complex. On the concrete walls, everything, even the wallpaper, were applied and kitchen cabinets were mounted to the concrete walls in the factory. The Looprocks app was used to reuse materials as earth and gravel that had been dug up. Anyone with a need nearby could request it or book the empty transport when the truck had delivered its material. In addition, NCC currently is investigating the use of the self-walking robot dog Spot© from Boston Dynamics.
- **PEAB** is also investigating the use of the self-walking robot dog Spot© from Boston Dynamics for measurements of progression and productivity against time plan.
- **Sandvik** has since 2004 developed self-driving, autonomous vehicles and an automation system, AutoMine. The system is used for loading vehicles and hauling in mines. Sandvik defines autonomous vehicles as a vehicle capable of sensing its environment and navigating without human input. Sandvik is also using onboard 3D-scanning to capture real-world data and create point cloud that is converted into a 3D model. The 3D-scanning technology is used in several applications underground, for example to navigate the drill rig so it knows where it is. It can also be used to determine the volume of material excavated in the tunnel or controlling against the mine plan whether there was overbreak or underbreak relative to the drift profile.
- **Skanska** has been involved in different automation and robotic projects over the last 10 years. In 2014, Skanska was part of a 3D printing concrete project with the University of Longborow in England. Skanska has also been involved in the development of a robotic arm that applies tiles on a wall or a roof in for instance a tunnel. Skanska has also been the initiator for the research projects aiming for automatic construction of reinforcement cages.

- **Volvo**, manufacturer of trucks and construction machines, performs research within the field of self-driving and automated processes or tasks. The last years the subsidiary, Volvo CE, has produced several new vehicles or prototypes with self-driving or autonomous capabilities to be used within infrastructure construction. An example is the Volvo LX03 prototype, a 5-ton wheel loader, fully autonomous, battery powered with a real-world example of a self-learning concept using a brain to make decisions, perform tasks, and interact with humans. Another example of self-driving and automation is the CX01 single-drum asphalt compactor concept which utilizes one vibratory drum and is kept upright by a self-balancing control system. The CX01 can be remotely operated or run in autonomous mode. The machine is operated either on diesel, hybrid or in electric powered mode. Since 2016, Volvo has a fully self-driving truck that operates in a mine, 1300 metres underground, at tough conditions. Volvo has also several interesting collaborations to test and develop their business offerings towards the construction industry. One is the Volvo CE Electric Site in collaboration with Skanska. They also have a partnership with Telia and Ericsson for 5G technology using a 5G network to test remote controlled machines and develop automated solutions.

In addition to the companies mentioned above, there are several other Swedish IndTech companies who are important as enablers for construction automation such as ABB, Ericsson, Telia, etc.

It is now approximately 34 years since Rahm (1988) wrote the list of different companies who had developed machines for construction automation in Sweden. In order to see which of these companies, and their products, that are still in production today, a search on the company's name and their product was made on internet. The result is presented in Table 4. It is interesting to notice that three out of eight products, even though they have been upgraded during the years, are still in production. It can also be noticed that all of the products developed by minor start-up companies are no longer in production, while all of the product developed by larger companies such as Epiroc (former Atlas Copco) and Electrolux are still in production and now constitute important parts of their product portfolio.

Table 4. List of robots used in the Swedish construction industry according to Rahm (1988) and the results from an internet search if they are active today.

	2022	1988
FORO: Tunnel drilling technique with a FORO drilling machine developed by Atlas Copco. In 2022, Epiroc is now an independent company from Atlas Copco, where tunnel boring machines (TBM) are manufactured.	X	X
BROKK 80/BROKK 100/BROKK 250. Remote controlled robot developed by Atlas Copco for demolishing concrete and other construction structures. In 2022, BROKK is now a world leading demolition robot company with 12 sales offices around the world.	X	X
DEMEC 520. A remote controlled robot used for demolishing purposes, and developed by Diamantex AB.	No operation was found	X
HANDY CRUSHER. A hydraulic cutting or shearing tool developed by Svenska Handycrusher.	No operation was found	X
LARVEN. A remote-controlled crawler used as load carrier to work in small spaces. Manufactured by Svets Mekano AB in Växjö.	No operation was found	X
LASER CONTROLLED ROTOR MACHINE. Developed by Leif Johansson, ABV and Chalmers Industri Teknik. (CIT) The machine was developed in order to avoid heavy and stressful operations or works during casting of concrete for slabs, arch's or roofs.	No operation was found	X
ELECTROLUX EUROCLEAN CLEANER ROBOT AXV-01. A vacuum cleaner which navigates with the help of ultrasound sensors developed by Electrolux AB in co-operation with a Japanese company. 2022 Electrolux is one of many robot vacuum cleaner producers.	X	X
AUTOMATIC MIXER developed by BELAB and ABS, Stockholm. The mixers add water automatically and mix the aggregates to a pre-determined mortar consistency.	No operation was found	X

4.3.3. Financiers and strategic innovation programs

One of the most important financiers for research within the infrastructure sector is the Swedish Transport Administration, who 2021 financed research for 758 MSEK , distributed on eight different portfolios. The most important program for construction is the portfolio “Bygga” with a volume 2021 of 112 MSEK (Styffe & Gustafsson 2022). Also worth mentioning with respect to automation is the portfolio for strategic initiatives, where

several projects on autonomous machines and vehicles have been performed the last years.

In addition to Trafikverket, the strategic innovations programs (SIP) Smart Built Environment and InfraSweden2030 are important financiers for funding research related to construction automation. Smart Built Environment was formed at 2016 as one of the strategic innovation programs, SIP, and has the goal to use digitalization to change structures and ways of working in the construction industry. The other SIP, InfraSweden 2030, started 2017 and works to support innovation in the transportation infrastructure by the use of new material, technology, ways of working, contracts processes and forms of partnership. Another important SIP for automation of the infrastructure sector is the Swedish Mining Innovation, which is a strategic innovation program for Swedish mining and metal producing industry. Another SIP of interest for construction automation is Process Industrial IT and automation (PiiA). In total, there exists seventeen strategic research program, all funded by Vinnova, the Swedish Energy Agency and Formas.

An important research financier who has funded several research projects on construction automation is the Swedish construction industry's organization for research and development (SBUF). A brief summary of some research projects related to construction automation funded by SBUF are as follows: A field test of a robot for application of shotcrete in tunnels developed by Meyco Logica was tested in Törnskogstunneln 2005 (Ellison 2006). A simulator for robot operators of shotcrete application has also been developed (Börjesson & Thell 2011), which resulted in the spin-off company Edvirt. SBUF also funded a project to study possible solutions for automatic placement of traffic cones in order to increase the safety for workers (Bäckström 2014). Another example is the report by Lidelöw & Dagman (2015), where the potential for new production methods in the construction industry such as 3D printing and the use of robotics were investigated. Development of automatic construction of reinforcement cages using robots has also been funded in the last years by SBUF in a project performed by Skanska, Robotdalen, ABB and Mälardalen University (Kjellgren 2019, Relfors 2021). Construction automation for concrete structures was the topic for another report performed at Lund University together with the companies Cementa, Cognibotics, FOJAB and PEAB (Jenning 2020). The report focused on the automation of concrete construction in prefabrication

and on-site settings, and contained both a theoretical review and results from performed workshops as well as practical laboratory tests. In this context, the areas for most needed improvements were seen to be learning and feedback structures, workplace conditions for the use of robotics as well as the cost factors in the production of individual elements and complex systems, mostly in the process of concrete pouring and rebar installations. Overall, 60 different technologies in automation and robotics were identified and rated according to their contribution and transformation potential with respect to productivity, workplace conditions, product quality, product innovation and environmental impact. Jennings (2020) considers the early holistic integration of robotic solutions from the design and construction planning crucial for successful value creation strategies. Moreover, Jennings (2020) suggests that by generating high-quality data from design to the as-built product, feedback loops can be established that enable continuous learning and the improvement of construction processes as well as building operations. The tests of the techniques in the project were also financed through the project “Uppkopplad byggplats” performed at Linköping University described in the previous section. 3D printing was also performed in a project funded by SBUF by the company Concreteprint to print a small cottage in concrete (Attefallshus) (Haslingen et al. 2022), see Figure 15.



Figure 15. 3D printed small cottage (Attefallshus) by the company 3D print (Photo: Tobias von Haslingen).

The Swedish energy agency, with the program E2B2, started 2013 and aims to contribute to a shift in the energy system as well as a resource-efficient and energy-efficient built environment through research and innovation. Hence, E2B2 includes research, development and innovation in the total energy use of buildings across their entire life cycle. Knowledge of people's lifestyles, how people use energy at home, and what choices are made are also included in the programme.

Even though not being a research financier, BIM Alliance constitutes an important association for the transformation of the construction industry. BIM Alliance was formed 2014 by merging the organisations OpenBIM, fi2 Förvaltningsinformation and buildingSMART Sweden with the goal to increase the use of BIM in projects, supply and manage standards and tools, and initialize and support common development projects.

4.4. Future trends

In 2019, Samuelsson (2019) made a mapping of digitalization projects within the Swedish construction industry funded by different financiers of research, which started between 2018-01-01 and 2020-09-20. The following definition were used to identify the digitalization projects: *“Projects or initiative that aim to develop the construction process or its actors with support of digitalization”*. 119 projects were found in the areas BIM, IoT, Analysis and Automation, where 19 (16%) of the projects were in the subgroup automation, the use of robots and/or 3D-printing. A word cloud of organizations leading research projects within digitalization according to Samuelsson can be seen in Figure 16.

Samuelsson (2019) reflects over the strategical ownership of the digitalization and concludes that no single organization can own the digital transformation. There exist different industry organizations, interest groups, standardization organizations and even strategic innovation programs. He also concludes that greater efforts in transformation is needed, so that not only single tasks are digitized. For this to occur, both development in ways of working, as well as processes and business models, needs to take place.



Figure 16. Word cloud of organizations leading research projects within digitalization (From Samuelsson 2021).

Another initiative is the “National roadmap for digital construction sites” by Jeppsson (2021). The proposed roadmap has two main proposals: (i) A collaborative forum for all company members in “Byggföretagen” and “Installationsföretagen”, where issues concerning digitalization can be discussed, and (ii) priorities made to reduce fragmentation. Six development areas were identified:

1. Agreed standards for information exchange
2. Open platforms for data exchange
3. 3D model used as legal document
4. Digital twin for both product and site
5. Connection standards and data standards that enable data flow through the construction process and supporting IT systems
6. Pilot project that shows the possibilities with robots and automation

Of the digitalization projects identified by Samuelsson 2019, a relatively small amount of all projects concerned manufacturing with automation or robots. This can give an indication that this area is difficult and more demanding to perform research within. At the same time, a developed product must reach a Technical Readiness Level (TRL) of about 7 to 8 in order to decide if the product will work and be useful. On the other hand, in a pure

digitalization project, the time to market is shorter, and it may be easier to early verify the benefits.

That development of products for automation with robots are more demanding to perform can also be concluded from the early studies by Rahm (1988), Tarandi et al. (1988) and Johansson & Åhman (1992). They all describe a future and anticipate a change – 34 years later, the status of progress in construction automation is almost the same.

It can be noticed, however, that in the last years several relatively large programs or centers have been established at Chalmers, Lund, KTH, Mälardalen, Linköping and LTU with focus on digitalization and construction automation. Concerning automation in the infrastructure area, research are mainly performed by LTU and KTH together with Mälardalen University.

The trend with an increased interest in construction automation can also be noticed at the Swedish construction companies, especially in the last two to three years, even though the extent of the research and practical trials with more advanced robots are rather limited to a few projects.

The research made by academia and the construction companies have mainly been enabled by the strategic research programs such as Smart Built Environment, InfraSweden2030 and Swedish Mining, together with the possibility to apply for funding for establishment of research centers from Vinnova and FORMAS. However, compared to the amount of money spent on research within the field of automation internationally, and in the Swedish IndTech companies, the investments are rather modest.

To sum up, construction automation is not a new concept in Sweden. Even though research started in this area almost 40 years ago, relatively modest progress has been achieved so far. The last two or three years, relatively large amount of funding has been given to Swedish universities and research institution. However, the funding are mainly towards digitalization, and not construction automation. At the same time, an increased interest in construction automation can be noticed from the construction companies, who now are actively taking part in several ongoing research projects.

With these favorable conditions that exists in Sweden today, one can wonder why the development and progress of automation and robotization hasn't reach any further in the Swedish construction industry. This will be further discussed in section 6.3.

5. Thematic Days

5.1. Introduction

Two thematic days were held in May 2021, discussing the technical possibilities and barriers as well as business models to enable commercially viable use cases. The thematic days were organized and moderated by the project group for the National Network with speakers and attendees from the fields of both construction, mining and robotics:

1) Thematic day 1: The technical perspective

The first thematic day focused on understanding the current and future technical application areas of automated construction.

Topic	Speakers
<i>Automation in Mining</i>	Peter Burman (Boliden) Jenny Greberg (LTU)
<i>Automation in Construction</i>	Ulf Håkansson (Skanska) Lars Pettersson (Skanska)
<i>Automation in Robotics</i>	Robert Andersson (LTH) Helena Eriksson (Cognibotics)

2) Thematic day 2: The organizational & economic perspective

The focus of the second thematic day was on organizational and economic conditions that are necessary for enabling implementation of automated construction. Lars Albinsson was invited as moderator.

Topic	Speakers
<i>What is required for implementation?</i>	Susanne Nelleman Ek (BIM Alliance) Lars Albinsson (Maestro)
<i>The role of the client</i>	Bernt Henrikssen (Automation Region)
<i>Business models</i>	Samuel Holmström (Lundqvist Trävaru) Professor Kent Eriksson (KTH)

The speakers at the thematic days represent some of the ongoing initiatives and projects in the Swedish construction industry where technologies for automated construction are being applied. Below is a brief summary of the results and the discussion from these days.

5.2. Thematic day 1: Technology

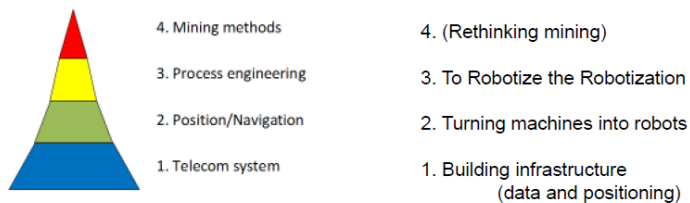
5.2.1. Automation in mining

In the mines, according to Peter Burman who is program manager for mine automation at Boliden, the main drivers for implementation of automation have been the target values of increased safety and productivity, and not the implementation of the technology itself. This approach has been applied in the implementation of automation in the mining industry and has steered the development of automated mining processes.

Furthermore, according to Peter Burman, the basis for digitalization of a mine could be divided into four steps (Figure 17):

1. Telecom systems (building infrastructure; data and positioning)
2. Position and navigation (turning machines into robots)
3. Process engineering (to robotize robotization)
4. Mining methods (rethinking mining)

The development of Mine Automation



Source: Greg Baiden, Penguin ASI

The basis for Mine Automation is a wireless data network in the mine.

BOLIDEN

Figure 17. The development of Mine Automation (From Peter Burman, Boliden with permission)

As evident from the list above, systems for communication is a prerequisite for successful automation and to turn the machines in the mines into “robots”. In order to obtain full automation of a process, Peter Burman further stress out that it is important to consider all tasks in the process, i.e. to robotize the robotization. For example, to robotize a robot for applying shotcrete implies that also the mixing of the shotcrete needs to be automated together with cleaning necessary parts after the work is completed, so that the machine can be used again, etc.

In a mine, all development concerns how to develop and enforce lean processes; everything is about the “flow” in the production, i.e. the transformation of a mine from an infrastructure operation to a smooth operating factory. In order to obtain this, all robots needs to be orchestrated so the different systems are integrated to work together in a smooth and safe way.

A key performance indicator (KPI) used by Boliden is the term “Lights out” for steering implementation of automation, see Figure 18. The term “Lights out” is a manufacturing methodology (or philosophy) that refers to how long robots can be self-sustained and independently continue their work without any human intervention or interaction. Lights out (manufacturing) is a manufacturing methodology rather than a specific process. Factories that run lights out are fully automated and require no human presence on site.

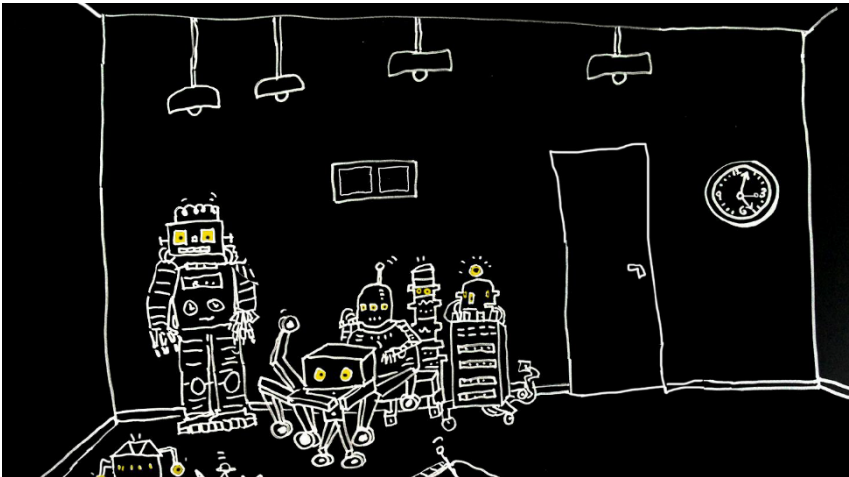


Figure 18. Lights out (From Peter Burman, Boliden with permission)

To drive automation in their mines, Boliden have established a roadmap for different automation activities, which includes 18 different projects.

Jenny Greberg, programme director at Swedish Mining Innovation and Associate Professor at LTU, describes that LKAB started using remotely controlled “robots” already during the 90s, even though the productivity was low. Today, the Swedish mines are world leading in mine automation. This is no coincidence. The Swedish mining industry have worked purposefully under long time to gather “the Swedish Mine Cluster” which include the Swedish mine companies, the suppliers, universities and SMEs. Together, they created a common vision and innovation roadmap, and have worked strategically at different levels with the government, the authorities, politicians and the EU-commission and with different forums for strategic communication. As an example, they have established the SIP, Swedish Mining Innovation, which is one of the seventeen Swedish Innovation Programs funded by Vinnova, the Swedish Energy Agency and FORMAS. The Swedish Mining innovation grant 55 MSEK annually. In addition, LKAB together with ABB, Epiroc, Sandvik and Combitech have also been granted the project Sustainable Underground Mining – SUM. The aim of this project is to set a global standard for sustainable mining at large depths, which is important to enable integration of different subsystems in order to “orchestrate” the robots. Their vision is that future mines are carbon dioxide free, digitalized and autonomous. An EU-project was also granted, Sustainable Intelligent Mining Systems, SIMS, with a total budget of 168 MSEK during the years 2017 to 2020. This project is now being continued under the acronym NEXTGEN-SIMS with an additional 160 MSEK in funding.

By being a business developer for their suppliers, Peter Burman says that a mine is a controlled area that can act as an advanced testbed for new technology. By doing so, Boliden and the other Swedish mines can utilize an unproportionally large share of their supplier’s research budgets by letting them test their products within the mine in a confined area. These suppliers include companies such as ABB, Ericsson, Epiroc, Volvo etc., with billions in research budgets.

5.2.2. Automation in construction

According to Ulf Håkansson, Technical Manager at Skanska, the construction industry has, compared to ordinary production industries, a

high degree of “one-piece productions”, unique movements and tasks, low volume and a high mix of tasks to be automatized, so called “*flexible automation*”. This implies that a CAD-model, BIM or a digital twin needs to be used for production and must be 100% correct. At the present time, this is seldom the case. In the future, therefore, more time will be needed in the detailed design phase. Algorithms for creating flexible automation must also be developed to allow steering of robots via a digital model.

A critical task in many infrastructure projects is tying of reinforcement of rebars for concrete structures. This work is heavy, with uncomfortable working postures. With the aim to improve occupational safety and health, productivity, and sustainability, Skanska initiated research to develop an automated construction of reinforcement cages. A proof-of-concept setup in scale 1:2 was developed together with Robotdalen and Mälardalen University. The setup consists of three robots-arms working together mounted in a gantry constellation. Two of the robots-arms holds the rebar in place, while the third robot-arm ties the rebar with a fully automated rebar tier from Husqvarna, see Figure 19. The movement of the robots was initially programmed. However this is not flexible enough. Therefore, the same proof of concept production facility was used, but with an algorithm developed for automated calculation of path planning and collision control direct from the CAD-drawing as illustrated in Figure 20.

SKANSKA

Byggautomation Armering - Armeringsstation

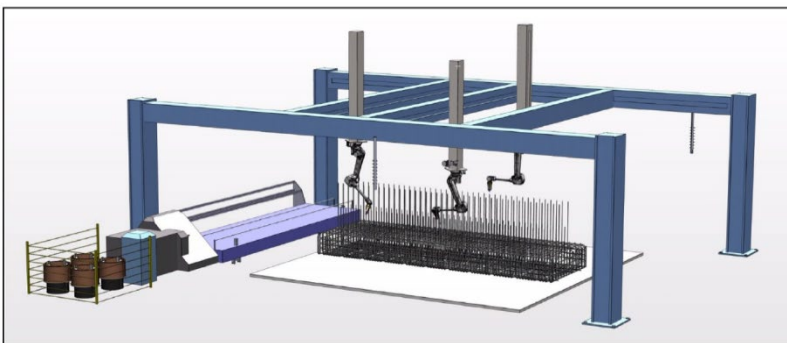


Figure 19. Robotic set-up for rebar works (From Ulf Håkansson, Skanska with permission)

Byggautomation Armering – Styrning av robotar

”Konvertering av digitala 3D modeller för styrning av industrirobotar”

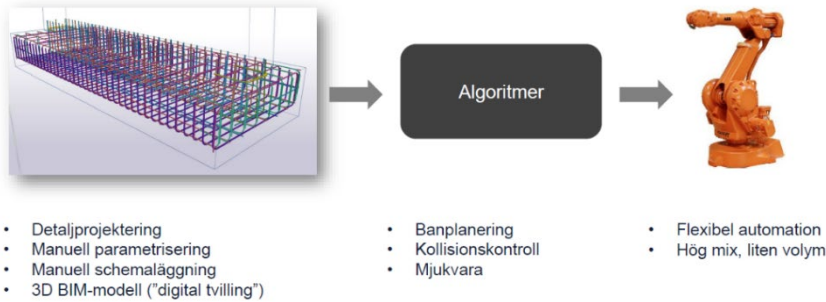


Figure 20. Stages of robotic control (From Ulf Håkansson, Skanska with permission)

Skanska plans to implement the production facility at the project Mälarbanan. In this project, 15 000-20 000 ton of reinforcement will be tied. The expected capacity will be approximately one hour per ton for the robots, while the capacity for manual labor is approximately ten hours per ton. Only considering the saved working time, Skanska expect to save about 6 000 SEK/ton, or 120 MSEK on the whole project.

Even though the project described above has been successful, Ulf Håkansson at Skanska are of the opinion that there are still many barriers towards the increased use of automation in construction. These relate to the project-based and complex nature of the industry, where the construction site is a mix of many actors, materials and processes that need to be coordinated in the evolving surrounding of the built environment (compared with the manufacturing industry where automation is being carried out in a controlled environment). There is also a strong persisting culture, lack of centralized funding and a lack of a “*sense of urgency*” Ulf states.

5.2.3. Automation in robotics

In industrial application with large production series, the robots are programmed to perform the exact same movement every time. However, according to Anders Robertsson who is Professor at the Department of Automatic Control at Lund University, this cannot be used in flexible automation required for construction automation with one-piece

productions, where the robot path is calculated based on the BIM-model. An important aspect in these cases is the ability of the robots to correct for small errors or deviations in the production. With the help from sensors, the performed work by the robot can be scanned/measured and compared against the BIM-model. The required correction can be calculated and given to the robot for adjustments. Here, fast feedback to the robot is of importance. To sum up, when flexible automation is used in a system for one piece production the control of the robot needs to be able to perform dynamic adjustments dependent on information from sensors.

Robert Andersson also describes the creation of the new centre for Construction Robots at Lund University. The centre is a cross disciplinary collaboration between Architects, Civil Engineering, Computer Science and Control Systems at the university together with companies from the construction sector, see section 4.3.1. One example of the applications that the centre is working on is their automated masonry, see Figure 21.

Helena Eriksson at Cognibotics and the Centre for Construction Robotics at Lund University describes that their constellation of partners has been successful in receiving research grants. In a SBUF funded project, “Produktionsautomation betong” (Jenning 2020), they investigated the progress within construction automation that has occurred since the work by Åhman (2013). The conclusions from this work were used for a research application to Boverket resulting in the project “Innovativt bostadsbyggande genom flexibla robotar i samverkan med människor” with a total budget of

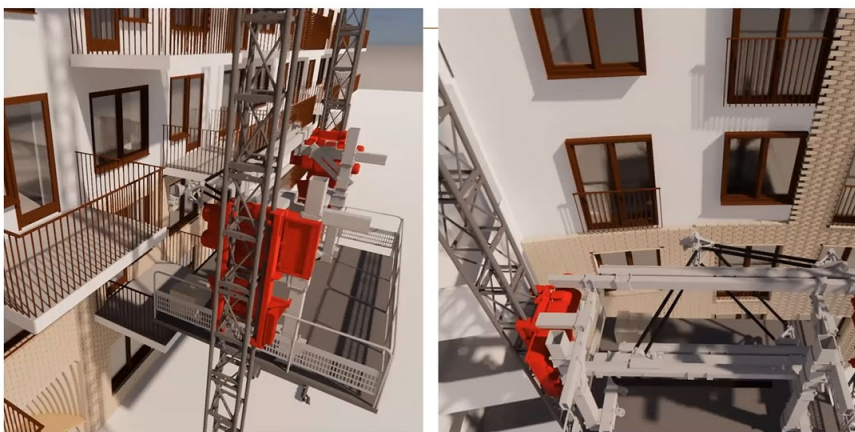


Figure 21. Example of how parallel kinematic robots can be used for masonry (From Henrik Malm (FOJAB) and Maike Klöckner (LTH) within the Vinnova project Acon 4.0, Centre for construction Robotics, LTH, with permission)

14 MSEK. Another application to Vinnova resulted in the project ACon 4.0, Innovative Agile Construction for Globally Improved Sustainability, with a total budget of 18 MSEK. The aim of the project is to reduce the fragmentation within the construction industry, connect digital design to production automation, develop safer and more equal workplaces, and to develop adapted robotization for collaboration with workers at the construction site. In total, the center has received funding of close to 40 MSEK in the last years.

5.3. Thematic day 2: Organization and business models

5.3.1. Implementation requirements

Albinsson (2019) mentioned that the CPI for the construction sector has increased eight times faster than in society in general over the period 1996 to 2016. Furthermore, building a house has large environmental impacts. For example, the actual building process of the house consume the same amount of energy as 50 years of operation. Thus, it is important that the construction process is as efficient as possible from a sustainable point of view.

Albinsson thereafter continued to describe the difference between an industrial production and craftsmanship. In industrial production, the design and the manufacturing process is separated, and all design decision are taken before the production starts. In craftsmanship, however, many of the design decisions are taken continuously during the actual production process. In principle, the degree of craftsmanship in production can be measured as the number of human decisions taken during the construction period. Today, the construction process is to a high degree based on craftsmanship and documents, see Figure 22.

Albinsson give examples of different efficient construction methods. For example, in the shipping industry the construction of the ship “Harmony of the seas” was performed in three years, from ordering to delivery. The ship can house 9000 guests, and is comparable to a city district. According to Albinsson, the shipping industry has found a construction method that is efficient. Industry 4.0, according to Albinsson, can be seen as one piece production to the same cost as with mass production. Large piece off-site production is used by the company Sizes for the construction of prefabrication modular based houses. All of these are examples off efficient production, and the question is raised: Why are these methods not more frequently used in the construction industry?



Figure 22. Example with high degree of craftsmanship at site with manual labour (From Lars Albinsson, Maestro with permission).

According to Albinsson, the problem mainly relates to business models and organization. As an example, a plumber only uses 20% of his time for actual productive work, while the rest of the time is spent on meetings, unspecified work and waiting. However, as long as the plumber is paid on an hourly basis, the plumber will not have any incitement for changing his business model. Another example is the supply chain and cost for buying material, where the craftsman, subcontractor, contractor all add 10% to the cost if the craftsman buys the material. In total, this will result in a 33% increase of the costs for the client. Once again, this is a profitable system for all involved parties except for the client, and no incitement for changes exists.

Furthermore, Albinsson gives another example where a centralized supply chain was used. By doing so, a 95% reduction of the material transport was obtained. In addition, if the material is cut at site, the craftsman also gets paid for excess material that has to be disposed. In other words, the buyer pays 33% more even for the disposed material, in comparison to automated one piece production where materials can be cut accurately, and the buyer only pays for the material actually used. No incitements exist for the craftsman to change this business model. To sum up, the existing business model for contractors does not drive change.

In addition, each project needs to fully carry their own costs. However, there are no overall innovation or change of processes that can be financed by single project costs, in comparison to a fully industrialized process. In order to change this, Albinsson recommends that: (i) one IT-platform for design, planning and production is used, (ii) that consultants and sub-contractors does not get paid on an hourly basis, (iii) and that the construction companies invest in production technology that is written off by multiple projects.

Susanne Nelleman Ek at BIM Alliance and IQ Samhällsbyggnad presented results from a recent project investigating the keys for new knowledge to come into practical use. In this project, a literature study was performed together with a review of success cases and deep interviews with people involved in these success cases. Based on these activities, conclusions concerning which keys that are necessary for new knowledge to come into practical use were drawn. Some of the main findings from this project were that: (i) a common, high level, and detailed reachable target is important for the organization, (ii) leaders within the organization need to convey a sense that everything is possible, (iii) ways of working for continuous change should be adapted, collecting data to be used for reaching well founded decisions, (iv) storytelling of striking examples should be used illustrating a vision and the way forward, (v) and projects and regions should be used as test-beds for new ideas for development and implementation.

5.3.2. The role of the client

Bernt Henriksen, Senior Automation and production specialist at Automation Region, has long experience helping industry companies to automate their processes. In the presentation, Henriksen gave examples of 18 different challenges when implementing automation, such as production costs, key performance index, and delivery precision, that needs to be more or less answered before investments can be made.

To help the companies in their process as a client, Automation Region has developed a tool for helping SMEs to implement automation. With the tool guide, the company can identify their needs and contain the following parts: (i) how does our process look like? (ii) which improvements can be made with automation, (iii) who are affected in the organization?, (iv) economy- what shall we consider?, (v) planning and resource allocation, (vi) pre-study, (vii) workshop, (viii) requirements, time schedule and budget, (ix) tender, (x) selection of contractors, (xi) follow-up.

However, Henriksen points out that his experience does not contain specific problems with one-piece production on site. Companies closest to the construction industry that Automation region has been in contact with are companies that produce pre-fabricated elements, such as Lundqvist Trävaru. An observation made by Albinsson is that two different strategies for construction automation can be distinguished: (i) automation of single activities in a traditional construction environment using single on-site robots, and (ii) modular systems, where large parts are constructed in an automated industrialized production process. Which of these ways that is the best strategy is not clear, according to Henriksen, but he means that it is probably difficult for smaller companies to succeed in developing on-site automation by themselves, since large financial investments are needed. During a discussion after the presentation by Henriksen, based on a question from LKAB, it was concluded that a test-bed and an agile way of working are important for development.

5.3.3. Business models

The initial vision for Lunqvist Trävaru was to become the Google of the construction industry, according to Samuel Holmström, CEO at Lunqvist Trävaru. Two other main drivers was, (i) that he did not like the construction industry and (ii) that IT-companies was cool. Based on the game SIMS, they got the idea to build models of their products and present their sales system on the internet. To further develop their idea, a prototype of this system was developed within the framework of a thesis work and Lundqvist Trävaru also hired a game developer.

Today, this configuration system is their main platform for their business. Customers can go to the Internet based system and define dimensions, locations of doors, windows, type of roof, etc., see Figure 23. Even drawings for the building permit is automatically generated. Every item is exactly specified down to the number of screws and how the items shall be packed for transportation. As customer, you specify the postal number and the closest contractor is identified for assembling the house at the same time as the total price of the house is given in real time.

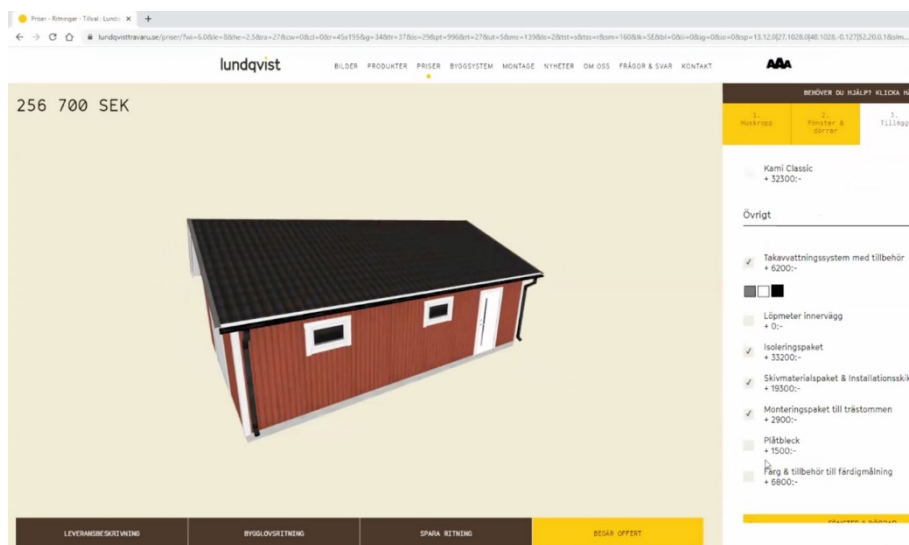


Figure 23. Example from Lundqvist Trävaru house configurator (From Samuel Holmqvist with permission)

Since they started to use their configurator system, the company has had a strong growth of 25% annually, and 98% of their turnover is based on sales on the internet according to Samuel Holmqvist. Of their total turnover, only 35% is today from own production, and they no longer consider themselves as manufacturing wood industry, but instead as a technique, logistic and sales company. With this new image of the company, they have also noticed a large difference when recruiting. Samuel is of the opinion that IT-personal are critical for their business model. Samuel thinks that especially two aspects are disturbing when talking digitalization: (i) that companies digitalize their existing processes, and (ii) the construction companies does not drive their own digital development. Instead, according to Samuel, it is external consulting companies that creates a system in the industry and wants to reach as many customers as possible, where they are simulating existing processes. By doing so, there is a risk that digitalization creates lock-in effects in their existing processes. It is important to own and have knowledge in-house, as evident from the description of Lundqvist Trävaru by Samuel.

6. Discussion

The use of automation and robotics to building and infrastructure constructions represents a fundamental shift in the way this sector works. On one hand, a variety of new technologies has the potential to address common problems of production inefficiencies, health and safety risks and negative environmental impacts. On the other hand, characteristics such as a high fragmentation, hardly controllable site conditions as well as temporary project alliances with a complex coordination of many actors and often divergent goals need to be addressed to navigate this adoption process and avoid expensive and counterproductive mistakes.

6.1. Current initiatives and trends

Internationally, since the 60s there has been an ever increasing trend in research and development in the areas of automation, digitalization and robotics in the construction industry. As was pointed out earlier by Bock (2015) the S-shaped trend has gone from early innovations in the field of conventional construction between 1970 and 2010, before turning into a disruptive growth phase of automated construction after 2010, leading to performance improvements and a more mature and wider implementation across the sector. Internationally, leading countries are USA, United Kingdom, South Korea, Canada, China, Germany and Switzerland with research ongoing in both universities and companies. The same trend can also be seen in the area of automation for infrastructure such as tunnels, highways, and bridges for design, construction, inspection and maintenance.

The use of BIM has increased the possibilities for automation and more efficient design and planning. In the long run, the entire lifecycle, from early-stage planning and design, to construction and maintenance, needs to be digitalized – enabling design for robotics, efficient logistics, an automated orchestration of the production and the maintenance as illustrated in Figure 24.



Figure 24. A digitalized process over the entire life-cycle is required for complete automation in the future

In the literature study, use cases cover the entire lifecycle from early-stage planning and design to construction and maintenance. In many of them, accurate geometric modelling and scheduling linked to a digital representation of the asset are the underlying prerequisites from an early project stage to enable automation and robotic work in the first place. Checks of as-built and model conditions allow not only for real-time progress monitoring, but also for remote or entirely automated operations. Hereby, it is often the combination of several technologies, such as sensors, drones and BIM tools that take the efficiency, accuracy and safety of the works to a higher level.

The literature study on infrastructure show that an accurate BIM model is a prerequisite for automation and robotic construction. Several examples of autonomous vehicles for excavation, compaction, and asphalt spreading and compaction are currently being developed. Additive manufacturing has been tested with success for automated construction of steel bridges and concrete pillars. Automatic fabrication of rebar cages using robots are also currently under development, which can be used as on-site factories for modular production. Sweden is one of the leaders and drives automation in the mining industry. In the last decades, mining operations have evolved from remotely controlled to more autonomous self-driving technology. The technology

developed in the mines can be used in tunnel construction with similar conditions.

Several examples using different types of sensor technology, combined with IoT and cloud technology have been used for automated monitoring and inspections. In the area of maintenance, however, the progress of automation has not reached as far as for inspections.

In Sweden, a number of initiatives are ongoing at the universities, where several has started in the last years, see Figure 25.

As shown in Table 4, that compares which of the Swedish companies listed by Rahm (1988) with those still active 30 years later, the conclusion may be drawn that smaller companies with advanced automation technology vanishes from the market. All of the products developed by minor start-up companies are no longer in production, while all of the product developed by larger companies such as Epiroc (former Atlas Copco) and Electrolux are still in production and now constitute important parts of their product portfolio. Other examples of initiatives that didn't manage are the plastering robot by MoRoCo, Build-r, Loop Rocks, and NCC Komponent. This points towards the fact that it is important to have strong finances and endurance to successfully develop and implement new products. The core value is to a large extent the methodology and the algorithms being developed. Thus, there is a need of long-term financial support for companies like those with development projects in automation to reach their full potential.

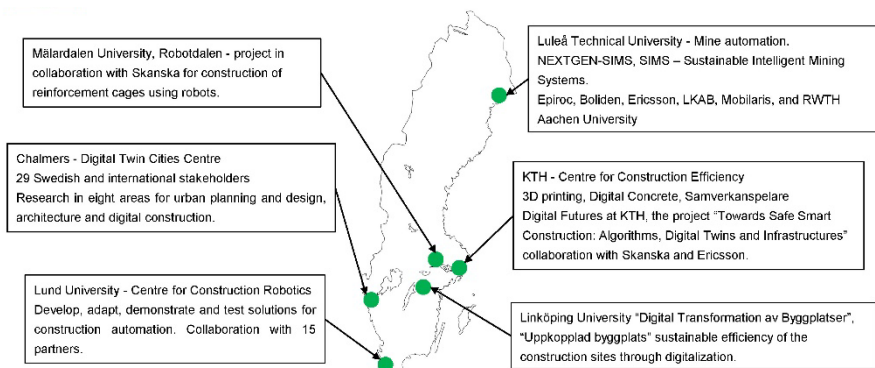


Figure 25. Examples of current initiatives at the Swedish universities

Unlike the car manufacturing industry that mostly uses static robots programmed to perform repetitive tasks in a controlled indoor environment, the construction industry needs robots to be flexible. To scale operations in an ever-changing environment, robots should be able to move around on site and grasp surrounding conditions using a variety of sensors. Especially in interaction with humans or other machines, accurate control and feedback loops are crucial to reduce collision risks and ensure a high construction quality.

To integrate automation in design, construction or maintenance processes, the abundance of potential use cases has to be prioritized. One way to start is to identify works on the critical path (e.g., rebar works), that can be performed by robots in an isolated fashion. However, for a long-term transformation, a holistic view is important. Instead of blindly automating individual processes, the objectives behind the transformation (e.g., higher productivity, better health and safety) should guide a reassessment of existing processes to then leverage technologies to streamline activities and make them safer. Hereby, it is important that the technology follows the workers' and customers' needs. Instead of enforcing the adoption of new solutions, attractive user interfaces are needed that are easy to navigate, even if the underlying technology is complex. Documenting the decisions made along this way will help to learn from earlier cases and provide guidance in this uncertain, rapidly evolving context.

6.2. Potentials and challenges

The total investments in the Swedish construction industry constitute approximately 11% of the Swedish gross domestic product, or 546 billion SEK, (Byggföretagen 2021), and the total investments in the transport infrastructure sector during the coming ten-year period will amount to 799 billion SEK (Regeringen 2021). An increased productivity and effectiveness within the transportation infrastructure can thus save large amounts to the society, reduce the use of natural resources and the emissions of carbon dioxide and strengthen the competitiveness of the Swedish construction industry. At the same time, productivity is not increasing as fast as in other sectors in the industry. According to Trafikverket (2021) has the costs in larger planned infrastructure projects increased more than the consumer price index (CPI), and according to Albinsson (2019) the costs in the

construction industry the last twenty years have increased eight times more than the CPI. Furthermore, according to (Boverket 2018), deficiencies and flaws in the construction industry annually costs between 83 and 111 billion SEK.

Already in the early work by (Tarandi et al. 1988), the main drivers for implementing automation in the construction industry was decreasing productivity in the construction sector compared to other sectors within the industry, dangerous und unhealthy work tasks, difficulties finding qualified laborers, and that the Swedish export in the sector needs to be improved, especially in the competitive environment that exists in the global construction industry.

The potential for implementing automation in the construction industry can be seen in the project by Skanska in their project for automate of the construction of reinforcement cages, where the productivity can be increased with a factor of ten with the new technique. At the same time, heavy work can be replaced and the work environment can be improved.

Today, there is a trend in digitalization which has contributed to major changes in different industry sectors. As an example, the use of email changed the communication between people in relation to the use of letters distributed through manual postal service. When digitalization changes an industry sector, the speed of change in that industry sector increases. This is a result largely affected by Moore's law, that states that transistor densities on silicon chips are doubling every 18 month (Moore 1975).

Moore's law affect hardware industry and makes it possible to release new hardware platforms, i.e. computers, mobile phones etc. with doubled processor effectivity about every 18 month. An example of this is the development and the release pattern of new Apple iPhones over the last decade. Increase in hardware effectivity makes it possible to add or increase the number of new software functions at a similar rate. Functions or extensions that might be to slow on the previous hardware platform, but work great on the next. Therefore, the software industry is accustomed to make several software releases every year and improving the use of their software. The last decades of cloud computing technology, virtual server technology and software development principles as DevOps (NoOps from Netflix), and Agile software development methods like Scrum, Kanban, etc., that are inspired by Lean Manufacturing has increased the speed of software development even more. Together with automated software release tools on

these cloud platforms, new software functions or adjustments can be released and installed multiple times over a 24-hour period. This efficiency is also to a large extent dependent on the scale of operation, i.e. the number of persons and the maturity of the Agile/DevOps organization, see for example organizations as Spotify, Netflix or Amazon.

This means that processor calculation power and software functions may be doubled every 18 month. In theory, a robot will have a duplicated processor calculation capability within 18 month and the adjacent software will be updated within this timeframe. This doesn't mean that productivity in the construction industry will double every 18 months, but it will affect the usage of advanced technology as it get adopted. Hence, this development of new technology has the potential to change the productivity in the construction industry in the future over a long time.

Companies that act, learn, and understand to harvest these productivity increases can get ahead in the long run. Organization that does not adjust to these technology shifts poses the risk to become uncompetitive with old ways of working, using the wrong business models or just be succeeded by new technology. This new technology may initially be expensive, but as the technology develops it will become cheaper and may change the business landscape – a disruptive technology, which is a well described concept (Christensen 1997). In Sweden, the collapse of Facit 1971-1972 due to the advance in electronics, is a well-known example of how technology can disrupt a market and what happens to companies that misses to adjust to a technology shift. Hasselblad is another Swedish example of a company that almost collapsed due to a board decision 1996 to not pursue the investments in their almost 15 years of development in digital technologies. Thus, due to the use of the digital technology new value propositions are created on the market and as the performance of this technology improves, it makes it attractive for high-end segments (Sandstrom 2011).

Entering the era artificial intelligent, Kurtzweil generalize Moore's law to cover all technology and predicts that the years 2000-2099 will correspond to 20 000 years of technology development at the speed of the year 2000 (Kurzweil 2001). This implies that the acceleration that we today exhibit as fast, will be even faster in the future – exponential growth.

To be able to take part in this development, there are however a number of barriers that needs to be overcome. The main barriers identified in this work are:

- The projects in the construction industry are complex where the construction sites consist of a mix of many actors, materials and processes that need to be coordinated in the surrounding built environment.
- Each project needs to fully carry their own costs, and there are no overall innovation, or change of processes, that can be financed by single project costs, in comparison to a fully industrialized process.
- The design and the process are tied together and relies on decision from craftsman at site. This way of working is a consequence of the way the digitalization are made with today's software. To be able to implement automation, a full digital twin has to be made.
- The business models with hourly rates and subcontractors are inefficient, but lack incitement for change.
- The supply chain is not centralized and no incitements exists for the craftsman to change their business model.
- The industry lack a "sense of urgency" to implement the new technology.

To overcome these barriers, some possible solutions could be to:

- adapt a more industrial production process to fully separate the design and the production,
- identify separate modules or tasks that can be automated,
- digitalize the whole process and use one IT-platform for design, planning and production, in order to reduce the number of decisions at site, i.e. use a digital twin that is 100% complete,
- invest in production technology that is written off by multiple projects in order to increase the ability for larger investments, and establish partnership for cooperation,
- rethink and reinvent new processes together with the clients,
- replace the business model where consultants and sub-contractors get paid on an hourly basis, and
- use a centralized supply chain.

Finally, by implementing automation, the workplace and the construction industry can become more attractive for engineers and recruiting becomes easier.

6.3. Requirements for implementation

The automation of the Swedish mines has been a success story and the Swedish mines are today world leading within their area. Even though the conditions for automation in a mine is different compared to a construction site, similarities exist, and the Swedish construction industry can learn from this work. Organization of the Swedish mining cluster, and together establish a common vision and a strategic roadmap for the future were probably key factors for this success. This type of national cooperation for a common vision cannot entirely be seen in the construction sector which is currently more fragmented. Several initiatives are ongoing in the area of digitalization and automation at the Swedish universities, in the construction companies, among suppliers and SMEs, and it would be desirable if those could cooperate against a common vision and also establish a strategic roadmap together.

This also implies that new strategic partnerships are needed in order to allocate investments promoting automation to the construction industry. The mining industry has collaborated in partner networks together with large corporations such as Epiroc, ABB, Volvo and Eriksson by promoting the mining industry as a field of application for these corporation's technologies. Similarly, automation in construction cannot be driven alone, but has to be developed in strategic partnerships and by promoting the construction industry as a lucrative field for applying solutions of automation and robotization.

It is also important to share knowledge and copy best practices in order to scale up the investments of automation in construction. The larger the market becomes, the faster the development is going to be. Industry clusters are a key to success including SMEs, large corporate firms, universities, services & exploration companies (e.g., Skanska, NCC, Peab) and equipment & system suppliers (e.g., Ericsson, ABB, Volvo).

A fully digitalized design process is also required in order to be able to implement automation for production and maintenance in the construction industry. How to set standards and develop system for the systems are here important research question that have to be addressed.

The use of robots in the Swedish construction industry is not anything new and work was ongoing already in the 1980s. Still, more than 30 years later not much has happened at the construction sites with respect to the implementation of automation. As seen in the comparison of the list by Rahm (1988) in Table 4, among those Swedish innovations that manage to survive and become successful, it appears important to have large companies being able to make long-term investments. This is not surprising, to develop and implement robots for automation is costly and demands large investments over long time – another reason for increased cooperation.

Another important factor for the successful implementation of automation in the Swedish mines, is the possibility to use the mines as test-beds. Of course, this may to some extent lower production, and for example LKAB has therefore allocated parts of their mines as separate test-beds to not interfere with production. For the infrastructure sector, the Swedish Transport Administration, has an important role as the largest client. Preferable, in the same way as for the mines, some parts of future projects should be allocated as test-beds for automation and implementation of new innovations. A problem with this strategy is that it would interfere with construction and the long-term perspective may be lost. Therefore, “artificial projects” acting as test-beds would be preferable. This is costly and requires large investments from the Swedish Transport Administration and other actors. If such unique test-beds were created, national cooperation among clients, universities, construction companies, suppliers, and SMEs are critical.

In addition, both public and private clients play a large role in the transformation towards increased automation in construction. The client must develop and implement competences and guidelines on how to priorities automation options. Procurement is a strong tool for promoting automation and enabling suppliers to commercialize on automation and robotisation. In procurement, clients need to focus on lifecycle efficiency instead of short-term economic benefits.

Furthermore, business models that promote increased automation and new ways of working is a strong tool for both public and private clients. However, the current business models tend to promote and encourage existing ways of working and may create lock-ins. Public procurement is a major driver of change, it is therefore important that skills and competences in these areas exists at the clients.

There are examples of construction companies that have adopted new business models wherein the business area/core business consist of service offers, customer involvement and product platforms. These companies have a shift in mindset and have profiled themselves as technology, logistics and/or sales companies rather than construction companies. They also have new recruitment strategies that attract talent from other industries.

The following key performance index (KPI) can be used as a measurement of the degree of automation in the construction industry:

- Number of decisions taken by a craftsman at site
- The amount of supplied goods that are missing on site or the time a craftsman has to wait for a product or the number of missing parts
- The lights out time. Is a philosophical term used to understand how long time the automation process can run without human intervention

6.4. Business, project and ecosystem implications

As visualized in Figure 26, the technological maturity (engineering sustainability) is a prerequisite for a successful project execution. To ultimately create a positive economic, social and environmental impact, the project governance structures and surrounding conditions in which robotics are implemented are important. To scale automation and robotics and enforce a sense of urgency to address current inefficiencies, action is required on both firm, project and ecosystem level.

On a firm level, the adoption of a user-centric lifecycle perspective opens up new opportunities for data-driven, service-oriented business operations. To leverage those opportunities, a company needs to build in-house capabilities to own or control operations like logistics, the customer journey and the product platform. This in turn requires a shift in staff training requirements and hiring practices.

In projects, this long-term perspective puts a high emphasis on the client's role and the procurement of right partners to jointly innovate beyond short term economic gains. Partnerships help to offset high initial investment costs and prevent repetitive struggles through inter-organizational learning. On top of construction works, the complementary infrastructure such as wireless networks need to be in place to enable automation and robotics applications

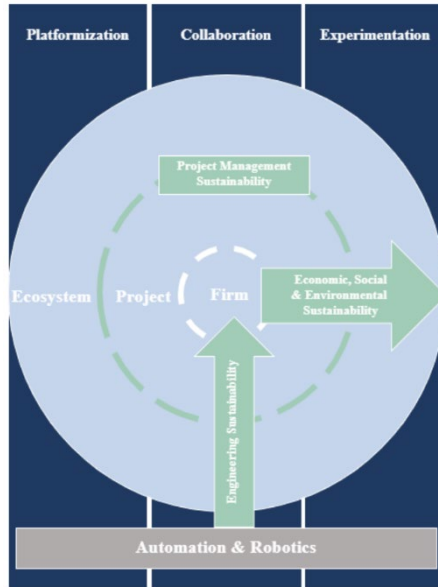


Figure 26. Impact of automation on infrastructure sustainability (Hoeft et al. (2021), CC–BY 4.0, <https://creativecommons.org/licenses/by/4.0>)

on site. In addition, financing and insurance contracts should reflect the changing conditions brought about by the extensive use of technology and consequent shift in project risks.

Even beyond single projects, there is a strong need for increased collaboration to create a safe and attractive industry. Where current technological immaturity limits the widespread adoption of automation, financing for prototypes and testbeds (minimum viable local pilot areas) is crucial to establish trust and present proofs of concepts. Successful demos need to be shared with the industry, showcasing best practices and learnings. In addition, there is a huge market opportunity for third parties if the sector provides test beds for tailored developments and attracts investments.

Overall, automation and robotics have an immense potential to promote more sustainable building and infrastructure constructions, be it from an economic, environmental or social perspective. This however requires more efforts to increase the technological maturity of solutions through iterative testing, cross-disciplinary collaborations and the integration of actors outside of the traditional sector (e.g., telecommunication, software). By leveraging digital twins and other platforms for interactions between industry actors,

actions can be streamlined and trust can be increased when building on a “single source of truth”. In addition, experimentation has to be encouraged both within companies and in project networks. Most of all, a clear vision about the “Why” behind automation and an innovation-friendly mind-set will be needed to align all the different stakeholders involved and channel their efforts into a real change of the industry.

7. Conclusions

The trends are clear, internationally and nationally there are an increasing trend in research and development in the areas of automation, digitalization and robotics in the construction industry. The same trend can also be seen in the area of automation for infrastructure such as tunnels, highways, and bridges for design, construction, inspection and maintenance. Use cases in automation cover the entire lifecycle from early-stage planning and design to construction and maintenance.

Automation has the potential to increase *productivity*, improve *occupational health and safety*, and *sustainability*.

A number of barriers have been identified. To overcome these barriers, possible solutions are to:

- digitalize the whole process and use one IT-platform for design, planning and production, in order to reduce the number of decisions at site, i.e. use a digital twin that is 100% complete,
- separate the design and the production, no decision at site,
- identify separate modules or tasks that can be automated,
- invest in production technology that is written off by multiple projects in order to increase the ability for larger investments, and establish partnership for cooperation,
- use a centralized supply chain
- rethink and reinvent new processes together with the clients,
- replace the business model where consultants and sub-contractors get paid on an hourly basis.

For large scale implementation, construction companies, universities, suppliers and SMEs should gather and set up a common *vision* and a *strategic innovation roadmap* to enforce automation and digitalization. The roadmap shall include strategies for long-term funding. In addition, test-beds are necessary and national coordination and cooperation among the stakeholders are critical.

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