Issue 20(3), 2020, pp. 87-102
https://doi.org/10.18757/ejtir.2020.20.3.4612

TU Delft OPEN

EJTIR

ISSN: 1567-7141
http://ejtir.tudelft.nl/

Drones in railways: Exploring current applications and future scenarios based on action research

Omid Maghazei[1]
Department of Management, Technology, and Economics, ETH Zurich D-MTEC, Zurich, Switzerland.

Matthias Steinmann[2]
Department of Production Engineering, Infrastructure Maintenance, Swiss Federal Railways (SBB), Bern, Switzerland.

Evidence shows that the applications of drones are increasing quickly in many industries. Railways are no exception. Due to fast advances in technology, drones are on the verge of breakthroughs that will affect future applications, implementations, and their consequences. Looking ahead, we elaborate on the potential for drones in railways. We use scenario planning and combine it with the findings of an action research project, which we conducted with Swiss Federal Railways (SBB). First, we explore the applications and future trends of drone use in railway operations. Second, based on seven identified factors that may affect the future of drones in railways by 2030, we develop three future scenarios: pessimistic, realistic, and optimistic. The study results help practitioners make informed decisions regarding future drone programs in railways. We also contribute theoretical insights into how high-potential technologies can unleash new capabilities in railway operations.

Keywords: *Drone technology, Railways, Scenario planning, Action research, Unmanned aerial vehicle (UAV).*

1. Introduction

Recent advancements in unmanned aerial vehicles—commonly known as drones—are unlocking huge business potential in various industries, such as agriculture (King, 2017), construction (Li and Liu, 2019), logistics (Goodchild and Toy, 2018), manufacturing (Maghazei and Netland, 2019), mining (Lee and Choi, 2016), and petrochemicals (Maghazei and Netland, 2018), as well as in warehouses (Wawrla et al., 2019). According to a study conducted by PricewaterhouseCoopers, *transport infrastructure*, at $45.2 billion, accounts for the highest market value for drones (Mazur and Wiśniewski, 2016; Mazur et al., 2017). For example, drones are used by the Union Pacific

[1] A: Weinbergstrasse 56/58, 8092 Zürich, Switzerland T: +41 44 632 0529 E: omaghazei@ethz.ch
[2] A: Hilfikerstrasse 3, 3014 Bern, Switzerland T: +41 51 220 11 11 E: matthias.steinmann@sbb.ch

Corporation in the United States to carry out federally mandated field testing (Ziobro, 2018), by Network Rail in the United Kingdom (UK) to survey railways for regular maintenance or after an incident (Bradley, 2016), and by the Dutch railway company ProRail to inspect switch point heating systems on tracks with thermal cameras (Flammini et al., 2016a). Although several railway companies have experimented with drones in real environments, the applications and future possibilities of drone technology in railways are not settled. In this paper, we explore the potential of drone technology in railways.

To examine drones in railways, we distinguish between the nature of technological innovation in railway operations' primary activities (e.g., new technologies in rolling stocks) and supportive activities (e.g., new technologies in maintenance services), informed by Geyer and Davies' (2000) theoretical notion. In each category of railway operations, the use of new technologies has very different characteristics. The knowledge gained from the use of new technologies in primary operations is often less applicable to the use of new technologies in supportive operations, and vice versa. Drone technology has especially promising potential for improving supportive activities in railways.

We follow an explorative research approach by combining scenario planning with insights from an action research project we conducted with Swiss Federal Railways (SBB). We identify the applications and future trends for drones in railways and then use three scenarios (pessimistic, realistic, and optimistic) to discuss the factors that have potential impacts on the use of drones by 2030. Finally, we discuss the implications of this study and elaborate on future research directions.

2. Background: Literature on the use of new technologies in railways

The characteristics of railways pose serious challenges for implementing technological innovations, mainly due to the complexity of railways as large technical systems with closely coupled subsystems (Lovell et al., 2011; Hughes, 1987). Technological innovation in railways is influenced by the interdependencies of two sets of activities: the *operational system* that includes all activities for delivering railway operations and *projects* that consist of activities for building new components in the operational system (Geyer and Davies, 2000). Although Geyer and Davies' (2000) theoretical notion provides a useful starting point to better understand the use of new technologies in railways, it does not offer a sufficient basis to make a clear distinction between primary and secondary railway activities, specifically in the nature of their technological innovations.

We distinguish between the nature of technological innovations in railways' primary activities (e.g., using new technologies in rolling stocks, tracks, and signaling systems) and supportive activities (e.g., using new technologies in maintenance and financial services) (cf. Geyer and Davies, 2000). Using new technologies in primary activities has more technological, technical, organizational, economic, social, political, and regulatory challenges than in supportive activities (see Geyer and Davies, 2000; Taylor, 1982). Furthermore, using new technologies in primary activities is linked to the execution of large-scale and capital-intensive projects and involves multiple actors, such as transportation planners, policymakers, infrastructure owners, technology suppliers, subcontractors, and engineering consultants, during the implementation. Whereas using new technologies in supportive activities is likely to be less capital intensive and to involve fewer stakeholders than primary activities (see Geyer and Davies, 2000; Taylor, 1982; Geerlings, 1998; De Tilière and Laperrouza, 2009).

The extant literature on the use of new technologies in railways' supportive activities provides examples of established new technologies with concrete instances of use. Richardson and Nigam (1999) studied the implementation of paging technology as a communication device in Indian railways, which could improve efficiency, reduce costs, and increase safety. Kour et al. (2014) reported the benefits of using radio frequency identification (RFID) technology to improve asset management and cost-effective maintenance planning through the provision of real-time information, automatic vehicle identification and tracking, and traffic and passenger information. Sensors and information and communication technologies (ICTs) could offer more unprecedented opportunities than in the past to increase the level of automation of supportive railway operations. For example, data analysis technologies could enhance smart maintenance in railways to predict breakdowns through condition monitoring and to spot equipment deterioration, such as track irregularities and geometry degradation (see Yokoyama, 2015; Saito et al., 2017; Sol-Sánchez and D'Angelo, 2017). Evidence shows that many new (digital) technologies are emerging quickly with unclear application areas in railways (Tokody and Flammini, 2017).

One of the new technologies emerging with high potential for improving supportive activities in railway operations is drone technology. Drones could eliminate human intervention, increase mission range, and reduce costs, risks, and time in large-scale metrology, which is a repetitive and dangerous task (Franceschini et al., 2010). Using drones for surveillance and monitoring of railway infrastructures could improve the efficiency of inspections, reduce costs, and increase the safety and flexibility of operations (Flammini et al., 2016a; Flammini et al., 2016b; Ikshwaku et al., 2019). However, the characteristics of drone technology differ from those of other new technologies used in railways' supportive activities. First, this distinction is the consequence of unprecedented drone functionality, such as the variety of flying capabilities, connectivity, mobility, and versatility (e.g., drone technology can be paired with various complementary technologies, including thermal imaging, laser scanning, material handling, etc.) (Floreano and Wood, 2015). Second, drones are still emerging, and the developers of the technology are still advancing capabilities to transform the technology into a reliable industrial tool (Maghazei and Netland, 2019). These technological uncertainties present new sources of challenges for evaluating the application areas of drones in railway activities. The main objective of this paper is to explore the current and future potential of drones in railways to fill this gap in the literature.

3. Research methodology

We used a participatory research design, by combining scenario planning and action research. Scenario planning allows researchers to stimulate "practical creativity" by thinking in new paradigms (de Brabandere and Iny, 2010, p. 1506), as well as to reduce decision makers' uncertainties and dilemmas regarding emerging technologies (Amer et al., 2013). For instance, Potter and Roy (2000) developed scenarios for the future of UK rail transport based on alternative market development factors including new technologies, Armstrong and Preston (2011) developed four scenarios for the future of intelligent infrastructure systems in railways, and Hansen et al. (2016) evaluated the relevance of new products and technologies for the future of rail automation in scenario-based technology road mapping. Scenarios that "are grounded in the reality of the present" are more informative and useful for practitioners (Goodier et al., 2010, p. 221). To generate practical insights and develop highly relevant scenarios, we carried out an action research project in which we identified current and potential applications, selected one of the feasible applications, and tested it in the field to envision the factors that would likely affect the future use of drones in railways.

To combine scenario planning with action research, we incorporated iterative cycles of action research (as defined by List, 2006) in scenario development steps (as defined by Schoemaker, 1993); see Figure 1. The first step is analyzing the context, which includes describing the case and defining the time frame, the scope, and the stakeholders. The second step is analyzing trends, which includes identifying future trends for drone applications in railways and selecting one application for field tests. The third step comprises two cycles of action research; each cycle includes planning, acting, and evaluating. The final step is developing final scenarios concerning the future of drone applications in railways.

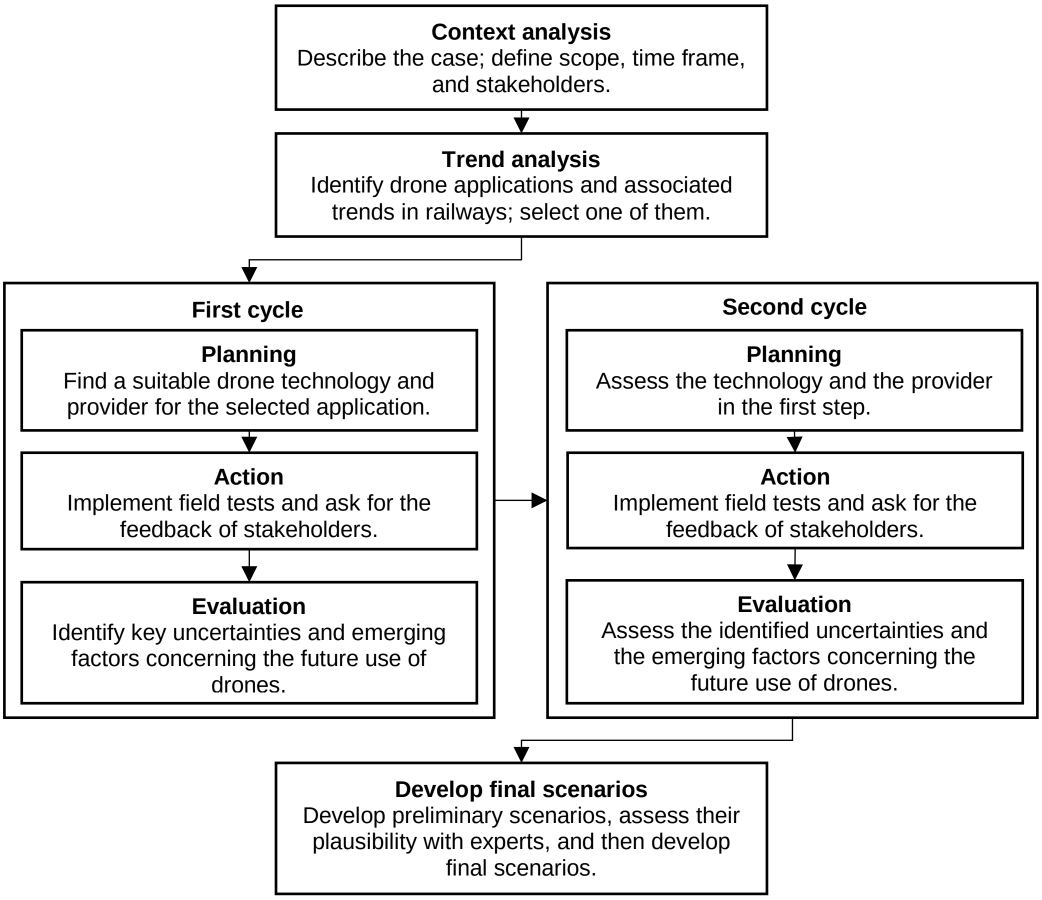

Figure 1. The research methodology: combining scenario planning with action research

3.1 Context analysis

We conducted an action research project with SBB in Switzerland. In this section, we briefly explain the characteristics of SBB operations and infrastructure, the scope and the time frame for future scenarios, as well as the main stakeholder of this research project.

Case description

The entire infrastructure network of SBB was valued at approximately CHF (Swiss Francs) 87 billion in 2018 (SBB, 2018). SBB owns 6,670 kilometers of tracks, 6,082 bridges, and 8,216 kilometers of contact lines, showing the magnitude of railway operations at SBB and its vast infrastructure (SBB, 2018). The SBB infrastructure is spread across Switzerland, from densely populated urban areas to hard-to-reach rural areas. The SBB tracks used for passenger traffic are electrified (SBB, 2018). According to a report published by the Boston Consulting Group, SBB achieved the highest ranking on the railway performance index in Europe, measured by intensity of use, quality of service, and safety, in three studies conducted in 2012, 2015, and 2017 (Duranton et al., 2017).

Scope and time frame

In 2017, SBB started a digitalization program called SmartRail 4.0 to increase the capacity of the network and the flexibility of SBB operations, as well as to reduce costs for the time horizon from 2020 to 2040. In 2017, SBB began to use drones to observe the streambeds above the railway tracks in clearly defined mountainous areas, which constituted the first and only commercial drone use by SBB as of June 2018. To explore existing applications of drones in railways, we conducted 10 informal interviews with middle managers at SBB, reviewed more than 300 pages of internal documents related to drone applications, and collected online materials. To select a time frame for future scenarios, we asked for feedback from the SBB managers and then decided to develop action-oriented knowledge (see Cunningham, 1976; Elden and Chisholm, 1993) for the use of drones in 2030, in the middle of the SBB SmartRail time horizon.

Stakeholder

SBB established the Center of Competence Drones to further explore and test the applications of drones at SBB. The main stakeholder of this research project is also this center, whose involvement enabled us to overcome the business bureaucracy at SBB and gave us the possibility of conducting field tests (see Zuber-Skerritt and Perry, 2002; Nair et al., 2011). Moreover, the center developed a collaborative environment for us to leverage existing organizational knowledge about drones in railways, as well as respond to the real needs of SBB (see Coghlan et al., 2012; Maestrini et al., 2016).

3.2 *Trend analysis*

We aimed to identify existing trends of drone use in railways, as well as select one application for field tests. To do so, we conducted eight semi-structured interviews with SBB managers from different fields of expertise (e.g., deputy head of the maintenance department and the project manager at the Center of Competence Drones) about the emerging trends. The average length of the interviews was 45 minutes, and we tape-recorded and transcribed all interviews, resulting in 69 pages of textual data. We followed the coding approach suggested by Strauss and Corbin (1990): First, we used open coding to identify empirical themes (e.g., drone applications). Second, we classified them into generic concepts (e.g., categories of applications). Third, we clustered them into aggregate dimensions in terms of future trends for drone use (e.g., use in the planning phase of projects).

The analysis also showed that the applications of drones in maintenance and project management would have enormous potential in the future of railways, and we decided to select one of the applications in that area for field tests. After considering the internal regulations at SBB and the current capabilities of commercial drones, as well as the feedback from the SBB managers, we selected "monitoring the safety of workforces in maintenance projects by replacing drones with safeguards" for the field test.

3.3 *Action research cycles*

In this section, we briefly explain the features of the test scenario that we developed for the field test, as well as the details of two iterative cycles of action research.

Developing the test scenario for the field tests

To gain a better understanding of the role of safeguards during maintenance projects, we conducted two specific observation sessions at SBB construction sites, as well as informal talks with SBB employees during the field observations. With the help of the Center of Competence Drones and worksite-safety specialists from SBB, we developed a test scenario that simulated a dangerous situation for maintenance workers due to railway traffic. In this test scenario, drones and related software packages must be able to constantly identify in real time whether workers are in safe or dangerous situations. The safe situation occurs when there is no railway traffic expected on a track or when workers maintain a distance of at least 1.5 meters from the railway track. The dangerous situation occurs when there is railway traffic and when workers are located closer than 1.5 meters from the track.

The first and second cycles

For the field tests in both cycles, we selected wired drone technology, which would remain connected to a power supply and perform wired data transmission, as a viable solution for the limitations of drone batteries and low flight endurance. In the first cycle, the selected drone service provider constructed an outdoor environment for the field tests on their premises in Germany. The test environment was an acceptable representation of the test scenario and included four people (from the service provider company) walking in a designated area indicating danger. We carried out the field tests in the presence of two safety specialists from SBB, and then we debriefed the SBB managers about the tests and discussed the results with them. In the second cycle, we decided to conduct field tests with the service provider in real SBB facilities (a marshalling yard near Zurich), using another wired drone technology. To increase the internal validity between the cycles, we used the same test scenario for the second cycle to compare the field tests. The field test was performed over active railway tracks, with workers wearing official protective gear, and the environment included the objects used in maintenance projects at SBB, which provided us with a test setting comparable to a real railway construction site.

3.4 Development of final scenarios

Based on the findings from the action research cycles, the semi-structured interviews, and insights from the informal interviews and observations, as well as the feedback from the drone technology and service providers, we constructed preliminary scenarios based on the scope, the time frame, and the factors that would have an impact on the future use of drones in railways. We developed preliminary scenarios and then reviewed them in a workshop that included experts in relevant technical fields (e.g., tracks, signaling, overhead-contact line, and surveillance) from the Center of Competence Drones and the Department of SBB Infrastructure. Based on the assessment by this group of experts, we modified the preliminary scenarios and developed three final ones.

4. Findings

4.1 Application areas

We identified the possible applications of drones at SBB and summarized the status of the applications as *in use*, *experimental*, and *future* (Table 1). We then classified the applications into four categories: 1) monitoring and inspection; 2) land surveying, photogrammetry, and mapping; 3) surveillance; and 4) building information modeling.

Table 1. List of drone applications at SBB

Drone applications	Status of applications	Category of applications
Observing streambeds above railway tracks in mountainous areas	In use	Monitoring and inspection
Information modeling of SBB buildings	Experimental	Building information modeling
Surveying areas to check whether cliffs are moving	Experimental	Land surveying, photogrammetry, and mapping
Inspecting empty wagons to identify defects	Experimental	Monitoring and inspection
Obtaining an overview of incidents in emergency cases (power line breakdowns, fire, etc.)	Experimental	Monitoring and inspection
Mapping the heat profile of buildings for energy-efficiency purposes	Experimental	Monitoring and inspection
Measuring the volume of gravels needed to repair track bodies	Future	Land surveying, photogrammetry, and mapping
Measuring distances for photogrammetry	Future	Land surveying, photogrammetry and mapping
Monitoring the safety of workforces in maintenance projects by replacing drones with safeguards	Future	Monitoring and inspection
Inspecting nets that protect rail tracks from falling stones and so on	Future	Monitoring and inspection

Inspecting the roofs of the platforms	Future	Monitoring and inspection
Conducting a preliminary visual check of switches or any unexpected failures (e.g., to determine false alarms)	Future	Monitoring and inspection
Supporting engine drivers in cases of incidents, such as brake failure	Future	Monitoring and inspection
Conducting visual checks, with drones available at certain distances (e.g., on every 50th power pole)	Future	Monitoring and inspection
Recording videos to monitor the progress of projects	Future	Monitoring and inspection
Monitoring work groups for process improvement and education	Future	Monitoring and inspection
Sending real-life feed of measures in projects	Future	Monitoring and inspection
Assuring quality during the construction process	Future	Monitoring and inspection
Collecting data (e.g., aerial images, thermal images, and noise) in emergency situations for the relevant teams	Future	Monitoring and inspection
Monitoring vandalism and surveillance (to protect trains against spraying and graffiti writing at night, stealing, etc.)	Future	Surveillance

4.2 Future trends for drone applications

The results show that drone applications in the area of maintenance have high potential in railway operations. In this section, we explain the future trends of using drones at different stages of maintenance projects.

Drones in the planning phase

Drones can provide a better overview of construction sites during the planning phase of a project. For instance, high-quality and up-to-date aerial images can provide a better overview of construction sites to spot the most suitable spaces for temporary installations, to evaluate vegetation around tracks, and to measure the volume of gravel needed for the renewal of track bodies. Drones also allow more data to be collected using multiple sensors and cameras, such as light detection and ranging (LiDAR) scanners and thermal cameras. Two of the main benefits of using drones during the planning phase are a reduction in the number of project managers’ field trips and the amount of time spent on them and increased frequency of the observations.

Drones in the execution phase

One of the main cost drivers at SBB is expensive maintenance operations and the associated cost of personnel safety. The analysis showed that SBB spent approximately CHF 90 million on safeguards for its personnel safety in 2015. Drones could support safeguards, similar to those in the field tests in this action research, which would likely reduce the number of safeguards and associated costs. Drones could also support worksite coordinators during maintenance operations to see and identify dangerous situations earlier and with a better overview. Aerial images in real time could have additional benefits for worksite coordinators, such as the ability to check whether the worksites have been properly cleared before releasing them for railway traffic. For instance, an interviewee stated:

> *Toward the end of the night shift, it’s important for the worksite coordinator to know if all teams can finish their work on time and if critical shunting takes place. With aerial images using drones, a worksite coordinator would have constant information in real time from multiple worksites simultaneously instead of calling all the supervisors on different worksites to get the necessary information.*

Another potential application of drones that can add value is controlling the quality of third parties' deliverables during the execution phase of construction projects. The SBB policy is to have at least one representative on each construction site to control the quality of each project, especially during its critical phases. The deputy head of the maintenance department stated that he could imagine having one person supervise multiple projects simultaneously if this person had real-time images and footage from all construction sites. These data can also be stored and used to support claim management. The data for quality control could be collected by drones. The ability to control the project quality using drones could also be helpful for SBB internal projects.

Drones can also be equipped with multiple sensors to collect various types of data to increase the quality control of construction operations in railways. For instance, a new foundation can be laid during one shift and include many tasks. Controlling the quality of this foundation, which is a crucial component for the durability of the entire railway body, could be done within a limited time. To date, this quality control has been performed randomly by using probes after the execution phase. A drone equipped with multiple sensors for measuring important parameters, such as thickness, could be a supportive tool for quality control.

Drones in the post-execution phase

Drone aerial images of railway operations could be used to identify best practices and training with which to improve project management. An interviewee stated, "Debriefings and education can be much more efficient using drones; you can support your argument with facts." Moreover, project managers could use drones when they need to monitor construction sites and the final stages of projects, reducing the number of field trips and the amount of time spent on them.

Drones in emergencies

Drones could also be used in emergency situations, where emergency teams have limited access to the incident areas or need to have quick access for early evaluation. Drones could provide aerial images with a better overview of incidents more quickly, as well as additional data, such as thermal images to map the heating profile, which could improve the decision-making process of relevant teams (e.g., firefighting and rescue) and critical management. Moreover, using drones as supportive tools could increase the response time of emergency teams in the case of breakdowns. This idea was picked up by one of the interviewees:

> *I can imagine a drone to be permanently installed close to important railway stations that are critical to the railway network. A drone can therefore instantly fly to the areas of failure. The repair team would then have additional information before going out and would have the chance to take the right tools and spare parts with them from the very beginning. That could help save a lot of time.*

4.3 *Future scenarios*

We followed the standard approach for developing scenarios that considers three to eight uncertainty factors and suggests developing three scenarios (Pillkahn, 2008; Schnaars, 1987). We identified seven uncertainty factors that would most likely affect the future of drone applications in railways: autonomous flights, artificial intelligence (AI), swarm technology, battery technology, regulations for flying beyond visual line of sight (BVLOS), data privacy, and senior management commitment.

We classified these uncertainty factors into three main areas of change in the future, namely, technological, regulatory, and organizational. To make better predictions for the future of drone applications, we created pessimistic, realistic, and optimistic scenarios, which are based on experts' translations of challenging (what could go wrong), most likely (expected), and visionary (surprisingly successful) possibilities of the uncertainty factors by 2030 (Amer et al., 2013; Bezold, 2010). See Table 2.

Table 2. Future scenarios for the future of drone applications by 2030

Areas of change	Uncertainty factors	Current state in 2020	Future scenarios for drone applications in railways by 2030		
			Pessimistic	**Realistic**	**Optimistic**
Technological	**Autonomous flights**	Autonomous flights are allowed only with the support of pilots, who will take over control of the flights if a failure occurs.	Autonomous flights will be identified as having high risks.	Drones will become reliable for autonomous flights only in limited applications with specific risk assessments.	Drones will become highly reliable with failsafe autonomous flights in wide areas of application.
	Battery technology	Battery technologies allow for flight times of less than 45 minutes; thus, wired drones are alternatives to overcome this problem.	Battery technology will undergo incremental changes to improve flight times to around 60 to 75 minutes.	Battery technology will allow long-range flights (e.g., around 90 minutes) but will inhibit the use of heavy payloads at the same time.	Battery technology will undergo a radical change, allowing the use of drones in many applications that need long-range flights (e.g., around 120 minutes), as well as mounting multiple sensors simultaneously in a drone system, to be used for multiple applications.
	Artificial intelligence (AI)	Drones with AI are still under research and are being developed for laboratory experiments.	Drones with AI will be available only as custom solutions.	Drones with AI will be commercially available only for very specific applications, such as land surveying and mapping.	Drones with AI will be commercially available for many applications, such as finding trends for monitoring and inspection, land surveying and mapping, and surveillance. The collected data will be fully integrated in organizations' information systems.

	Swarm technology	Swarms of drones are still under research for experimental works.	Swarms of drones will still not constitute a reliable technology in railways.	Swarms of drones will be commercially available for niche applications.	Swarms of drones will be commercially available, with many established use cases.
Regulatory	**Flying beyond visual line of sight (BVLOS)**	Flying BVLOS is allowed for specific use cases (only in specific countries) but is not allowed in populated areas.	Flying BVLOS will still require permission.	Flying BVLOS will be regulated, not only in specific use cases but also in populated areas.	Flying BVLOS will be allowed without the need for specific permission.
	Data privacy	Recording of worksites is possible only in specific use cases, with limited access to the footage (both live and recorded).	Recording worksites and data use will become more restricted than in 2020.	Recording worksites will be possible for established use cases, and access to the footage will be possible for specific users.	Recording worksites will be entirely regulated at the industry level without limitations, and footage will be available for many stakeholders in organizations.
Organizational	**Top management commitment**	Drones have not yet been perceived as constituting a disruptive technology for many application areas in railways.	Drones will receive little support from senior management teams, and decisions about using drones will not be strategic.	Drones will receive support only for established use cases with clear returns on investment.	The rollout of drone programs will have full support from senior managers for established use cases, as well as experimental and future applications.

Current state

The current state of drone technology in terms of autonomous flights and flight endurance imposes constraints on the feasibility of many use cases. Short flight endurance due to the limitation of current batteries often inhibits the use of drones in repetitive tasks, such as monitoring maintenance worksites for safety reasons, as well as in autonomous flights. AI and swarm technology are currently under research, and drone developers are still experimenting with technologies that use AI to gain actionable insights, as well as drones that work collaboratively in large-scale operations.

Regulations for drone applications are lagging behind the technological development. Current regulations allow video surveillance for monitoring technical procedures to avoid accidents on construction sites. However, there are certain constraints on using drones at SBB. For instance, drones can hover above a railway track only when there is no railway traffic. During flights, drones must keep a minimum distance of 5 meters from electrically conductive items. Moreover, drones must have no red or green lights, and flying at night is also prohibited. One of the main concerns of drone regulations is associated with flying BVLOS. Organizations such as railway companies, with huge infrastructures and time-intensive operations, can significantly benefit from BVLOS flights, yet failsafe systems are necessary to ensure the reliability of drone systems to land safely in case of incidents. Data privacy remains a major challenge, which all interviewees mentioned as an inhibiting factor when using drones.

Finally, senior management commitment signals to what extent a potential application is perceived as adding value in organizations. Using drones for different applications and evaluating returns on investment can help in elaborating real benefits and will encourage organizations to trust drone technology, and helps managers to support investments in drones for mainstream adoption. Implementing innovative applications of drones could also help organizations improve their public relations and brand image.

Future scenario 1: Pessimistic

The first future scenario we suggest is pessimistic, where technology incrementally improves current railway operations. In this scenario, drones offer value-adding applications in railways, such as monitoring construction sites by providing high-definition footage and taking pictures, resulting in cost savings and faster planning operations during many construction projects. Drones are also used to monitor the progress of projects by taking videos and images. Due to the limitations of drone technology, piloted drones can fly only where there is no train traffic. Data privacy is not an issue as long as the footage and the images capture only the infrastructure on the ground, and the workforce is not filmed.

Future scenario 2: Realistic

A more realistic scenario appearing from the analysis is that drones enhance and replace current railway operations beyond an incremental contribution. In this scenario, drones constitute a mainstream technology for inspection that is able to quickly conduct inspections in emergency situations by providing on-board data, as well as in regular maintenance by aiding the collection and analysis of off-board data. Flying BVLOS is regulated for specific use cases, and it can be done by autonomous flights, mostly for repetitive tasks, such as inspection. The use of AI is an addition to drones but is unlikely become a key aspect of decision making. Furthermore, drones have become supportive tools for worksite coordinators for monitoring the progress of projects. The drones send live feeds of the process and of quality assurance by collecting more data from worksites and communicating details with the supervisors of different worksites.

Future scenario 3: Optimistic
A final future scenario is optimistic regarding drone technology. In this scenario, maintenance operations benefit from drones with AI that identify trends concerning irregularities and degradations of infrastructure. Piloted and autonomous drones have found applications in railways. Autonomous drones likely are programmed to perform repetitive tasks, such as inspections and monitoring, and piloted drones are programmed to check unexpected incidents. Drones are equipped with multiple sensors, such as thermal cameras and LiDAR scanners, to provide additional data during maintenance operations. Moreover, drones have significantly reduced the number of safeguards. Drones with multiple scanners are the main tools for aerial mapping and land surveying in railways. A drone is a common sight at every construction site, contributing to planning, monitoring, quality control, and claim management, and has become a supportive tool for project management by worksite coordinators. Swarms of drones have increased their capabilities in large-scale projects, reducing the length of inspection operations during maintenance, and offering new use cases with high efficiency in the area of surveillance and monitoring.

5. Discussion

5.1 Practical implications
Digitalization offers unprecedented opportunities for transforming railways into intelligent systems (Tokody and Flammini, 2017), and drone technology contributes to this transformation as a mobile, flexible, and versatile device for collecting and transferring data, with growing capabilities in the future. This study helps illuminate the potential applications of drones in railways and could help practitioners make informed decisions concerning the adoption of drone programs in railways' supportive activities. The findings from this research could also be used in other industrial settings that exhibit characteristics similar to the railways' environments. For example, executing construction projects and mega-projects for ground transportation systems and infrastructure facilities could demonstrate dynamics similar to those of railways, and drone technology could offer comparable applications in the planning, execution, and post-execution of those projects. Moreover, the findings from this research could inform future studies on exploring emerging digital technologies, identifying current and future application areas, and evaluating benefits and challenges in the railways, such as the use of augmented reality in railways' supportive activities, particularly in maintenance operations (see Kans et al., 2016).

5.2 Theoretical implications
This study contributes to the literature on technological innovation in railways by foregrounding the distinction between the respective uses of new technologies in primary and supportive activities of railway operations that comprise a large technical system (cf. Geyer and Davies, 2000). Exploring the potential of drone technology in railways shows that using new technologies in supportive activities for railway operations involves fewer technological, operational, organizational, political, and regulatory challenges than in primary activities (cf. Bekius and Meijer, 2018; Geerlings, 1998; Taylor, 1982; De Tilière and Laperrouza, 2009).

One promising research direction is the development of a framework that evaluates the levels of interdependencies and the impact of new technologies on primary versus supportive operations along a continuum (e.g., highly dependent on primary activities, dependent on primary and supportive activities, and highly dependent on supportive activities) to discuss the dynamics of using new technologies (in terms of evaluation, implementation, and consequential effects) from different parts of the continuum (cf. Walrave and Raven, 2016). The capabilities of drone technology are still advancing, which increases the uncertainties of application areas, the implementation process, and the consequential effects of drones. Exploring the levels and sources of the uncertainties of new technologies and the impact of various uncertainties on the evaluation, implementation, and consequential effects of technological innovations in railways suggests another promising research direction (Roca et al., 2017).

5.3 Methodological implications

There are different approaches, such as simulation and systems engineering, for evaluating the potential of a new technology with high uncertainties in railways (see, Lo et al., 2013; Lovell et al., 2011; Suzuki et al., 2016; van den Hoogen, 2019). In this work, we designed a participatory research approach that is less commonly used for empirical analysis of current and future applications of a new technology in railways. We combined scenario planning with action research (see Ramos, 2002) to provide more practical insights when researching the potential of drone technology in supportive railway operations. This combination can improve the creation of scientific knowledge by offering "a way of testing the applicability and validity of foresight knowledge within local contexts" and being more sensitive to global systems (Ramos, 2002, p. 10) by viewing the focal entity as part of a larger world (List, 2006). The iterative nature of action research can improve the development of multiple futures, and applying a future perspective at each iteration can help researchers acquire a long-term vision (List, 2006).

5.4 Limitations

We note a few limitations of this study. First, it is based on data from a single case. Future studies could collect data from multiple sources to identify additional uncertainty factors concerning environmental conditions, different levels of automation in railway companies, and country-specific regulations and standards, among others. Second, various types of drone technologies have vast potential in railways, but this study focused on multirotor technologies. Fixed-wing drone technology also has considerable potential in railways, especially in land surveying, mapping, and photogrammetry applications. Furthermore, drone technology is a versatile system that could be equipped with multiple sensors and could provide different applications, and future studies could include a wider range of drones with different capabilities. Third, practical research on drones often requires multidisciplinary approaches that could involve more experts from different domains, such as technical, technological, organizational, and regulatory, which, in turn, would allow exploration of additional uncertainty factors in the future of drones in railways. In particular, the involvement of information technology experts could help researchers and practitioners understand future trends in fleet management systems or the fifth-generation (5G) wireless technology in data transmission and its impact on flying BVLOS and autonomous flights.

6. Conclusion

The applications of drones are increasing, and evidence shows that drone technology could improve certain operations in railways. Drawing on existing literature on the use of new technologies in railways, we distinguished between primary and supportive activities of railway operations in terms of their respective technological innovations. Drone technology will likely increase the efficiency of supportive activities in railways. We combined scenario planning with insights from action research conducted jointly with SBB, to explore the applications of drones in supportive activities of railway operations and to develop future scenarios based on the factors that will affect the use of drone technology in railways. The findings of this research can enrich theoretical thinking concerning the dynamics of using new technologies in different categories of railway operations, as well as help railway practitioners make better decisions concerning the adoption of drones in their settings.

In particular, drones have immense potential in the planning, execution, and post-execution phases of maintenance projects, as well as in emergencies. We defined three scenarios—pessimistic, realistic, and optimistic—for drone applications in railways by 2030. In the pessimistic scenario, we predict that railways will adopt drones for visual checks and monitoring applications only. In the realistic scenario, and with further improvements in the technology, drones will become the main inspection tools and powerful supportive tools for project management in railways. In the optimistic scenario, drones can radically change certain operations in railways, such as inspections, with the advancement of integrating drones with AI and swarming technologies, as well as more freedom in the use of autonomous flights.

References

Amer, M., Daim, T. U. and Jetter, A. (2013), A review of scenario planning, *Futures*, 46(-), 23-40.
Armstrong, J. and Preston, J. (2011), Alternative railway futures: growth and/or specialisation?, *Journal of Transport Geography*, 19(6), 1570-1579.
Bekius, F. and Meijer, S. (2018), The redesign process of the timetable for the Dutch railway sector: a theoretical approach, *International Journal of System of Systems Engineering*, 8(4), 330-345.
Bezold, C. (2010), Lessons from using scenarios for strategic foresight, *Technological Forecasting and Social Change*, 77(9), 1513-1518.
Bradley, V., (2016) Network Rail uses latest technology to help secure future of historic Devon rail line, *Network Rail*, available at: https://www.networkrailmediacentre.co.uk/news/network-rail-uses-latest-technology-to-help-secure-future-of-historic-devon-rail-line (Accessed 14 February 2019).
Coghlan, D., Cirella, S. and Shani, A. B. (2012), Action research and collaborative management research: more than meets the eye?, *International Journal of Action Research*, 8(1), 45-67.
Cunningham, B. (1976), Action research: toward a procedural model, *Human Relations*, 29(3), 215-238.
de Brabandere, L. and Iny, A. (2010), Scenarios and creativity: thinking in new boxes, *Technological Forecasting and Social Change*, 77(9), 1506-1512.
De Tilière, G. and Laperrouza, M. (2009) Developing and deploying innovative technologies in a liberalized European railway system, *Proceedings of 9th Swiss Transport Research Conference (STRC)*, Citeseer, Monte Verita, Switzerland.
Duranton, S., Audier, A., Hazan, J., Langhorn, M. P. and Gauche, V., (2017) The 2017 European Railway Performance Index, available at: https://www.bcg.com/en-ch/publications/2017/transportation-travel-tourism-2017-european-railway-performance-index.aspx (Accessed 5 May 2019).
Elden, M. and Chisholm, R. F. (1993), Emerging varieties of action research: Introduction to the special issue, *Human Relations*, 46(2), 121-142.
Flammini, F., Naddei, R., Pragliola, C. and Smarra, G. (2016a) Towards automated drone surveillance in railways: State-of-the-art and future directions, *In:* Blanc-Talon, J., Distante, C., Philips, W., Popescu, D. & Scheunders, P., eds. *International Conference on Advanced Concepts for Intelligent Vision Systems (ACIVS)*, Springer, Lecce, Italy.
Flammini, F., Pragliola, C. and Smarra, G. (2016b) Railway infrastructure monitoring by drones, *International Conference on Electrical Systems for Aircraft, Railway, Ship Propulsion and Road Vehicles & International Transportation Electrification Conference (ESARS-ITEC)*, IEEE, Toulouse, France.
Floreano, D. and Wood, R. J. (2015), Science, technology and the future of small autonomous drones, *Nature*, 521(7553), 460-466.
Franceschini, F., Mastrogiacomo, L. and Pralio, B. (2010), An unmanned aerial vehicle-based system for large scale metrology applications, *International Journal of Production Research*, 48(13), 3867-3888.
Geerlings, H. (1998), The rise and fall of new technologies: Maglev as technological substitution?, *Transportation Planning and Technology*, 21(4), 263-286.
Geyer, A. and Davies, A. (2000), Managing project–system interfaces: case studies of railway projects in restructured UK and German markets, *Research Policy*, 29(7-8), 991-1013.
Goodchild, A. and Toy, J. (2018), Delivery by drone: An evaluation of unmanned aerial vehicle technology in reducing CO2 emissions in the delivery service industry, *Transportation Research Part D: Transport and Environment*, 61(-), 58-67.
Goodier, C., Austin, S., Soetanto, R. and Dainty, A. (2010), Causal mapping and scenario building with multiple organisations, *Futures*, 42(3), 219-229.

Hansen, C., Daim, T., Ernst, H. and Herstatt, C. (2016), The future of rail automation: A scenario-based technology roadmap for the rail automation market, *Technological Forecasting and Social Change*, 110(-), 196-212.

Hughes, T. P. (1987), The evolution of large technological systems, In: Bijker, W. E., Hughes, T. P. & Pinch, T. *The social construction of technological systems: New directions in the sociology and history of technology*, MIT Press, Cambridge.

Ikshwaku, S., Srinivasan, A., Varghese, A. and Gubbi, J. (2019), Railway Corridor Monitoring Using Deep Drone Vision, In: Verma, N. K. & Ghosh, A. K. *Computational Intelligence: Theories, Applications and Future Directions-Volume II*, Springer, Singapore.

Kans, M., Galar, D. and Thaduri, A. (2016) Maintenance 4.0 in railway transportation industry, *In:* Koskinen, K. T., Kortelainen, H., Aaltonen, J., Uusitalo, T., Komonen, K., Mathew, J. & Laitinen, J., eds. *Proceedings of the 10th World Congress on Engineering Asset Management (WCEAM 2015)*, Springer, Tampere, Finland.

King, A. (2017), The future of agriculture, *Nature*, 544(7651), S21-S23.

Kour, R., Karim, R., Parida, A. and Kumar, U. (2014), Applications of radio frequency identification (RFID) technology with eMaintenance cloud for railway system, *International Journal of System Assurance Engineering and Management*, 5(1), 99-106.

Lee, S. and Choi, Y. (2016), Reviews of unmanned aerial vehicle (drone) technology trends and its applications in the mining industry, *Geosystem Engineering*, 19(4), 197-204.

Li, Y. and Liu, C. (2019), Applications of multirotor drone technologies in construction management, *International Journal of Construction Management*, 19(5), 401-412.

List, D. (2006), Action research cycles for multiple futures perspectives, *Futures*, 38(6), 673-684.

Lo, J., van den Hoogen, J. and Meijer, S. (2013) Using gaming simulation experiments to test railway innovations: implications for validity, *Winter Simulations Conference (WSC)*, IEEE, Washington, DC, USA.

Lovell, K., Bouch, C., Smith, A., Nash, C., Roberts, C., Wheat, P., Griffiths, C. and Smith, R. (2011), Introducing new technology to the railway industry: system-wide incentives and impacts, *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, 225(2), 192-201.

Maestrini, V., Luzzini, D., Shani, A. B. R. and Canterino, F. (2016), The action research cycle reloaded: Conducting action research across buyer-supplier relationships, *Journal of Purchasing and Supply Management*, 22(4), 289-298.

Maghazei, O. and Netland, T. (2018) Exploring the potential applications of drones in the petrochemical industry, *EurOMA 2018*, EurOMA, Budapest, Hungary.

Maghazei, O. and Netland, T. (2019), Drones in manufacturing: Exploring opportunities for research and practice, *Journal of Manufacturing Technology Management*, Forthcoming.

Mazur, M. and Wiśniewski, A., (2016) Clarity from above, *PwC*, available at: https://www.pwc.pl/en/publikacje/2016/clarity-from-above.html (Accessed 22 August 2019).

Mazur, M., Wiśniewski, A., Smith, J. and McMillan, J., (2017) Clarity from above: transport infrastructure, *PwC*, available at: https://www.pwc.pl/en/publikacje/2016/clarity-from-above-transport-infrastructure.html (Accessed 25 February 2019).

Nair, A., Malhotra, M. K. and Ahire, S. L. (2011), Toward a theory of managing context in Six Sigma process-improvement projects: An action research investigation, *Journal of Operations Management*, 29(5), 529-548.

Pillkahn, U. (2008), *Using trends and scenarios as tools for strategy development: shaping the future of your enterprise*, Publicis Corporate Publishing, Erlangen, Germany.

Potter, S. and Roy, R. (2000), Using scenarios to identify innovation priorities in the UK railway industry, *International Journal of Innovation Management*, 4(2), 229-252.

Ramos, J. M. (2002), Action research as foresight methodology, *Journal of Futures Studies*, 7(1), 1-24.

Richardson, P. and Nigam, A. (1999), New technology introduction and implementation: The case of paging technology in the Ratlam division of Indian railways, *Creativity and Innovation Management*, 8(4), 233-241.

Roca, J. B., Vaishnav, P., Morgan, M. G., Mendonça, J. and Fuchs, E. (2017), When risks cannot be seen: Regulating uncertainty in emerging technologies, *Research Policy*, 46(7), 1215-1233.

Saito, Y., Motoyoshi, S., Konishi, T., Matsuura, K. and Yokoyama, A. (2017), Innovative changes for track maintenance by using ICT, *Procedia CIRP*, 61(-), 790-795.

SBB, (2018), "SBB Infrastruktur", Bern, Switzerland.

Schnaars, S. P. (1987), How to develop and use scenarios, *Long Range Planning*, 20(1), 105-114.

Schoemaker, P. J. (1993), Multiple scenario development: Its conceptual and behavioral foundation, *Strategic Management Journal*, 14(3), 193-213.

Sol-Sánchez, M. and D'Angelo, G. (2017), Review of the design and maintenance technologies used to decelerate the deterioration of ballasted railway tracks, *Construction and Building Materials*, 157(-), 402-415.

Strauss, A. and Corbin, J. (1990), *Basics of qualitative research*, Sage publications, London.

Suzuki, O., Sato, E. Y., Nukaga, N., Sakikawa, S., Katsuta, K. and Morita, K. (2016), Research and development driving innovations in global railway systems/services, *Hitachi Review*, 65(9), 413-419.

Taylor, C. (1982), Railway innovation and uncertainty, *R&D Management*, 12(1), 37-48.

Tokody, D. and Flammini, F. (2017), The intelligent railway system theory, *International Transportation*, 69(1), 38-40.

van den Hoogen, J. 2019. *The Gaming of Systemic Innovations: innovating in the railway sector using gaming simulation.* Delft University of Technology.

Walrave, B. and Raven, R. (2016), Modelling the dynamics of technological innovation systems, *Research Policy*, 45(9), 1833-1844.

Wawrla, L., Maghazei, O. and Netland, T., (2019) Applications of drones in warehouse operations, *ETH Zurich, D-MTEC, Chair of Production and Operations Management*, available at: https://pom.ethz.ch/publications/white-papers.html (Accessed 28 December 2019).

Yokoyama, A. (2015), Innovative changes for maintenance of railway by using ict–to achieve "smart maintenance", *Procedia CIRP*, 38(-), 24-29.

Ziobro, P., (2018) Drones Are Watching: Railroad Irks Workers With Unmanned Aircraft, *The Wall Street Journal*, available at: https://www.wsj.com/articles/drones-are-watching-railroad-irks-workers-with-unmanned-aircraft-1521028800?ns=prod/accounts-wsj (Accessed 17 May 2019).

Zuber-Skerritt, O. and Perry, C. (2002), Action research within organisations and university thesis writing, *The Learning Organization*, 9(4), 171-179.