Measurement and sonification of construction site noise and particle pollution data

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Abstract

Purpose – The noise and dust particles caused by the construction transport are by most stakeholders experienced as disturbing. The purpose of this study is to explore how sonification can support visualization in construction planning to decrease construction transport disturbances.

Design/methodology/approach – This paper presents an interdisciplinary research project, combining research on construction logistics, internet of things and sonification. First, a data recording device, including sound, particle, temperature and humidity sensors, was implemented and deployed in a development project. Second, the collected data were used in a sonification design, which was, third, evaluated with potential users.

Findings – The results showed that the low-cost sensors used could capture "good enough" data, and that the use of sonification for representing these data is interesting and a possible useful tool in urban and construction transport planning.

Research limitations/implications – There is a need to further evolve the sonification design and better communicate the aim of the sounds used to potential users. Further testing is also needed.

Practical implications – This study introduces new ideas of how to support visualization with sonification planning the construction work and its impact on the vicinity of the site. Currently, urban planning and construction planning focus on visualizing the final result, with little focus on how to handle disturbances during the construction process.

Originality/value – Showing the potentials of using low-cost sensor data in sonification, and using sonification together with visualization, is the result of a novel interdisciplinary research area combination.

Keywords Construction logistics, Urban planning, Sonification, IoT sensors, User evaluation

Paper type Research paper

1.Introduction

The world is currently amid an urbanization trend; this trend means that there is a strong demand for new houses, apartment buildings, workplaces, hospitals, schools and supportive infrastructure to be built (Pearce and Ahn, 2017). Construction is heavily dependent on logistics activities, with 60–80% of the gross work involving the purchase of materials and services (Scholman, 1997). A site receives in general 2–10 deliveries or 8–10 tons of material per day, and construction transport makes out 30% of the urban goods transports (Guerlain *et al.*, 2019). Thus, noise and dust particles are inevitable during a construction project as long as machines and equipment are used, vehicles are moved and deliveries are unloaded or loaded (Kantová, 2017). The sources of air pollution are of course multiple; however, due to the rapid urbanization, construction transport is a large contributor (Wu *et al.*, 2016). Hence, construction transport creates disturbances on the surrounding society that are experienced by different stakeholders. Fredriksson *et al.* (2021a) identify construction transport stakeholders as internal or external to the project, with internal stakeholders being those

who are directly involved in construction projects and external stakeholders those who are significantly affected by construction activities (e.g. neighbors, road users, local authorities), but are not part of the project.

The noise and dust particles caused by the construction transport are, by most stakeholders in the vicinity of a construction site, experienced as intruding and disturbing (Ng, 2000), and constitutes a health risk, especially if experienced for prolonged time periods. For example, noise exposure may induce hearing impairment, hypertension and ischemic heart disease, annoyance, sleep disturbance and decreased concentration abilities and school performance (Passchier-Vermeer and Passchier, 2000). Exposure to particulate matter (PM) of different size fractions is also associated with an increased risk of cardiovascular disease (Polichetti *et al.*, 2009) and other health issues (Kim *et al.*, 2015). To decrease the disturbances caused by construction work is urgent due to increased construction activity (Azarov *et al.*, 2018).

The need to decrease disturbances of construction and its transports have been highlighted by municipalities in several countries, such as Sweden, Norway, the UK, Belgium, Austria and The Netherlands (Fredriksson *et al.*, 2018). One way to decrease the disturbances is to improve the knowledge of their impact. Today, the question of construction logistics is in most cases forgotten during the urban planning process (Janné *et al.*, 2021). There are two main reasons behind this: lack of logistics knowledge among the municipalities conducting the transport and urban planning (Lindholm and Behrends, 2012; Janné and Fredriksson, 2019) and a remaining lack of focus on and understanding of logistics in the construction industry (Sundquist *et al.*, 2018; Vrijhoef and Koskela, 2000). However, to decrease the disturbances of construction transport, there is a need to consider disturbances in the surrounding area when planning a construction project and its logistics (Ning *et al.*, 2019). Especially as there exists tradeoffs between measures to decrease disturbances of construction transport. For example, one way to decrease emissions caused by construction transport is to use off-peak deliveries (early morning or evening); however, nighttime loading and unloading of heavy materials cause noise disturbances for residents in the vicinity of the construction site.

Furthermore, being able to communicate these tradeoffs to stakeholders is important in the citizen dialogue (contributing to SDG11 – making cities and human settlements inclusive, safe, resilient and sustainable). Often, visualization is used to communicate data and information; however, visual representations can easily become complex and hard to interpret (Zagermann *et al.*, 2016). Adding sound, i.e. sonification, can support visualization and facilitate understanding of the visualized data (Hermann *et al.*, 2011).

The purpose of this study is to explore how sonification can support visualization in construction planning to decrease construction transport disturbances.

This study has been part of the Vinnova-financed project Disturbance Free Cities (in Swedish: Störningsfri Stad). Disturbance Free Cities was a three-year project, with the goal of developing knowledge and competence that allows for the development of planning systems that can visualize the traffic impact during urban planning to decrease its disturbances. For this, noise (see further discussions in Ballesteros *et al.*, 2010; Kerr *et al.*, 2002) and dust particle levels (see discussion in Cheriyan and Choi, 2020) data are needed.

Construction is among the least digitized industries (Barbosa *et al.*, 2017), and is an industry with low margins, where cost overruns are common. The use of internet of things (IoT) technology facilitates the efficient management of construction projects and transport. The data gathered through IoT can mainly be used for two purposes: (1) real-time data for immediate decision-making or (2) for forecasting the impact of future decisions (Oke and Arowoiya, 2021; Louis and Dunston, 2018; Woodhead *et al.*, 2018). IoT technology can collect data from several units and store them in a central unit, which is cost, compared to a person visiting each device to collect data manually (Louis and Dunston, 2018). Though, presently,

the cost of gathering this type of data is high due to expensive sensors (Mydlarz *et al.*, 2017; Khan *et al.*, 2021). Therefore, the possibilities of low-price IoT devices to collect and transmit data remotely is of interest to the construction industry (Ghosh *et al.*, 2020; Kang *et al.*, 2021).

There is also a need to understand what level of data quality is enabling sonification. There are well-designed and sophisticated microphones and devices for assessing and measuring the sound levels in different frequency ranges that are used in, for example, sound recording studios and technical audiology (see e.g. discussion on microphones for noise measuring in Lee and Fleming, 1996). However, these devices are developed for indoor use and are delicate (sensitive to temperature, humidity and dust) and expensive. Furthermore, presently used environmental acoustic outdoor monitoring is usually only conducted for short-term measurement periods as equipment, setup and personnel are costly (Mydlarz *et al.*, 2017). However, in construction, here are great risks that the sensors must be replaced during the project time (Loyola, 2019) as the physical environment is rough, where sensors are affected by rain, wind, dust, and in worst case, physical violence (Murty *et al.*, 2008). There are consequently good reasons for exploring the potentials of cheap and easily accessible components, and for monitoring and collecting data remotely, to measure noise at construction sites. However, using cheap sound sensors might decrease the data quality, but as the price factor can be 100 to 1, a possible lower data quality can be justified as long as data quality is "good enough" for the purposes of its use (see e.g. discussions in Lima and Oliveira, 2016; Kivelä and Hakala, 2015; Vidanã-Vila *et al.*, 2020; Hallett *et al.*, 2018). This reasoning can also be transferred to measuring particle concentration (Wang *et al.*, 2015), and there are several studies that explore the use of low-cost particle sensors (Kelly *et al.*, 2017; Bulot *et al.*, 2020; Khan *et al.*, 2021). Consequently, low-cost sensors can supplement the use of expensive and often rare regulatory-grade measurement devices (Malings *et al.*, 2020) to capture an outdoor disturbing phenomenon in a rough environment, such as construction transport.

To answer the purpose, two research questions have been developed:

RQ1. What is the potential of using low-cost IoT measuring devices to capture data for noise and particle levels at a construction site?

RQ2. How can sonification help to create an understanding of the recorded data as a basis for construction planning?

The research questions were answered by utilizing and further developing an IoT data recording device, as well as making a sonification design for the collected data and an evaluation of this sonification via an online test.

2. Background
This section first presents the background of construction logistics and transport. Second, the basic structures of sonification are presented. Third, we discuss the use of IoT to capture noise and dust particles at the construction site.

2.1 Construction logistics and transport
Construction projects are usually divided into two types; housebuilding and infrastructure projects, where this paper focuses on housebuilding projects in urban areas. In such projects, construction logistics can be divided into two primary functions: the management of logistics activities *on* construction sites, on-site logistics and the transport of resources and materials *to and from* construction sites, off-site logistics (Janné and Fredriksson, 2019). A building construction site has three major incoming flows: material, equipment and labor, and two outgoing flows: waste and excavated materials. All these flows have low transport efficiency today; e.g. low fill rates, empty running and/or oversized vehicles (Lundesjö, 2015). The low transport efficiency leads to

unnecessarily high levels of emissions, noise and vibrations from construction transport, but it also impacts upon productivity in the construction project.

The responsibility for planning and coordinating the supply chain and construction site resides with the main contractor (Azambuja and O'Brien, 2008). The main contractor faces the challenge of managing multiple transports with different materials, products and resources to and from the construction site as well as to keep disturbances low in the vicinity of the site. Transport arrives with materials to be unloaded, or to pick up waste or Earth and rock masses, in which case they need to be loaded. All loading and unloading generate noise and dust, but the level and amount depend on the specific materials. To avoid too much material accumulating on site, over the past few decades, the construction industry has started to implement the just-in-time (JIT) system (Lundesjö, 2015). Though, this has increased the number of transport as they arrive more frequently. For materials to arrive JIT, the planning of the construction transports needs to be coordinated with the planning of the construction activity, and the focus among main contractors is to have an as efficient project as possible, leading to ques of trucks waiting to be let in on site, and therefore, congestion outside the site. There are also tradeoffs between material handling, storing and transportation. For example, in waste management, sorting more fractions leads to better prerequisites for recycling but also requires a larger storage space and lower fill rates during transportation (Kurdve et al., 2019), resulting in more transports to and from site and movements at site.

Construction logistics typically have an impact on several economic, social and environmental criteria (e.g. cost, traffic safety, noise and particle emissions). Previous studies, e.g. Ballantyne et al. (2013), have noted that cities and authorities have not traditionally focused on goods transport (among which construction transport is part) or on coordinating the needs of different stakeholders. Instead, goods transport and logistics has been viewed as a problem for the logistics industry to solve (Lindholm and Blinge, 2014). However, decreasing disturbances of construction logistics and its transport is a critical issue to maintain a good relationship with residents and businesses (Fredriksson et al., 2021a). To handle these issues, municipalities have started to think of how to include these in urban planning (Fredriksson et al., 2021a). Goodman and Hastak (2006) see the urban planners as the ones responsible for coordinating the logistics stakeholders in urban development. The decisions made by the municipalities regarding, for example, development areas and zoning plans, restrict which decisions can be made by main contractors. Furthermore, effective stakeholder engagement is an important question in construction project management (Mok et al., 2018). However, stakeholder participation in urban mobility and logistics is still only applied in a fragmented, limited manner (Macharis and Bernardini, 2015). According to Janné and Fredriksson (2019), there is normally only one-way communication from a public body and/or the building supervisor on anticipated impacts. Effective participation requires a deeper understanding of the concerns of all stakeholders (Macharis et al., 2009). There is a need to communicate the impact of construction logistics and its transport in urban planning as well as in stakeholder communication.

2.2 Sonification for data representation

In visualization, there are challenges for the visual perception, such as simultaneous brightness contrast and the Mach band phenomenon (Ware, 2013), which negatively affects the interpretation and experience of visual representations. Additionally, if too much visual information is presented, e.g. with large or complex visual representations, there is a risk of cognitive overload (Zagermann et al., 2016). By adding sonification to visualization, more effective data representations can be designed (Rosli and Cabrera, 2015). Therefore, audiovisual analytics have the potential to efficiently provide information to a user (Rind et al., 2018; Ferguson and Brewster, 2018).

Sonification is the transformation of sound in accordance with data (Hermann *et al.*, 2011). Sonification can be audification of data, where data are converted to a soundwave or translated into frequencies (see e.g. Hermann *et al.*, 2011; Pinch and Bijsterveld, 2012; Franinovic and Serafin, 2013). However, a sonification can go beyond just audification. Parameter mapping sonification is when sound parameters and musical elements are mapped to and adapted by data (Dubus and Bresin, 2013; Hermann *et al.*, 2011). In this way, a sonification can be designed, or composed, and then altered by data, different variables and different values. By using parameter mapping sonification, the sonification can be designed based on a music-theoretical and aesthetic approach, which can allow both convey of information and being experienced in a desired way. Musical sounds and elements enable the use and manipulation of musical components such as *pitch, timbre, harmonics* and *sound level* (see e.g. Zwicker and Fastl, 2013; Juslin and Laukka, 2004; Levitin, 2006). Mapping data to musical sounds makes it possible to convey information and meaning, as well as emotions (see e.g. discussions in Rönnberg and Löwgren, 2016; Winters and Wanderley, 2014).

Sonification should be designed to be objective and systematic (Hermann, 2008), and used to provide an awareness of the data and of changes in this data, as well as provide a ticket-to-talk (Rönnberg and Löwgren, 2020). Considering this, the representation of precise individual values might be of less importance than experiencing the combination of the entire data (see e.g. discussion in Supper, 2014).

There are different approaches for sonification of urban noise and particle pollution data in the literature. St Pierre and Droumeva (2016) explored sonification of urban air pollution, including particle matter, using a granular synthesis approach with click rate increases for increased levels of particles. This sonification approach was experienced as intuitive by users. Blandino (2018) used sonification, signal processing and sound transformation of sounds present in the environment, on mobile devices to engage the user with the toxic release inventory. Berger and Bill (2019) used field recordings in a virtual reality (VR) setting to sonify and visualize urban noise levels, where measured sound levels were mapped to the sound level of the sonification to convey an immersive experience of noise environments. In a similar fashion, Zerza and Park (2020) explored the *Urban (Un) Seen*, an audiovisual installation presenting noise data for community participation and creating awareness of urban noise. Griffiths *et al.* (2021) used simple synthesized sounds to sonify particle matter levels, among other sensor data. This sonification, utilizing pitch and timbre, was presented to kayak paddlers for exploration of data of the surrounding environment while paddling. Other, perhaps more artistic, examples are Brian Foo's sonification of Beijing air quality data (https://datadrivendj.com/tracks/smog/access date: 2022-01-03), Rubin and Thorp Herald/ Harbinger (https://vimeo.com/250393598 access date: 2022-01-03) and the digital artwork "I Breathe" by Cha Blasco (https://vimeo.com/314758208 access date: 2022-01-03), where air quality and pollution index are sonified and explored in real time using data sonification, and the audience gets an interactive and emotional experience of the air.

In many of these examples, the goal is to use sonification to provide an awareness of environmental data and for public engagement. The aim of the sonification in this study is to explore the use of sonification for communicating construction site data collected using low-cost IoT sensors to stakeholders in construction, logistics and urban planning. The approach used in this study is parameter mapping, where sonification creates an abstract musical representation of construction site data.

3. Method

This is an exploratory study following a single case research design for testing the sensors and gathering data, and a small-scale online survey for exploring the potentials of

sonification in construction through user evaluations. Single case was selected because it allows for an in-depth understanding of a phenomenon in its context (Yin, 2017). The case was selected as it represented a rare opportunity, i.e. five data recording devices were allowed to be mounted at the construction sites in the development project of Ebbepark (https://ebbepark.se/, access date: 2022-01-03) in the center of Linköping, Sweden. The development project was part as a testbed in the research project Disturbance Free Cities. The development project includes 750 apartments, 75,000 m^2 of office space, a parking house and leisure areas. The development project started in 2017 and is to be finished in 2024. The small-scale online survey for user evaluation was sent out the participants in the research project Disturbance Free Cities. A small-scale online survey was selected because it was a good way of quickly gather information from several different potential users. The respondents include developers, main contractors, construction logistics consultants, urban planners, traffic planners and construction logistics researchers. All have more than ten years of experience in their respective trades. Hence, these were seen as potential future users with a good knowledge of the context of construction planning. In total, 40 persons were contacted, and 24 responded.

The research process involved seven steps, see Figure 1. First, the sensors to be included in the data recording device were identified and, second, these were assembled in a box to keep them safe at the site (here after referred to as the device). Third, the devices were mounted, in total five, at the construction site (Figure 2), and the capacity was tested. Fourth, it was ensured that the mounted devices transmitted recorded data to a central database and a simulation of these data, from three out of five locations, was conducted and sonified. The data simulated were noise level in three frequency intervals and particle levels. Five, the sonification was evaluated together with a simple visualization via an online questionnaire. Sixth, the results from the evaluations were discussed in a workshop with participants from the research project reference group, and finally, seventh, the outcome was used to generate new research ideas for future studies.

3.1 The data recording device

The data recording device consisted of three different sensors being controlled by the Raspberry Pi 4B, see Figure 3. The device was designed to be used outdoors, and the hardware was contained in a plastic container protecting against the environment. The three different sensors measured sound, particles, temperature and humidity. The measurements of sound as well as particle levels were used in the present study.

The measurement device was designed to be able to record a variety of data and transmit these wirelessly via 4G network. The criteria for the measurement device were discussed and formulated together with the research project group and the literature. The criteria for the
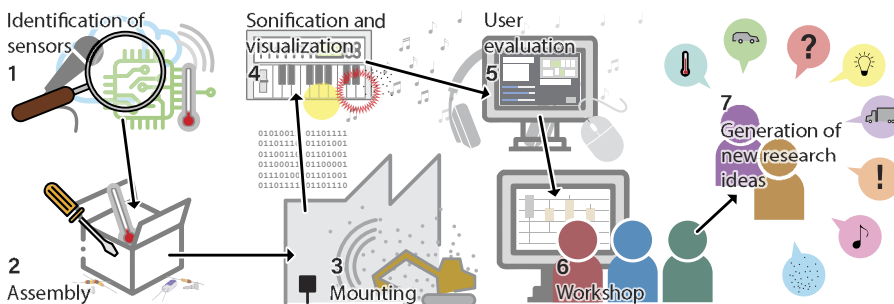

Figure 1.
The research process: (1) identification of sensors, (2) assembly of data recording devices, (3) mounting of the devices, (4) sonification and visualization design, (5) user evaluation, (6) stakeholder workshop, (7) generation of research ideas

Figure 2.
The five different
locations of data
recording devices on
site at the Ebbepark
construction project in
central Linköping,
Sweden

Figure 3.
Overview of the data
recording device with
power supply (grey
boxes), Raspberry Pi
4B (pink), temperature
and humidity sensor
(yellow), particle
measuring sensor
(purple), audio device
(orange), microphone
(green) and 4G
connection sending
JSON objects to
database (blue boxes)
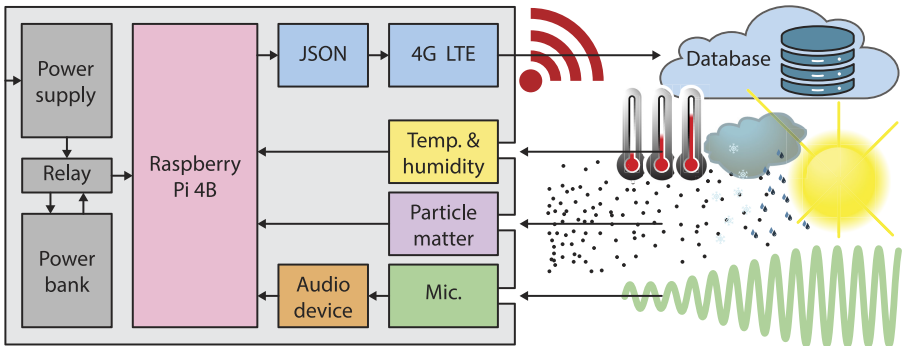
computer collecting, processing, storing and transmitting the data were low power
consumption, enough processing power for parallel signal processing of the data
measurements, having both USB 2 and 3 ports for a variety of different sensors and
devices, and an operating temperature of 0 to 50℃. The Raspberry Pi 4B met these criteria
with its 1.5 GHz 64-bit quad-core Cortex-A72 (ARM v8) processor and is in a low-cost range
(approximately €35). The criteria for the sound sensor measuring noise levels were having a
linear frequency response in relevant frequency bands between 100 and 5,000 Hz (Ballesteros
et al., 2010). The sound measurement was also required to be recorded with a sample
frequency of 44.1 kHz and 16-bit resolution. The Nedis MICMJ100BK microphone and the
Xtrfy SC1 USB audio device were able to fulfill these criteria as well as being low price units
(with a total cost of approximately €30). The criteria for the particle sensor were that it must
be capable of registering parallel measurements of PM2.5 and PM10 with a relative error of
maximum 15%, and being appropriate for outdoor measurements in a Swedish climate
ranging from −10 to +40 ℃. The Nova Fitness SDS011 met these criteria (Badura *et al.*, 2018;
Budde *et al.*, 2018) and was as well in a low-cost range (approximately €30). The criteria for
the temperature and humidity sensor were that humidity should range from 0 to 100% RH
(relative humidity) and temperature range from −30 to 40 ℃, with sensor sensitivity of 0.1%

RH and 0.1℃. DHT22 was found to fulfill these criteria and being low-cost (approximately €10). The criteria for the wireless 4G module were that it should be a USB device supporting the Long Term Evolution (LTE) standard on a multitude of frequency bands (B1/B3/B7/B8/B20/B28) providing LTE FDD packet data service with up to DL150Mbit/second and UL50Mbit/second data transferring speed with transmitting power of up to power Class 3 (+23dBm). The Huawei E3372h-320 met these criteria and was also in a low-cost range (approximately €40).

The Raspberry Pi OS with Linux kernel 5.4.72 was used with additional Python applications using different libraries such as SPIdev, Socket and PyAudio. All sensor data were gathered at the edge device and encapsulated into a JavaScript object notation (JSON) formatted object together with timestamps, identity and message type information. The JSON object was sent to a cloud server over the internet, simultaneously the raw data were saved at the data recording device.

3.1.1 Sound measuring device. The audio interface Xtrfy SC1 was used to record noise data. The Xtrfy SC1 is a low-cost USB external audio interface with a mono-microphone input, capable of digital audio recording at up to 96 kHz sample frequency and 24-bit resolution. Connected to the microphone input of the audio device was a low-cost Nedis MICMJ100BK omni-directional microphone. All audio recording was done in 44.1 kHz sample frequency and 16-bit resolution. The Raspberry Pi collected data for 10 s and then waited for 20 s (while the particle sensor was running). All signal processing needed to extract relevant data was done in the Raspberry Pi using PyAudio (0.2.11), before these data were transmitted to the database, see Figure 4.

The Nedis MICMJ100BK microphone is a small-diaphragm microphone having a signal-to-noise ratio of 50 dB, a sensitivity of −54 dB and a frequency range of 100 to 10 kHz. The frequency response and linearity were measured in an anechoic room using one Tannoy Reveal studio monitor and playing a rising chirp sound and compared to one small-diaphragm condenser microphone with known frequency response and linearity (one Milab VM-44). As the correct frequency response of the VM-44 microphone was known, nonlinearities in the speaker could be compensated for when analyzing the frequency response of the MICMJ100BK. The linearity of the frequency response of the Nedis microphone, see Figure 5, was deemed to be linear enough not to have a major impact on the noise measurements for the present study. Also, the frequency response below 100 Hz was quite accurate and linear compared to the reference microphone. For frequencies above 5 kHz, the linearity was not good; however, the microphone was considered adequate for the noise measurements used in the present study as lower frequencies are the main problems in a construction setting (see discussion in Ballesteros *et al.*, 2010).
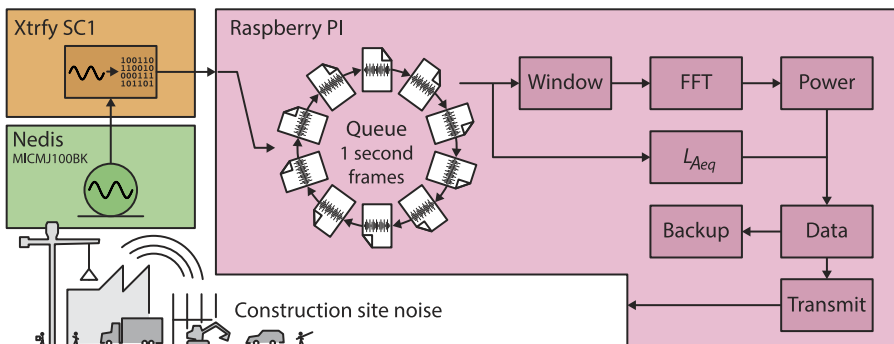
The digital audio data from the audio device were in the Raspberry Pi 4B segmented into 1 s frames and put in a queue for signal processing. In the Raspberry Pi, two parallel strands of signal processing were performed, resulting in two different noise estimates. These were (1) power in 1/3 octave bands and (2) LA_{eq} level. The first stage of signal processing divided the 1 s audio frame into smaller windows and used fast Fourier transform (FFT) to divide the signal into different frequency bands, resulting in 24 bands from 22 Hz to 5 kHz, on which the power was calculated for each band individually. Parallel to this, the LA_{eq} level was calculated. LA_{eq} is the equivalent continuous A-weighted sound level, i.e. the sound level in decibels having the same total sound energy as the fluctuating level measured. This resulted in detailed noise measurements for different frequency bands as well as average noise level. All measurements (power in 24 frequency band as well as the LA_{eq} level) were saved as the hourly average, and both saved locally as a backup in the Raspberry Pi as well as compressed and transmitted to the database.

3.1.2 Particle measuring sensor. A Nova Fitness SDS011 laser sensor was used to measure particle levels. The laser inside the particle sensor hit particles as these passed through a detection area, creating a light scattering. The scattered light was transformed into electrical signals that were amplified and processed. The number of particles and the diameter of these were obtained by analysis as the signal waveform had certain relations with the diameter of the particles. Particle concentrations between 0.3 and 10 μm can be measured by this device. PM10 refers to particles with an aerodynamic diameter smaller than 10 μm, and PM2.5 refers to particles with an aerodynamic diameter smaller than 2.5 μm. The SDS011 sensor can be sensitive to humidity (Badura *et al.*, 2018; Budde *et al.*, 2018), why it was mounted inside the data recording device.

A small fan, 35 mm in diameter, integrated in the SDS011 supplied the sensor with air. The fan ran for 20 s while the sensor collected particle data for PM2.5 and PM10. When the measurements were done, both the fan and the particle measuring sensor were turned off for 10 s, resulting in two measurements every minute. This periodic cycle of the particle measurements was used to reduce noise and vibrations caused by the fan that otherwise negatively affected the noise measurements.

3.2 Sonification of construction site data

For the sonification design sketch, both noise level and particle matter data had to be simulated due to communication issues between the database and the sonification software. The simulated data were, however, similar to the real-world measured data with 24-h periodicity. The sonification was designed for three frequency regions (low, mid and high) by

Figure 5.
Frequency response comparison between the reference microphone used, Milab VM-44 (blue) and the low-cost microphone, Nedis MICMJ100BK (red). Based on this, it was decided that the low-cost microphone was sufficient for measuring noise up to 5,000 Hz
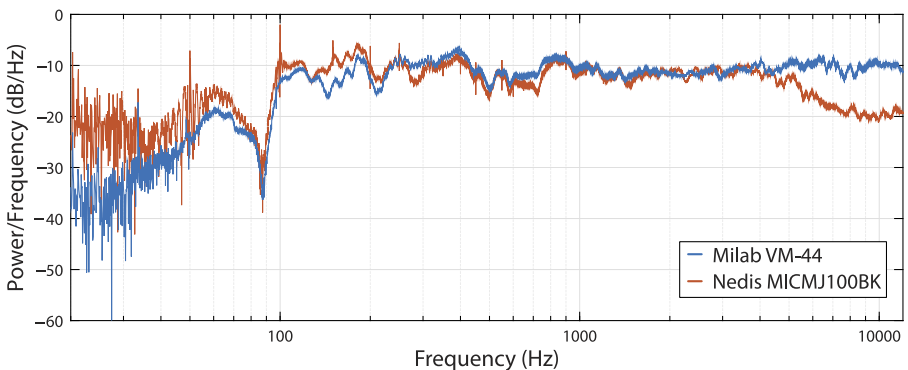
averaging the noise levels in the corresponding 1/3 octave bands, and the sonification of particle matters represented an average of the levels of PM10 and PM2.5. The reason for averaging the two measurements of particle matter was that the SDS011 tends to overestimate the measure of particle matter (Budde *et al.*, 2018). Data representing three locations at a construction site were simulated for the user evaluation.

SuperCollider (version 3.11.2) was used to create the sonification of the measured construction site noise and particle levels. SuperCollider is a real-time audio synthesis environment and programming language (McCartney, 1996, 2002) suitable for interactive and parameter mapping sonification. Data, i.e. sound level in three frequency ranges as well as particle matter levels, from each individual data recording device were connected to corresponding synth definitions in SuperCollider. The data manipulated the sound parameters in the synth definitions independent of the other sensors and synth definitions. The number of synth definitions used in SuperCollider was dynamically increased as new data recording devices were connected. The simulated data were transmitted via the open sound control (OSC) (Freed, 1997; Wright, 2005) to SuperCollider.

SuperCollider and electronic sounds were used for the sound design, as this provided extensive control over sound parameters and enabling parameter mapping to the data. The sounds were designed to create an immersive electronic drone sound capable of creating an emerging musical sound for the entirety of the measurements at the construction site, which real-world sounds would hardly be able to provide without turning into chaotic noise. Furthermore, the use of real construction site sounds would complicate the scaling of time when listening to one week of data in a few minutes, in a way that synthesized sounds would not. The sonification should be able to bring forth individual sounds and changes to these sounds simultaneously for a multitude of locations at the construction site. In SuperCollider, each synth definition used to represent noise levels consisting of three saw-tooth waveforms, one of these on the fundamental frequency and the other two detuned above and below the fundamental frequency. The sound of these were mixed with a sinusoid waveform one octave below the fundamental frequency, as well as white noise. The mix of sound sources were then sent to a low-pass filter before sending to an output module, which mixed all sounds from the synth definition with some additional reverberation.

Within each synth definition, a number of sound parameters were mapped to the data, see Figure 6.

(1) The pitch of the fundamental frequency was quantized to create a better musicality of the sonification. The tones used were C, Eb, F, G spread over almost eight octaves (i.e.
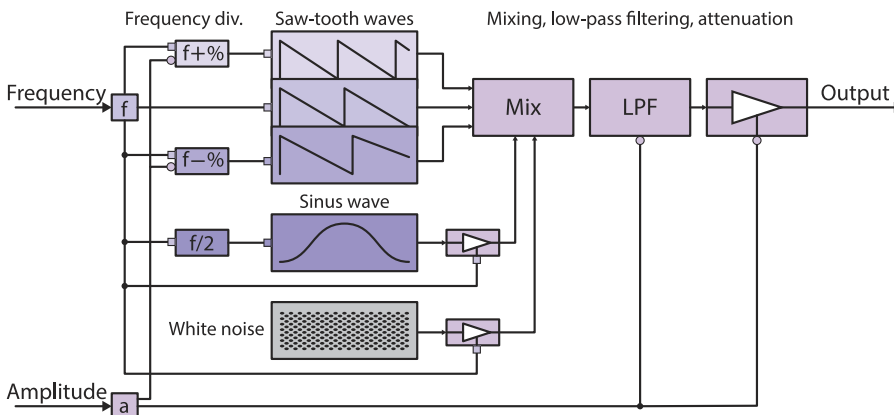
Figure 6.
The structure and signal path of the synthesis in the synth definitions, with saw-tooth waveforms, sinusoid waveform, white noise, mixing, low-pass filtering and attenuation mapped to the input frequency and amplitude data

from Eb at 38.89 Hz to *G* at 6,271.93 Hz). These tones were chosen for creating overall pleasant and relevant harmonics (Pallesen *et al.*, 2005). The pitch registered by the data recording device was mapped to the discrete steps in frequency of the sonification, with increased pitch for higher frequency. This created a tonal approximation of the frequencies picked up by the data recording devices, creating a musical drone sound rather than exact representation of frequencies.

(2) The frequency measured by the data recording device was also linearly to exponentially mapped to the sound level of the white noise, with higher sound level for the noise with increased frequency. This mimicked a richer high frequency content when sounds at the data recording device location contained more noisy attributes, and thus altered the overall timbre of the sonification. The change to more complex timbre that the addition of noise created, should create a larger response in a listener compared to the simpler less energy-rich timbre used at lower sound levels (Iakovides *et al.*, 2004).

(3) The frequency information from the data recording device was linearly invertedly mapped to the sound level of the sub-octave sinusoid wave, with higher sound level for low frequencies to completely attenuated for frequencies above 500 Hz. This was used to amplify the low-frequency harmonics that can be caused by machinery or idling engines. As an example, the firing rate of a diesel engine is typically below 100 Hz (Roberts, 2010).

(4) The sound level from the data recording device was linearly mapped to the cutoff frequency of the low-pass filter, with lower cutoff frequency for lower sound levels. This approach was used to create a softer and more dull timbre of the sound, when sound levels at the location of the data recording device were lower. A duller timbre is less activating or engaging for a listener compared to a more energy-rich timbre (Juslin and Laukka, 2004).

(5) The sound level from the data recording device was also linearly mapped to the sound level from the synth definition, with louder sonification for higher sound levels and panned in stereo (left and right) according to the location of the data recording device. This was used to recreate the impression of varying sound levels at the specific location (like Berger and Bill (2019) but simpler), and louder sounds tend give a higher activity (a higher arousal level) in the listener compared to a lower sound level (Volioti *et al.*, 2016).

(6) The sound level measured by the data recording device was finally also linearly to exponentially mapped to the fine-tuned pitch of the additional slightly detuned saw-tooth waveforms, with a higher degree of dissonance for higher sound levels. More complex harmonies and more dissonant chords are experienced as more unpleasant (Pallesen *et al.*, 2005) and activating (Iakovides *et al.*, 2004) compared to harmonious chords. This was done to mimic the experienced disturbance from loud sounds at the location.

Another synth definition was created to sonify the levels of particles, i.e. levels of PM2.5 and PM10. A high frequency popping sound was designed to sonify these data. This synth definition created randomly occurring (stochastic) clicks or impulses, see Figure 7. The density of the random impulses as well as the sound level of the impulses were linearly to linearly mapped to the level of measured particles, creating louder and more intense crackling or sparkling sounds for higher levels of particles (inspired by the sonification approach by St Pierre and Droumeva, 2016). The output of this synth definition was also panned in stereo.
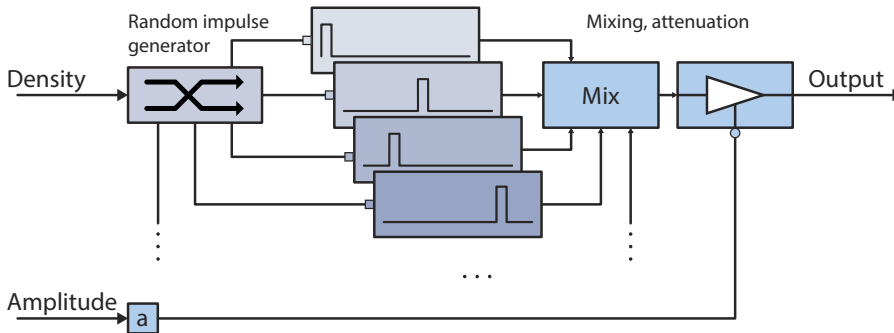
3.3 Evaluation of sonification
The sonification design draft was evaluated through a small-scale survey, in the form of a online questionnaire inspired by the BUZZ questionnaire (Tomlinson *et al.*, 2018). The

statements used in the questionnaire considered to what extent the sounds were representative of the data, i.e. how difficult it was to understand which sound represented what type of data, how difficult it was to understand the mapping between data and sounds, i.e. how the data changed the sounds, and the pleasantness of the sounds. After all sound variants had been evaluated, the questionnaire asked how relevant the respondents experienced the sonification, as well as in what situation sonification could be useful (i.e. in consulting, planning and communication). All statements were ranked from 1 (negative, such as hard or unpleasant) to 7 (positive, such as easy or pleasant). In the end of the evaluation, additional free text answers could be given.

The evaluation was performed online using prerecorded data, text information explaining the visualization and sonification, a video displaying the visualization and sonification, as well as the questionnaire statements for the specific sonification, see Figure 8. Data representing three frequency domains (low, mid, high) as well as particles from three separate locations (1, 2, 3) at the construction site were used.

3.3.1 Visualization used for the evaluation. For the evaluation of the sonification design, a simple animated visualization was used to support interpretation of the sonification, as

Figure 7.
The structure and signal path of the synthesis for the sonification of particle levels, with a random impulse generator (i.e. dust2.ar in SuperCollider) as well as attenuation mapped to the input density and sound level

Figure 8.
The online test, showing information about the sonification top left, the demonstration video top right (showing one sensor place and data in the low frequency) and the questionnaire to the bottom left

shown in Figure 8. This visualization indicated the locations of the data recording devices and presented a simple visual representation of noise levels and particle levels. In the visualization, the level of LA_{eq} was mapped to the color of the circle representing the locations of the three data recording devices individually where green represented on average low levels of noise, while red indicated high noise levels, see Figure 9. The noise levels in the low-frequency range were mapped to the line width of the circle, the levels in the mid-frequency range were mapped to the transparency of the fill of the circle and the high=frequency level was mapped to the fuzziness of the line. Finally, particle level was mapped to the number of small black dots reminiscent of visual static noise.

3.3.2 User evaluation. For evaluating the sonification, 40 persons were asked to respond to the small-scale online survey and responded 24. The respondents were selected based on their experience of managing urban construction projects and worked daily with designing and planning construction transport and responsible for all communication with future tenants, but also stakeholders in the vicinity of the construction site. The respondents include developers, main contractors, construction logistics consultants, urban planners, traffic planners and construction logistics researchers.
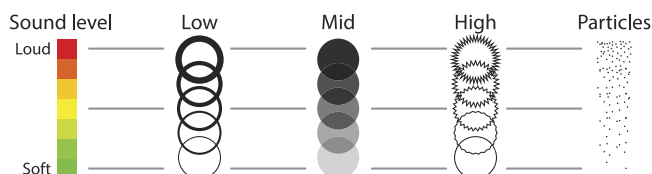
The results from the questionnaire were analyzed visually using box plots. As the data are nominal and the number of respondents low, it was decided not to use statistical analysis but present the data visually and discuss these findings in a transparent way, with examples from the free text answers.
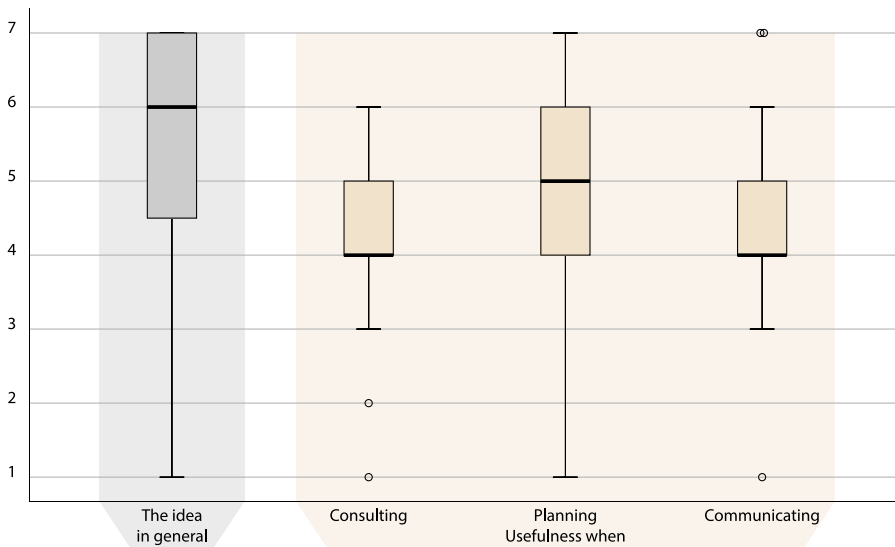
4. Analysis of user evaluation of sonification

In general, the idea of using sonification to present construction site data was experienced as relevant (median 6, range 1–7), see Figure 10. It was rated as useful in most situations relating to a construction site, and as slightly more useful when planning the work compared to when consulting or communicating this type of data. The sonification design was according to the free text answer of one of the respondents experienced as "*really helpful in construction planning and also [in] making construction transports sustainable.*"

The sound design was in general rated as not that representative of the data, see Figure 11. The overall rating for the sonification of high frequencies (median 5.5, range 1–7) was rated more representative compared to the other. The sonification of high frequencies contained white noise as well as tones, which might explain that this sonification design was experienced as more corresponding to high-frequency noise at a construction site. Sonification was a novel experience for these respondents, and this inexperience might have negatively affected the understanding of the sound representation. One respondent stated in the free text answer that with more experience, "*you would probably interpret the sounds more automatically.*" The rationale behind the sonification design was to create synthesized auditory representations that could be perceived simultaneously providing multiple levels of data and information. However, this rationale was not clearly stated in the introduction to the evaluation, making it more difficult to make the connection between the sound and the represented data.
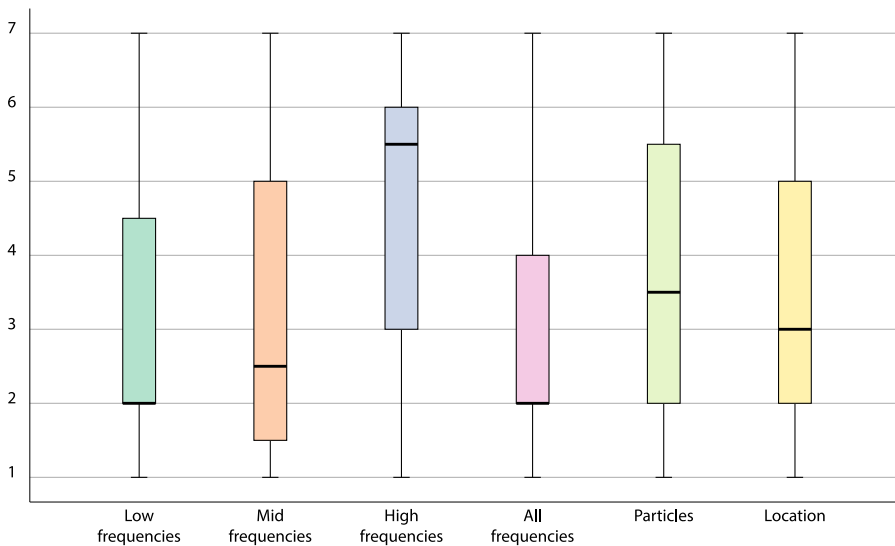
Understanding the mapping between data and sonification was in general rated as easy, see Figure 12. This result suggests that overall, the mapping approach chosen was successful. The mappings, frequency interval (low, mid and high) of the sounds at the construction site were mapped to pitch and sound level, were perceived as understandable both when tested individually as well as in combination (all). The mapping was experienced as relevant as it gave rise to insights in the data, as an example one respondent stated in the free text answer that "*the low-frequency sounds, probably heavy traffic, etc. gave rise to an increase in the number of particles.*"

Figure 12.
Box plot showing the rated understanding of the mapping between the data and each individual sonification
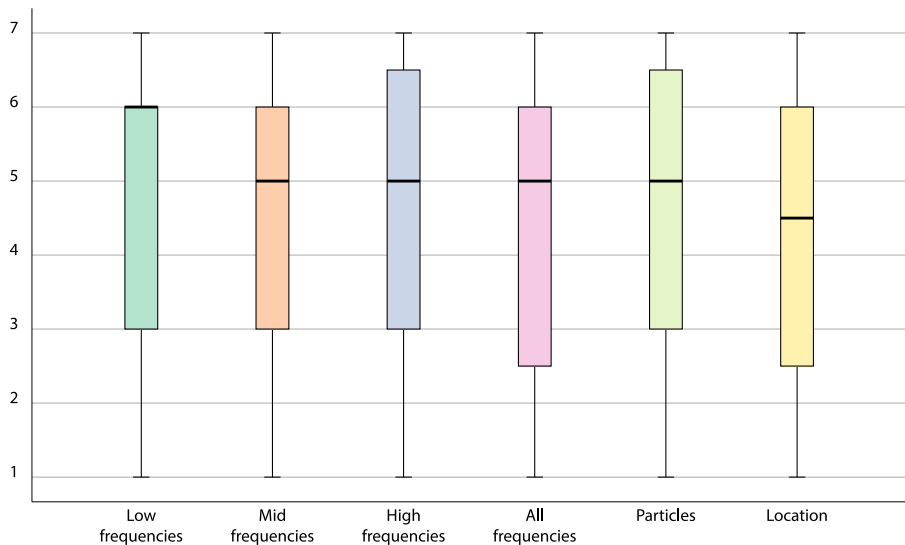
The experienced pleasantness of the sonification was in general rated as unpleasant, see Figure 13. The mid (median 2, range 1–6) and the high (median 2, range 1–6) frequencies were in general experienced as least pleasant to listen to. These two ranges had higher-frequency content compared to the low frequency, which created harsher sounds that might have affected the experience negatively.

5. Discussion and future work
Two research questions were introduced in the introduction, these are discussed below.

Figure 13.
Box plot showing the rated experience of the pleasantness of each sonification
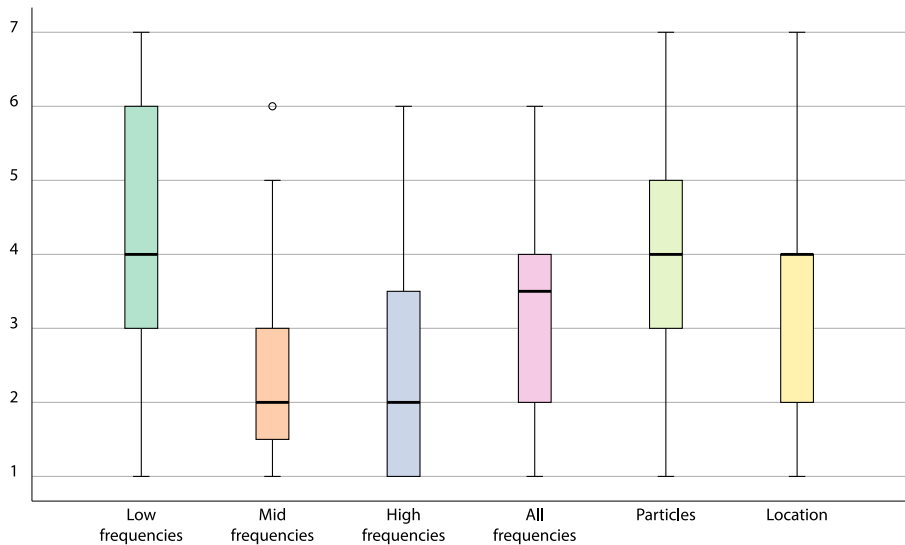
5.1 RQ1: What is the potential of using low-cost IoT measuring devices to capture data for noise and particle levels at a construction site?

The work done in this present study suggests that the data collected through the low-cost sensors is "good enough" for sonification. The estimate of "good enough" was based on the literature, as well as via discussions with the research project reference group. The choice of sensors is important as the quality of low-cost sensors and the calibration of these differ between brands and between units. The SDS011 particle measuring sensor used in the present study has been shown to be sensitive to humidity, and that the sensor tends to overestimate levels of particles, and especially so in humid conditions (Badura *et al.*, 2018). Nevertheless, as the option would be not being able to measure levels at multiple positions at a construction site due to costs, the SDS011 sensor delivers "good enough" data (Budde *et al.*, 2018), and therefore being an acceptable compromise between accuracy and price for collecting noise data in this study. Also, the effect of the slightly poorer precision in a low-cost sensor could be compensated for by calibration of individual sensors in relation to a high-quality measurement device. Similarly, using a low-cost microphone might come with compromises in terms of frequency and dynamic range. The Nedis microphone used in the present study did not have a linear frequency response below 100 Hz or above 5 kHz, and the microphone data sheet stated the frequency range to be between 100 Hz and 10 kHz. Even if sounds at a construction site exist in low frequencies, many sounds have the peak sound level around 100 Hz, and then decreases in sound level above 5 kHz (Ballesteros *et al.*, 2010). Based on this, the microphone was considered to have a good frequency response and linearity for the purpose of the present study.

In the study, the challenging environment of the construction industry was experienced. During the tests in the present study, several of these problems and the specific challenges related to the temporariness of the construction site were experienced. For example, the box containing all measurements instruments was quite small, and the close proximity between different sensors, the Raspberry Pi and the power supply, to start with caused interference and disturbances. As an example, the power supply caused interference in the microphone, usually apparent at 50 Hz, why the placement of, and screening between, different instruments inside the box is important to consider before positioning the box in the field. Also, the failure in power supply and the risk of people just moving the equipment without notifying was also experienced. There is consequently a lot of wear and tear on these devices, and it is important to quickly capture sensor quality problems (Loyola, 2019). Hence, this study shows, as the study by Bebelaar *et al.* (2018), the importance of a powerful microcomputer to the network. The Raspberry Pi 4B used in the present study is a low-cost computer and well capable of both recording and storing data, performing signal processing and transmission of data. Even though the Raspberry Pi sufficiently managed all tasks required in the present study, future work could explore different low-cost alternatives for providing reliable, powerful and low-cost data recording devices to be used at construction sites in urban environments as well as in other domains to see if other alternatives can provide the same services to a lower cost or better quality.

5.2 RQ2: How can sonification help to create an understanding of the recorded data as a basis for construction planning?

Effective stakeholder engagement is important (Mok *et al.*, 2018); however, creating stakeholder awareness of construction transport is hard (Fredriksson *et al.*, 2021b). From a construction perspective, the ability to "represent" the sound and particle disturbances of a construction site in advance was appealing to some of the research project reference group. According to the outcome of the workshop with the reference group, there are today several acoustic consultants working with the sound environment in our built environment, and the

use of sonification would complement their dialogues with stakeholders. The sonification design used in the present study was an exploration of using sonification for this type of data and for this type of user, and the idea of sonification was in general rated by the respondents as relevant and a useful tool. However, the sound design used in the sonification was not experienced as that representative of the data. A cause for this might be the use of electronic sounds rather than more realistic construction sites and manufacturing sounds. The design decision for using electronic sounds was to facilitate miniscule manipulation of the sounds, where different data from separate locations could be sonified simultaneously. Construction site noise could have been recorded and used in the sonification; however, this type of sound is often experienced as and associated with something negative (Kivelä and Hakala, 2015), which would have been counteractive to the intention with the research project. For future work, more types of data will be sonified, such as amount of traffic, direction of traffic to and from the construction site, humidity and temperature, and by designing the sounds, for example by using electronic sounds, all data can be sonified, and together form an auditory overview of one or multiple construction sites. The mapping between data and sound was experienced as understandable, and future work could further explore the use of different sound design approaches to explore how to best communicate construction site data. The use of auditory icons, i.e. short sound samples (Hermann *et al.*, 2011) signifying different events and data levels, could also be explored in future studies.

Sonification can be designed in two directions, either with a more artistic approach being more aesthetic and musical or with a data empirical approach being able to represent data more precisely (Neuhoff, 2019). Some of the sounds used in the present study were experienced as unpleasant. The sonification of the high frequencies contained noise and was rated as representative of the data but also as the most unpleasant sonification. It could be questioned whether sonification needs to be experienced as pleasant to be a useful tool for representing data. Nevertheless, if a sonification is unpleasant or annoying, there is a risk that people will not listen to, or use, the sonification regardless of how well the sounds depict data (Lemaitre *et al.*, 2012). Therefore, the user's experience of the sonification must be considered when designing sonification (Nakayama *et al.*, 2017). The tones used in the present study were chosen to provide a pleasant and relevant musical harmony (Pallesen *et al.*, 2005). However, sometimes, these intervals become small (a major second), which might have been experienced as less pleasant for some of the respondents compared to the perfect fifth or minor third also used. Therefore, future work should further explore the use of intervals and harmonies in future work. In this study, the idea of sonification was in general rated as relevant and a useful tool when consulting, planning and communicating. The focus of the evaluation performed within the present study was sonification; however, the sonification was presented along with a simple visualization. The use of visual information and the combination of visualization and sonification should be further explored to give a better understanding of how these two ways of representing data best can be combined.

6. Concluding remarks
The purpose of this study was to explore how sonification can support visualization in construction planning to decrease construction transport disturbances. This was done by setting up a data recording device, designing a sonification and evaluating this with relevant users. The results from the evaluation of the sonification, the outcome from the literature review as well as from the workshop with the research project reference group, showed that the low-cost sensors used could capture "good enough" data, and that the use of sonification for representing these data was experienced as a relevant and possible useful tool in construction planning and construction logistics; however, it was also found that there is a need to further evolve the sonification design and better communicate the aim of the sounds

used. The amount of data was limited to one site only, and the number of users in the sonification evaluation was rather few. Thus, future work should also evaluate the use of sonification of simulated, or preferably historic, construction site data from several sites and widen user evaluation, to include by both practitioner and citizens stakeholders.

The implication for research is the interdisciplinarity of the study, i.e. how it is necessary and possible to combine the research areas of construction logistics, sonification and urban planning to solve urgent societal issues such as increasing construction transport disturbances due to densification of urban areas. *The implication for practice* is that the study presents new ideas of how to support visualization with sonification planning the actual construction work and its impact on the vicinity of the site. According to the reference group sonification, with an updated sonification design based on the feedback given would be a useful tool for planning and scheduling of construction logistics. Presently, urban planning and construction planning focus on visualizing how it will be once it is finished, though little focus on how to handle disturbances during the construction process. This process can take up to 20 years for large urban development projects such as the Stockholm Royal Seaport or Frihamnen in Gothenburg. Thus, a child can grow up and leave home before the project finishes, and hence, it is important to increase the understanding of how stakeholders of a construction site experience the same both from a visual and audio point of view. Therefore, through improved planning, *the implication for society* is the potential to decrease noise and particle pollution and reducing negative effects on citizens by construction transport. Though, there are limitations of this study.

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