Something doesn't sound right: Sonification for monitoring business processes in manufacturing

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***Abstract*—In manufacturing processes a problem during production, such as a e.g. a broken machine, can lead to a standstill and thus to a loss in revenue or even to a contractual penalty. Monitoring staff in manufacturing and in other industries therefore usually observe their business processes with systems that present process-related events and data by using different types of data visualization. This has several drawbacks, e.g. that either users cannot efficiently perform other tasks while observing their monitoring application, or in case they look at their screens only infrequently, that they risk to miss potentially time-critical events or alerts. Therefore we propose to combine current visual-based process monitoring systems with techniques from the area of sonification (the presentation of data using sound). Many factories already contain auditory alerts and alarms, but these usually do not convey a lot of information and are often considered to be obtrusive and distracting. We developed a sonification framework that can receive events from execution engines and preprocess and sonify them according to user-defined settings and filters. Different sonification prototypes for both, event-based and quantitative data (such as KPIs), have been developed and discussed during a focus group meeting with users and scientists from the domain of industrial management and production monitoring.**

***Keywords*-Human-Computer Interaction; Sonification; Business Process Monitoring; Production Monitoring**

I. Introduction

Nowadays, it is becoming increasingly important for enterprises to be able to monitor their process executions in real-time in order to be able to quickly adapt to or, even better, anticipate potential problems and opportunities [1], [2]. Additionally, real-time monitoring enables companies to obtain a current overview over their processes', and subsequently their businesses performance. This is especially true for manufacturing and logistics processes, as a standstill in production (caused e.g. by a faulty machine or an empty stock of raw materials) can lead to a substantial loss of profit. This is why an increasing amount of data (e.g. production-related sensor data) is being monitored, a trend that is supported by the fact that modern assembly lines are becoming more and more automated, which enables increasingly automated data collection. On the other hand, machine maintenance experts are often able to evaluate if a machine is about to break down, or a specific part needs to be replaced soon, by listening to the frequencies and patterns of the sounds a machine produces, a technique referred to as vibration analysis [3]. Even though this is still an important ability for maintenance experts, nowadays such machine vibrations are often also recorded and analyzed in retrospect by using automated data analysis and visualization [4]. Furthermore, many production-related aspect cannot be monitored by listening to machines, such as e.g. stock levels or Key Performance Indicators (KPIs).
This is why in manufacturing domains, but also for other types of business processes, different user groups (e.g. maintenance staff, engineers, supervisors and managers) rely to different extents on monitoring systems that present the data mainly by applying different visualization techniques. Maintenance staff and engineers use these systems to keep constantly informed about the development of indicators and values such as machine and production-related sensor values, current stock levels of raw materials, or exceptional situations during manufacturing, for example line breakdowns. Management staff on the other hand is typically more interested in KPIs that are recalculated in regular intervals, such as current average throughput times, energy consumption or other performance related indicators that may be related to a specific production-line, but can also cover a whole plant. Monitoring these events and indicators with visualization-based systems has a few drawbacks:

- In typical monitoring scenarios, users take a look at their monitoring application every once in a while. In this case, they might see possibly time-critical events or alerts too late.
- In some environments, e.g. in large production facilities, users might monitor processes in full time. In that case, they cannot effectively perform other tasks at the same time.
- Many information are conveyed in textual form, but users can only read a certain amount of text in a given time frame.
- Especially in automated production, there can occur a high number of events and there can be many KPIs to monitor, screen space however is limited.

However, especially in smaller factories or for maintenance personnel and engineers, process monitoring is typically a passive activity, which is usually being performed while concentrating mainly on another task (in contrast to e.g. process analysis, a task that users typically dedicate their full attention to). However, visual means are often not ideal for areas in which monitoring occurs in parallel to other activities, as they require our visual focus and thus make it hard to work on another task at the same time. On the other hand, as our auditory senses have already proven to be able to support extensive and fine-grained process monitoring (such as in the case of the aforementioned vibration analysis), it does not seem far-fetched to investigate complementing existing visual monitoring system with auditory monitoring techniques. Many machines already apply auditory alarms and alerts, but these are typically designed to only convey events that require immediate action, e.g. by conveying that a predefined threshold value has been exceeded. Often they do not convey the exact nature of the alert or problem, forcing the users to check a machine or screen in order to find out if an action from him or her is really required (and which one). Furthermore, information that might lead up to an alert and that might in certain cases be of interest to users even before a predefined threshold has been reached, or such that might be important to users in certain situations but for which no predefined alert rules have been defined, are not considered. Moreover, as alerts and alarms only convey the occurrence of a (supposedly) exceptional situation that requires immediate action, they are not designed to be aesthetically pleasing but to grab immediate attention. However, especially if thresholds are defined too low and therefore *unnecessary* alerts are raised, over the course of a work day they can be annoying and distracting, especially to those people who are not targeted by the alarm to begin with.

Therefore, we suggest to combine existing visual process monitoring techniques with methods from the area of sonification in order to tackle some of the mentioned drawbacks of current process monitoring. Sonification is "‘the use of non-speech audio to convey information” [5], and according to [6], it has a few characteristics that make it especially suitable for process monitoring:

- It does not need a visual focus and can be processed passively, thus users can work on another task and get aurally informed about process performances at the same time.
- We are very sensitive to even small changes in rhythms and sequences because sound is inherently a temporal medium, while visualization is primarily a spatial medium. Therefore sonification is very suitable to convey information that changes over time, such as process-related events and alerts or KPIs (Key Performance Indicators).
- Sound is very good at attracting attention, therefore alarms and alerts usually base on sound instead of visuals.

Due to these characteristics, several researchers (such as [7]) argue that audio is more suitable than video in cases of peripheral monitoring activities (where monitoring is performed as a background task). Therefore, it seems like a logical step to complement state-of-the-art business process monitoring systems, that mostly base on visual means, with methods from sonification. However, so far there exist only a few approaches that deal specifically with this domain (e.g. [8] and [9]), but there exists research for specific types of processes, such as e.g. production monitoring [10].
Therefore, we developed a sonification framework that can receive events from execution engines and preprocess and sonify them according to user-defined settings and filters. Different sonification components for both, event-based and quantitative data (such as KPIs) have been developed that can be connected and interchanged in a modular fashion. This auditory-based prototypical monitoring system is being tested in the context of the ADVENTURE project (http://www.fp7-adventure.eu/), which focuses on creating a framework to combine and monitor virtual factories in a pluggable way with the aim to manufacture a particular product.

This paper first points out the related work in terms of process monitoring as well as sonification, especially in regards to business process and production monitoring. Afterwards, the developed sonification concept and the developed prototypes will be described. These prototypes have been discussed during a focus group interview with users and scientists from the domain of industrial management and production monitoring. The paper finishes with a summary of the results of the focus group and consequently a guide for future improvements of the sonification concept and prototypes.

II. Process monitoring and sonification

There is a wide array of different topics and challenges in business process monitoring that need to be researched. [11] investigate the challenges of monitoring the process status across the different organizations in a supply chain. According to the authors, users need real-time information about the status of production and delivery, critical events, as well as about KPIs. The collection and processing of this data is challenging, as data from different IT systems needs to be combined with data from *smart objects*, such as sensor networks. Another important aspect of process monitoring is compliance monitoring. Research such as [2] investigates how to support companies in monitoring the violation of compliance rules (e.g. laws or company-internal codes of conduct). The authors state that an important aspect of compliance monitoring is to give the users feedback on detected violations. Approaches such as [1] investigate how to detect process instances that deviate from normative behavior. The authors tackle this challenge by means of complex event processing.
These approaches have in common, that they often concentrate on tackling the challenge of the collection, processing, and aggregation of data. Although most authors state that presenting this data to the user is crucial, this is typically not the main focus of research. In such cases that consider this aspect, data representation is based on purely visual means. Thus, the mentioned challenges of visual process monitoring still need to be alleviated.

A. Applications and benefits of sonification

On the other hand, as already mentioned, maintenance experts already use their auditory senses to identify or anticipate possible machine problems, a technique referred to as vibration analysis. Crucial vibration properties are amplitude, frequency, phase and modulation [3]. The technique of sonification builds on the specific characteristics of our auditory perception, such as e.g. the ability to detect even smallest changes in sounds. Traditional application areas for sonification have therefore been areas where the users' visual focus is needed elsewhere (such as e.g. in cars, cockpits or operation theaters) or as a support for blind or visually impaired people. However, as sonifications can not only be used to draw the users' attention to something by e.g using sound as an alert, but also to convey quantitative, structural and semantic data, it is increasingly being applied as a supplement to traditional visualizations. As already mentioned in the introduction, there is hardly any research dealing specifically with the use of sonification for business process monitoring. The only exceptions seem to be our own previous research into this direction. In [9], we analyzed the data structure of business process execution data and investigated how data of similar structure has previously been successfully sonified. Building on these results, we developed a first prototype for event-based sonifications as well as a technical architecture and a GUI for multi-modal process monitoring, all of which we presented in [8]. The paper at hand in contrast presents a first prototype for the real-time sonification of quantitative data (such as sensor data or KPIs) as well as the results of the conducted focus group discussion.

Although there seems to be no further research dealing explicitly with sonification for business process monitoring, there exist approaches that apply sonification for monitoring in areas such as industrial production processes (e.g. [10]), network and web-server behavior (e.g. [12]) or computer program execution and debugging (e.g. [13]). Several studies proved, that sonification is an effective means for monitoring. In [13], sonification has been applied to support program code debugging. The authors conclude that users were able to successfully locate errors in a program that they previously thought to be correct. In [14], sonification has been applied for the monitoring of an assembly line. The authors concluded that participants of a study who had visual as well as auditory feedback were able to perceive more information than those in a visual-only group. Gaver et al. explore with their ARKOLA Simulation the production processes of a bottling plant in a multi-modal representation that combines visual and auditory means [10]. Their system sonifies events that occur during the production process by conveying real-world recordings of such events, such as e.g. a "spilling sound" in case liquids were spilled.The authors concluded that the auditory feedback helped in diagnosing problems in the production process. Both mentioned systems for an auditory monitoring of productions ([10] and [14]) concentrate on a sonification of individual event occurrences. However, in modern automated manufacturing with a high data density, quantitative KPIs increasingly gain importance over the conveyance of individual event occurrences. Specifically, for the conveyance of quantitative sensor values from machines and assembly lines, different sonification techniques and methods are adequate than for conveying purely event-based data.

B. Challenges of sonification

Of course, sonification is not suitable for all types of data and tasks. In general, as sound is primarily a temporal medium - sound can only exist over time and one cannot, unlike in an animation, freeze a discrete state in time it usually does not prove very beneficial for data that does not have a temporal dimension (like static process models). As process monitoring is per definition temporal as well, this is not a problem for the domain at hand. Furthermore, sonification is usually not as suitable as visualization when it comes to conveying concrete text or numbers. An activity name or an exact number can for example aurally only be conveyed using speech (which can be very distracting). Therefore, sonification is often rather used to convey trends and developments, while a corresponding visual display can then be used to obtain detailed, concrete information (such as exact numbers), if necessary. As pointed out by [15], complex auditory displays are relatively new and therefore, unlike for visualizations, the skills to interpret such are not widespread in our society yet. Thus, potential users of auditory displays generally require more training than those of visual displays. This challenge can be alleviated by designing sonifications as intuitive as possible, e.g. by using fitting natural sounds to convey the occurrence of certain events (so called auditory icons) or by applying intuitive mapping analogies. In order to do so, specific attention has to be paid to what data dimension is mapped to which acoustic property (e.g pitch or tempo) and how (e.g. linear or exponential). Aesthetically, auditory displays can range from being very *musical*, e.g. by conveying data by notes on a classical instrument such as a piano, to basing on abstract sounds (such as basic wave forms) or pre-recorded audio samples. [15]

Furthermore, there are certain challenges that specifically have to be overcome when applying sonification for real-time monitoring, as defined in [6]:

- Potential intrusion and distraction
- Fatigue and annoyance
- Aesthetic issues
- Comprehensibility and audibility

The first two challenges are based on the fact that users of potential auditory process monitoring systems may have to listen to them for several hours a day. Therefore, at least during *normal operation* such systems should be unobtrusive in order not to cause fatigue and annoyance. On the other hand, there are situations (such as critical warnings or alerts), in which it is desired to grab the users' attention. Furthermore, in general, the more information a sonification tries to convey, the more active attention is required [16]. This could negate one of the greatest advantages of auditory process monitoring, its possibility of passive listening that enables concentrating on parallel activities. Thus, it has to be kept in mind that humans can only process a certain number of audio streams and acoustic mappings in parallel, especially passively. On the other hand, it is desirable to aurally convey at least a certain number of parameters and events in order to free users from observing screens as much as possible. This trade off between awareness and disturbance has been researched, among others, by [10]. In any case, it is crucial to maximize the effectiveness by concentrating on sonifying only those parameters and events that are most relevant to the user, e.g. by offering customizable filtering mechanisms, and to convey the other parameters by means of visualization. The number of data dimensions and events that are conveyed in parallel can be maximized by applying principles from perception, such as the segregation of different audio streams by applying different timbres, and the avoidance of similar frequency ranges and positions in the stereo field [15].

Sonifications that are designed while keeping these factors in mind should be able to attract the users' attention when deviations or specific situations occur. Otherwise, such sonifications should be unobtrusive enough to enable the user to concentrate on his/her main task and perceive information in the background. An example of this principle could be driving a car. The sound a car motor makes during *normal* operation is usually still subtle enough to let the user concentrate on his/her main task, in this case driving, while sudden changes in the motor noise attract the users' attention and may even give an experienced driver an idea about the nature of possible technical problems.

III. Sonification Concept

Figure 1 shows a conceptual view of the proposed multi-modal monitoring concept. The general idea of the sonification concept we developed is as follows:

- The proposed system taps into event notifications that are being issued from execution engines during process execution in real-time (e.g. starting/stopping of activities, errors etc) over its API.
- KPIs that are calculated based on these individual events can either also be received from an execution engine/BPM system, or calculated by our system, if possible.
- Both data, events and KPIs, are send to the mapping component which translates the data into sonification commands, depending on the users' wishes - both in terms of what data in what level of detail he or she is interested in (filtering) and how it should be translated to sound (mapping). These options will be customized by the user over a web-based user interface (not yet implemented). Independent of the user settings, the sonifications of events and KPIs (or other quantitative data, such as sensor values) will base on different concepts:
- Events will be sonified whenever they occur, for example by playing a short melody that conveys information such as the related activity and the type of event.
- Quantitative parameters, such as KPIs or sensor values, differ from discrete events in that they are continuously recalculated (or measured), therefore they will be mapped onto continuous sound streams. These sound streams are ideally designed in such a way that during *normal* operation they are unobtrusive and hardly noticeable, however immediately draw the users' attention in case e.g. a KPI suddenly changes its value.

For both types of data, different prototypical sonification components have been created, the ones deemed most promising are presented in the following.

A. Event-based prototypes

The event-based prototypes base on the principal of musical motifs (short musical sequences). In general, for each of the different event types (e.g. activity started), a short melody consisting of three or four notes was created. We tried to incorporate an intuitive mapping from event type to melody, which is why the start of an activity is conveyed by a melodic sequence that is *rising*, and the stopping of an activity by one that is *falling*. The instrument, that a melody is played on, depends on the activity. A short video recording of this prototype can be found under: http://www.youtube.com/watch?v=SehcO8bcQqE.
First (not generalizable) experiments suggest that users are generally able to infer the event type from the played melody, but often not the activity from the used instrument. However, as users seem to be able to distinguish at least a handful of instruments, it can be expected that users might learn to identify the activities for smaller processes after a training period. This event-based prototype as well as the technical aspects of our monitoring system in general and the proposed user interface have been described in more detail in [8].

B. Parameter-based prototypes

As already mentioned before, KPIs and other quantitative data (such as sensor data) are being mapped to continuous sound streams. Therefore, during *normal* operation, the resulting sonifications should be as unobtrusive as possible in order to enable long term hearing without fatigue. A first prototype based on drone-sounds (drones are continuous background sounds), that have been synthesized in real-time, has been deemed to strenuous to listen to for a longer period of time. Background soundscapes consisting of natural sounds (such as waterfalls or birds) have successfully been applied by e.g. [12], as they are deemed to be non-intrusive while at the same time distinguishable in office environments. Thus, natural sounds such as wind or rainfall noises also build the basis for our developed prototypes. These prototypes allow the mapping of different parameters to acoustic properties of these sound loops. Example recordings of these mappings can be found under:

🔊 http://soundcloud.com/tobias_hildebrandt/

For the first prototype, three mappings have been deemed especially promising:

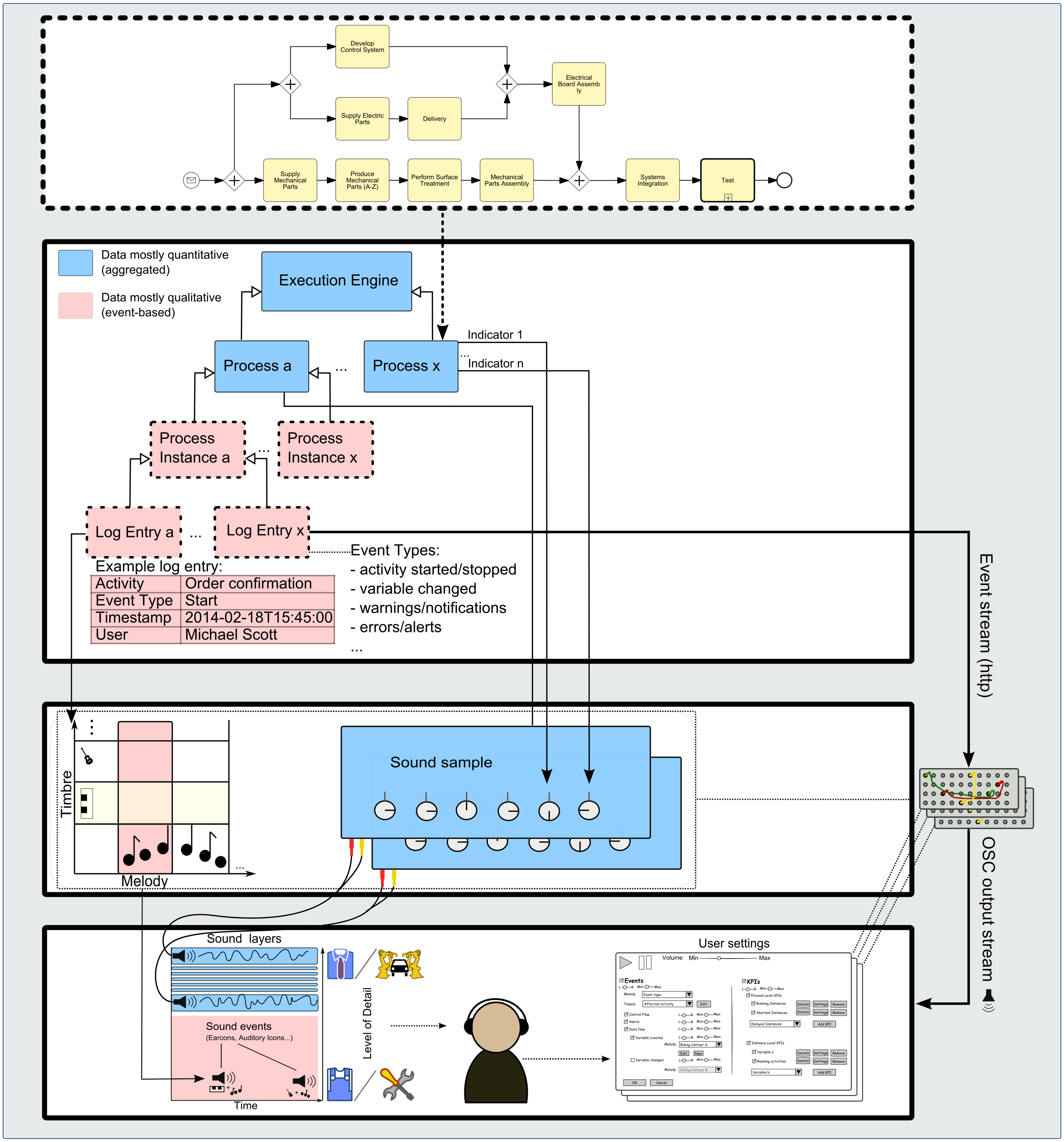

Fig. 1. Multi-modal monitoring concept

1) Playback speed: One parameter can slow down or accelerate the playback speed of the background sample (in this case a recording of rain sounds), which leads to a lower or higher pitch. [1]

2) Multiplication with sine wave: One parameter is mapped to the frequency of a sine wave, which is multiplied with the background sample. This leads to a modified envelope (the development of the amplitude over time)

[1] direct link: https://soundcloud.com/tobias_hildebrandt/kpi-sonification-playback

of the background sample. [2]

3) Multiplication with formant: One parameter is mapped to the frequency of a formant synthesizer, which is multiplied with the background sample. This also leads to different envelope modification of the background sample. [3]

In first (not-generalizable) evaluations participants were usually able to identify the points in time when a parameter changed its value (and thus influenced the sound file). For both wave-multiplication mappings (2 and 3) participants seemed to be able to recognize intuitively if the value was increasing or decreasing, this direction could however not be recognized without instructions for the mapping on playback speed (mapping 1). A rising value in mapping 2 has been associated by participants with something getting increasingly urgent, which makes this mapping suggest itself for parameters that are related to warnings or alerts. Mapping 3 conjured up associations with ”static noise” or ”something that is broken”. Therefore this mapping might possibly suggests itself for parameters that are related to critical events or states, however keeping in mind that it was also deemed artificial-sounding and unpleasant. For mapping 1, no salient association has been observed. The most promising approach, mapping 2, has been selected for further evaluation in a focus group.

IV. Focus group

After a generic and flexible framework for the preprocessing and sonification for process data had been developed, our next step was to find out which sonification types (sonification of individual events vs. aggregated parameters) are suitable for different user groups (e.g. technicians, supervisors) in different settings (e.g. factory floor, office) and in different scenarios (e.g. manual versus automated production). Furthermore we were interested in general constraints on auditory process monitoring in such environments, and in suggestions regarding our prototypes. The methodology that seemed to fit such a semi-structured discussion best seemed to be a focus group.

A. Methodology

The focus group consisted of two moderators and six participants from different European countries. The main goal for the selection of the participants was to discuss auditory process monitoring in manufacturing from different angles, which is why the focus group consisted of practitioners as well as researchers. In order to be able to differentiate the monitoring needs and requirements for different manufacturing industries and company sizes, we approached members of a consulting and systems development company who deal with different types of companies and thus different production monitoring scenarios. This group of practitioners was complemented by a participant who has in-depth knowledge of process monitoring in his specific domain. The following persons participated in the focus group discussion:

- Participant A is the operations and improvement manager at a medium-sized engineering and manufacturing company. He has been able to gain broad experience in monitoring and improving business processes, specifically concerning quality standards.
- Participants B and C are the directors of a small company that provides training, consulting, and systems in the area of production monitoring. Participant B, the managing director, has over 20 years experience in control systems within the manufacturing industry. Participant C, the technical director, has broad experience as a control systems consultant as well as in information communications technology. Participant D works in the same company as a development manager.
- Participant E is an associate professor and research project manager in the area of business process engineering and industrial management at a university, participant F is a researcher at the same department.

The focus group interview was structured by a couple of open questions while the moderators asked further questions if deemed necessary. The discussion was started by giving a short introduction into the general topic of sonification and our proposed concept. Afterwards, short audio recordings of the event sonification prototype and the parameter-based sonification prototype were presented. The reason for this was to enable the participants to familiarize themselves with the concept and possibilities of sonification, but also to receive feedback on the prototypes. Following the discussion on the presented prototypes, the participants were asked if they could imagine (a) the usage of sonification for production monitoring in general and (b) the concrete application of the two presented prototypes/concepts. A more detailed discussion concerning which kind of sonification would be suitable for which user-group under which constraints followed, concluding with feedback and suggestions. The following subsections summarize the results of these discussions and quote noteworthy statements.

B. Benefits and challenges of sonification in production monitoring

Several potential challenges for the usage of sonification in production monitoring, independent of the developed prototypes, were mentioned:

- Deaf people are not able to hear sonifications. (B)
- In many production environments people have to wear noise protection. (A) - Response: Noise protection headphones can be used to transmit sonification. (B)
- Visual displays are very contained (spatially), audio travels and can therefore create noise pollution. On the other hand, employees could use headphones. (C)
- Previously, many machines conveyed verbal warnings that have been deemed too irritating and have been deactivated. (B) - Response: Non-speech sonifications are

[2] direct link: https://soundcloud.com/tobias_hildebrandt/kpi-sonification-sine-wave

[3] direct link: https://soundcloud.com/tobias_hildebrandt/kpi-sonification-formant

different than speech as speech needs to be processed actively, while tones can be processed more passively. (D)

In general, it seems that auditory process monitoring is already an accepted technique in the manufacturing sector:

- ”On the other hand, quite often some processes already DO have sound. So if you walk past it, it will go ”BIP BIP” and you know everything is fine.” (B)
- ”Sometimes when our machines broke down, when it’s missing cork stoppers, for example, it spreads a red light. Sometimes our customers ask us to introduce a buzzer. Alarm.” (A)
- ”Perceptually, what it is, is: previously, you would have people working in a factory for 25 years, and they would know things by sound, by smell, these sorts of things. What we’re doing is, removing the need for the 30 years, we are taking the knowledge. But we are still using the same almost holistic approach, where you are listening instead of actively doing things, and you could still properly hear. But you’re taking the knowledge, you are already doing the knowledge, but instead of (,) you are still using the same method that the experts used, it’s just (,) in a different world.” (D)

To summarize: a few challenges concerning the usage of sonification in production monitoring have been mentioned, however most arguments have subsequently been weakened by other participants. Furthermore it seems that auditory monitoring already has a place in production monitoring where multi-modal monitoring combining different senses has even been described as *holistic*. Furthermore, customers have been specifically asking to equip machines with auditory warnings.

C. Remarks on event-based prototypes

After the presentation of the event-based prototype, the participants were asked if they would be able to identify the different event types in the presented prototype, and possibly even the related activities. Several of the participants (but not all) stated that they would be able to, while a few comments on the presented prototype have been made:

- There is a limit to how many different instruments can be remembered and distinguished. (C)
- ”Just to play devil’s advocate - what if somebody said: I already have something that beeps in a negative way, when something is wrong? If somebody said that, what would be the counterargument?” (C) - Response: ”It is different - suppose a machine is working, it seems that everything is OK. But you can say, there is something in the movement not normal (Participant imitates machine noise). Something strange. In a situation like that, you can imagine the normal pattern. You need to correlate this, if you correlate it, you can identify the difference.” (E)
- A sonification of this type can get annoying, depending on the frequency of sonified events. (C)

To summarize: most participants mentioned that they would be able to at least identify the different event types from the played melodies while this seems more difficult for the related activities. A few critical remarks have been made, which will be addressed later in this chapter.

D. Remarks on parameter-based prototypes

During the presentation of the KPI-based prototype, the participants were ask to identify changes in a fictitious KPI by noticing changes in the resulting sonification. Most of the participants were able to do so without further instructions. As this second prototype is more subliminal than the first, event-based one, concerns regarding the attention that is necessary to perceive changes were raised:

- It should be tested if people could still hear changes in sound while they are talking to other people. (D)
- The monitoring personnel would have to actively pay attention to derive the desired information from the sonification. (B) - Response: ”There is a part of your brain which kind of tunes in into that background, which is like: danger! You know, you are kind of like, something’s not quite right.” (C)
- Instead of mapping to natural background sounds, the KPIs should be mapped to music in a play list. (A)
- The KPIs can be mapped to several acoustic parameters of played music (such as low-pass-filters). (D)

To conclude: at least several of the participants seemed to be able to notice sonification-induced changes during audio playback. Participants raised suggestions regarding further testing and new sonification methods for future prototypes.

E. Auditory-process monitoring in different scenarios and settings

In general, all participants claimed that they believe that sonification can be useful in production monitoring, however only under certain conditions and in specific scenarios. One participant suggested that a possible sonification in production monitoring would have to go beyond already existing auditory alarms and offer something new (B). During the course of the discussion it became clear that the potential user group (factory workers, maintenance staff, engineers or supervisors and managers) as well as the work environment (on the factory floor or in a separated office) both heavily influence the circumstances under which auditory process monitoring is beneficial. Concerning the usage of sonifications on the factory floor level, one participant recounted his personal experiences on working as an operator for a big manufacturer of consumer electronics several years ago.

> ”We constantly had a sound testing booth. The whole floor could hear it. The noise was not much different to these (remark: the presented event-based prototype). As an operator: first you kind of notice it. But in factories, unlike what we are doing, which is sort of creative work, you are doing a mechanical job. You got into a different mindset. As long as the frequency of it isn’t too infrequent or changing, its OK. If its quite constant, as a factory worker, it’s OK. So I dont think, being annoying I dont think you

should worry too much about. From a maintenance or a operator perspective, you have got so many annoying noises around anyway, doesn't matter." (D)

At a later point however the participant remarked that such a noisy environment also poses challenges to sonification in terms of perception. Later he remarked that the sonification of the statuses of individual machines could prove difficult in case the sound source would be located at those machines, unless the machines are far away. He therefore concludes that sonification should concentrate on aggregated KPIs, such as line-wide KPIs or even factory-wide KPIs. Another participant suggested to convey an auditory alarm to maintenance workers in case there is a problem with machines (C). However, even though most participants seemed to support the idea of sonification on a shop floor level, one participant stated that such a system would be too disturbing (B).
In contrast to the application of auditory process monitoring on the shop floor level, the participants seemed unambiguously positive towards its usage in office scenarios (such as e.g. in maintenance or supervisor offices). One participant stated that auditory process monitoring might be beneficial to supervisors to free them up from looking at a screen, if designed in a subliminal fashion (C). This statement was complemented by another participant:

"If it's one guy in an office, and he's monitoring something, then maybe yes. Someone on the shop floor, no." (B)

The same participant continued to suggest that a sonification of the current status might make sense in engineering offices, as they are typically separated from the factory floor. Independent of the workplace (shop floor vs. office), the participants also suggested that the requirements for and potentials of sonification differ depending on the type of data that is to be conveyed. Several participants are positive towards the sonification of individual events in case they are conveyed in quite regular intervals (B, D). One participant suggested to keep in mind which action is desired from the user when monitoring KPIs. He exemplified this by stating that the sonified KPIs should convey data that goes beyond what could be conveyed by mere alarms. He further stated that a performance analysis with the aim to improve production processes is usually done in a weekly basis on historic data, not in real-time. Another participant suggested to use sonification to convey the statuses of Kanban systems (E)

F. Summary and discussion of results

To conclude, during the focus group participants stated several points that need to be considered when developing sonifications for this domain, specifically that they have to be subliminal, and that they have to offer more than plain auditory alarms. Particularly, the proposed system has to take into account which actions have to be taken by the users when they hear changes or events conveyed aurally. A critical remark has been made concerning the differentiation of different instruments. This is a valid remark, as even though recognition in sonifications typically increases with training time, the number of different activities that can be identified in such a way are limited. For small processes with only a handful of different activities, the presented approach might however provide a valid method. The remark, that the presented approach could possibly be annoying, depending on the frequency, cannot be dismissed easily. Therefore, as already mentioned, the presented approach is probably only suitable for processes that consist mostly of manual tasks and that therefore exhibit a relatively low frequency of occurring events. Concerning the KPI-based prototype, it needs to be evaluated if the subtle changes can still be perceived (and interpreted) during operation in a factory. Other mapping techniques, such as the mapping onto music files, need to be investigated.
Concerning potential scenarios, it seems apparent that a majority of the participants does not see the main potential of sonification for production monitoring on the factory floor, but instead mainly in offices of engineers and production supervisors, although there seem to be some conflicting opinions regarding this. All participants however seem to agree on the usefulness of sonification in engineering and supervisor offices, both for event-based (as long as it offers more insight than auditory alarms, and its frequency does not vary too much) as well as for sonification that bases on quantitative parameters (as long as it is subliminal). Concrete scenarios that have been mentioned include the sonification of machine statuses for maintenance personnel, the sonification of factory- or line-wide KPIs for supervisors/engineers and Kanban sonifications.
Fig 2 summarizes the suitability of different sonification approaches (event-based vs. indicator-based) for different user groups and different data densities.

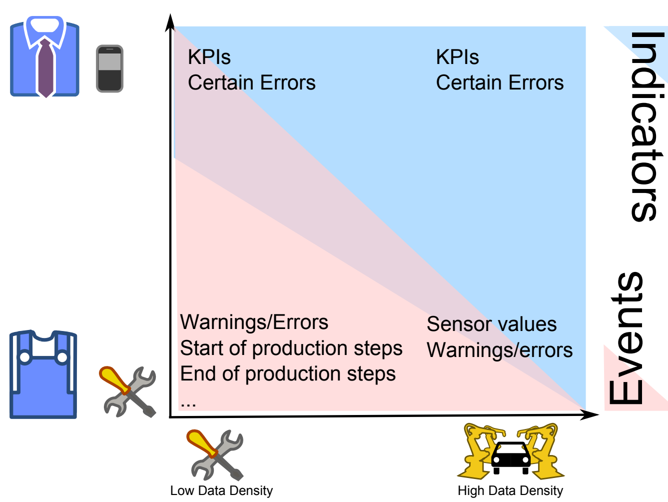

Fig. 2. Suitability of sonification approaches for different scenarios

V. Summary and Outlook

Even though our auditory perception has been successfully used for the monitoring of business processes, especially in manufacturing environments, its usage often does not go beyond simple alarms and alerts. This is surprising, as our auditory perception is especially well suited for this task. A major reason for this is that audio can be perceived passively, while visuals usually need active attention. This is why sonification has been researched in several monitoring scenarios, however specifically for business process monitoring and for production monitoring there exist only few research approaches into this direction.

This paper presented a sonification-based monitoring concept, for which a generic and flexible framework has been built. Several prototypes for both, event- and parameter-based monitoring have been created and evaluated within a focus group discussion. During this focus group, potential scenarios for auditory production monitoring have been discussed. A consensus has been reached that such a system would have the highest potential in office scenarios (for different user groups such as engineers and supervisors), while its usage on a shop floor level was more controversial. Furthermore, it was suggested that the system should be designed in such a way that it is both unobtrusive and not distracting, but alarming and attention-grabbing when necessary. This might put limits on the presented event-based sonification concept based on melodic motifs and suggests that the also presented natural-sound-based approach of the parameter-based sonifications might be more promising, as such sounds are generally considered to be more unobtrusive. This links with the fact that several participants suggested that an auditory monitoring system has to go beyond simple conveying of event occurrences - something that existing auditory alarms already offer, albeit in a less detailed and fine-grained manner. Furthermore, as suggested, typical users of such a monitoring systems are likely to be engineers and supervisors instead of line workers, and thus are more likely to be interested in aggregated quantitative parameters anyway.

Therefore, we will build on the presented concept of using natural sounds to convey KPIs and sensor data, and try to incorporate important events such as warning or errors into this system where necessary. In general, the system will however focus more on aggregated data and states, as these have been mentioned to be more interesting to the potential user groups. A sonification concept similar to that developed by [12] seems best suited to fulfill these requirements. In their system, different types of natural sounds are integrated into a homogeneous *soundscape*, like it can be found in nature (e.g. a forest environment containing sounds of wind, rain and birds). Instead of mapping different parameters onto one of such streams (e.g. wind), we will use different prerecorded samples of the same element that represent different states (e.g. wind in different strengths, from breeze to storm) that will be exchanged in real-time, depending on the values of KPIs or sensors. Instead of using short melodies to convey event occurrences, it might be better suited to use sounds that fit into the *acoustic environment* such as recordings of frogs or birds. This should result in a sound stream that is unobtrusive and possibly even soothing. This as well as how effective the resulting sonification will be in directing the users' attention and conveying information will be tested in quantitative evaluations.

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