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The Musician's Context Ontology: Modeling the context for smart musical applications

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A R T I C L E I N F O

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A B S T R A C T

The paradigm of context-aware computing allows storing situational and environmental information in such a way that its interpretation can be done easily and more meaningfully. In turn, this understanding is used to anticipate users' needs, and proactively provide them with situation-aware content and experiences. Whereas context-awareness has been investigated extensively in the computer science and IoT disciplines, it has been largely overlooked by the research community dealing with musical interfaces design. Existing musical instruments are not equipped with the ability to understand the context around them, namely who is the musician playing them, what musical activity is being conducted, as well as where and when. Enhancing musical instruments with context-awareness has the concrete potential to enable novel kinds of interactions between musicians and musical content in a large variety of situations, from playing alone to playing in a group, from music learning to music composition. To accomplish such a vision of intelligence embedded in musical instruments it is necessary to model the context around their users. In this paper, we present an ontology devised to represent the knowledge related to musicians and musical activities, the "Musician's Context Ontology" (MUSICO) to facilitate the development of context-aware musical applications. There was no previous comprehensive data model for the domain of musicians' context, nevertheless, the new ontology relates to several existing ontologies, including the Internet of Musical Things Ontology to represent Internet of Musical Things ecosystems and the Music Ontology that deals with the description of the music value-chain from production to consumption. This paper documents the design of the ontology and its evaluation with respect to specific requirements gathered from an extensive literature review and interviews with musicians. The utility of the ontology is demonstrated by a smartphone application that enables to search for musicians based on both textual and content-based musical queries. MUSICO can be accessed at: https://w3id.org/musico#.

1. Introduction

Context-aware computing is a computing paradigm in which the information about people, places, and things collected from sensors is exploited proactively to provide users with dedicated services. This computing paradigm allows one to store situational and environmental information linked to sensor data, making interpretation more accessible and meaningful. This understanding anticipates users' needs and proactively provides them with enriched, situation-aware, usable content, functions, and experiences. Context-awareness is a core feature of ubiquitous and pervasive computing systems [1,2], as well as of the Internet of Things (IoT) paradigm [3]. Perera et al. [4] provide a comprehensive overview of this concept.

Domain ontologies have been extensively used in context representation and context-aware computing [4,5] because of their properties of sharing a common understanding of information structure among people and software agents [6]. They also allow for the analysis of domain knowledge, separating domain knowledge from operational knowledge (i.e., decoupling the knowledge from the application and program codes), and reusing domain knowledge across other ontologies [7]. A context ontology defines a common vocabulary that describes context information and is particularly useful in context-aware computing.

The availability of sensor technology, embedded systems dedicated to audio processing and networking tasks, and consolidated methods for context-aware computing have fostered the vision for a novel class of

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musical devices with advanced context awareness and proactivity capabilities, the so-called Smart Musical Instruments (SMIs) [8]. These are IoT devices dedicated to music production, encompass sensors, wireless connectivity, and embedded processing. These instruments are essential components of the so-called Internet of Musical Things (IoMusT), an extension of the IoT paradigm to the musical domain [9]. SMIs can interact, both locally and remotely, with a plethora of connected devices, i.e., Musical Things (e.g., smartphones, computers, voice-based assistants, cloud-based repositories, or other smart instruments). This enables the creation of ecosystems of interoperable devices connecting musicians with their machines, musicians with other musicians, and musicians with their audiences. Once data related to the context has been extracted from the sensing acquisition equipment, it needs to be represented meaningfully. In particular, a context model is needed to define and store context information in a machine-readable form.

Examples of commercially available SMIs are the smart guitars by Lava Music[1] and HyVibe.[2] However, these SMIs do not take into account the context surrounding a musician in a comprehensive and organized manner as proposed in the present study, resulting in applications devoid of proactive capabilities, which are restricted to a few aspects of the instrument's sound engine configuration (such as personalization mechanism).

Whereas context-awareness has been investigated extensively in the computer science and IoT disciplines, it has been largely overlooked by the research community dealing with musical interface design. The application of such concepts to the musical domain thus far has been limited to developing recommendation systems for music listening. This research was fostered by big corporations focusing on music streaming services (e.g., Spotify, Apple Music, Pandora) [10,11]. Moreover, existing SMIs and current musical interfaces are not equipped to understand the context around them, namely who is the musician playing them, what musical activity is being conducted, and where and when. Enhancing musical instruments with context-awareness and proactivity capabilities has the concrete potential to enable entirely new interactions between musicians and musical content in a large variety of situations, from playing alone to playing in a group, from music learning to music composition. To accomplish such a vision of intelligence embedded in musical interfaces, it is necessary to model the context around their users.

Several ontologies have been created for the musical domain, including the Music Ontology [12], the Studio Ontology [13], the Audio Effects Ontology [14], the Jazz Ontology [15], the Music Meta Ontology [16], the Polifonia Ontology Network [17], the DOREMUS ontology [18], the Music Notation Ontology [19], Music Note Ontology [20], or the Audio Features Ontology [21]. However, none of the existing ontologies nor the combination thereof was sufficient to comprehensively represent a musician's context, as they were not initially conceived for such a purpose. Whereas recent preliminary efforts have also been conducted to represent the IoMusT [22] and the SMIs [23] domains, a specific ontology to represent musicians and musical activities has not been devised yet, i.e., the context has not been represented yet in a structured manner. This includes profiling musicians and modeling the environment and the social context in which a particular musical activity is performed.

This paper presents an ontology devised to represent the knowledge related to musicians and musical activities, the *"Musician's Context Ontology" (MUSICO)*. The proposed ontology not only is needed for enabling the creation of unprecedented context-aware musical applications. It is also helpful to make interoperable data collected from different sources about musicians and their musical activities. Interoperability is crucial for smart musical applications' success and market uptake. It allows avoiding the fragmentation of IoMusT applications currently present in other domains of the Internet of Things.

We describe the design process of MUSICO and its first (and current) version, i.e., 1.0.0. The description of MUSICO follows the MIRO (minimum information for the reporting of an ontology) guidelines [24]. For reference, the paper reports the MIRO designations (e.g., E.9 for Ontology relationships), where the specific information item is provided. The ontology name (A.1) and its need (B.1) have been already introduced. We demonstrate the utility of the ontology by implementing a smartphone application that enables to search for musicians based on both textual and content-based musical queries. The ontology is available at https://w3id.org/musico# (A.4) with license GPL3 (A.3).

2. Related works

2.1. Related ontologies

This section describes the main ontologies (B.2) that are related to the context-awareness capability of musical instruments envisioned in [8] and that have been utilized in MUSICO. The decision for reusing some of these ontologies was mainly motivated by the intention to facilitate interoperability, while others were reused to connect MUSICO to the SMIs and IoMusT domains. Such ontologies have been retrieved through the research of literature and online resources (D.1 and D.2), as well as were evaluated as part of the design process (D.3).

The Music Ontology. The modeling of the music value-chain from production to consumption was proposed in [12] with the definition of the Music Ontology. The ontology's focus is placed on editorial metadata, such as artist's name and title associated with audio recordings. The ontology also details the major steps in the music production workflow for recorded music, from composition, through performance and recording, to release.

The Friend of a Friend Ontology. The Friend of a Friend ontology provides a framework to represent information about the users, their interests, as well as their relation to social relationships [25]. This widely adopted ontology has been also used in musical applications such as recommendation systems (see e.g., [26]).

The Event Ontology. Musical activities such as composition or performance, are an essential component of a musician's context. A suitable ontology for representing such a knowledge is the Event Ontology,[3] which has been utilized in the Music Ontology to describe transitions between states of intellectual works.

The Time and Timeline Ontologies. The timing of a musical activity (e.g., playing during the evening) is another important aspect that needs to be modeled when considering a musician's context. A widely used ontology to describe times and durations is the Time Ontology reported in [27], which is suitable for representing temporal aspects of musical activities. The Timeline Ontology[4] extends the Time Ontology to represent a finer granularity of temporal events, and was primarily conceived to be used in conjunction with the Event Ontology.

Geonames. The place in which a certain musical activity occurs (e.g., performing in a concert hall located in a city) represent an important aspect of the context of a musician. A suitable ontology for this purpose is Geonames, which contains classes for accurately describing the geographical locations.[5]

The Emotions Ontology. Emotions and mood are essential aspects of music [28]. To represent the associated knowledge we leveraged the Emotion Ontology, an ontology covering all aspects of emotional and affective mental functioning [29].

The Internet of Musical Things Ontology. The emerging field of the IoMusT consists of the extension of the Internet of Things paradigm

1 https://www.lavamusic.com/
2 https://www.hyvibeguitar.com/
3 http://purl.org/NET/c4dm/event.owl#
4 http://purl.org/NET/c4dm/timeline.owl#
5 http://www.geonames.org/ontology/documentation.html

to the musical domain [9]. This area lies at the intersection of different domains including the Internet of Things, music technology, artificial intelligence, and human–computer interaction. The IoMusT relates to the networks of computing devices embedded in physical objects (Musical Things) dedicated to the production and/or reception of musical content. The Internet of Musical Things Ontology[6] was proposed to facilitate interoperability across heterogeneous Musical Things, so for Musical Things within an ecosystem to communicate through a common language [22].

The Smart Musical Instruments Ontology. The SMIs are an emerging class of Musical Things, which encompass sensors, actuators, embedded intelligence, and wireless connectivity to local networks and to the Internet. The Smart Musical Instruments Ontology[7] was conceived to cope with interoperability issues across heterogeneous SMIs exchanging information between each other and a plethora of Musical Things [23]. The ontology relates to existing ontologies, including the SOSA Ontology for the representation of sensors and actuators [30], the Audio Effects Ontology dealing with the description of digital audio effects [14], and the IoMusT Ontology for the representation Musical Things and IoMusT ecosystems [22].

The Studio Ontology. The Studio Ontology was devised to represent the domain of technical workflows occurring in music production [13]. It is a framework consisting of a set of modular ontologies, including the Connectivity Ontology, the Device Ontology, the Mixer Ontology, the Multitrack Ontology, the Microphone Ontology, and the Signal Processing Ontology. The ontology provides an explicit, application and situation independent modeling of the studio environment and involves hooks provided by the Music Ontology.

2.2. Analysis of the related works and the need for a new ontology

The ontologies summarized in Section 2.1 were first accurately analyzed in order to assess whether one of them or combination thereof could allow to represent the domain under study. No ontology nor their combination was sufficient to represent in a comprehensive manner the context of a musician: they were not capable of representing fully the identity, activities, temporal aspects, and spatial aspects, which are the core aspects of a context as reported in [4,31].

For example, the Music Ontology [12] allows to represent the knowledge associated to a recorded musical piece (including attributes such as the genre of the piece or who recorded it), but it does not allow to represent the act of playing such a piece in a live scenario, with which instruments, at which venue and when. Moreover, such an ontology only deals with human musicians, there is no possibility to describe virtual musicians, which are instead essential in several smart musical applications. The ontology however does not accurately describe all possible roles a musician can cover, such as composer or music student. Other important details concerning a musician are not specified such as the level of professionalism or the ability to play more than one instrument. In addition, the Music Ontology does not represent musical activities other than performances, and more importantly, does not represent sufficiently the act of tacking part to a musical activity.

Similarly, while the Polifonia Ontology Network does model the event Performance, it does not focus on other types of musical events related to specific musical activities (such as jam sessions or music lessons). Moreover, although the Polifonia Ontology Network provides ways to define the role of a musician, we aimed to specify such roles in greater detail. We also focused on defining particular attributes of musicians, such as their level of expertise, degree of multi-instrumentalism, or presence of a disability. Furthermore, while the Polifonia Ontology Network allows for modeling an artist as either human or artificial, our modeling aimed for a deeper level of refinement by specifying the exact roles that an artificial agent could take in specific musical activities (e.g., a virtual teacher). We also clarify that the development of our ontology started before the Polifonia Ontology Network was published. Nevertheless, as detailed in the paper, we aligned some relevant concepts of our ontology to those of the Polifonia Ontology Network.

In a different vein, the Internet of Musical Things Ontology [22] and the Smart Musical Instruments Ontology [23] only represent the domain of devices and related applications that can be used by a musician, without however linking them to a musician (human or virtual) and to the act of playing. Along the same lines, the Emotion Ontology [29] lacks connection with musician and with the emotions and moods felt, expressed, displayed, or recognized by a musician, in particular during a musical activity.

These and other aspects are crucial for the proper representation of the musicians domain and, as a consequence, for the creation of smart musical applications for them considering the IoMusT paradigm. Such aspects were then turned into specific requirements which are listed in Section 5.1. Of course, the insufficiency of the existing ontologies was due to the fact that they were initially conceived to represent a domain different than that of the musicians. The realization of the impossibility to represent the wanted domain in an appropriate matter motivated the need for the creation of a dedicated ontology.

Nevertheless, we aimed at following one of the best practices of ontology modeling, which is the reuse of existing ontologies. For this reason, we used publicly available ontologies that already covered in part the domain under investigation, being however aware of their limitations and the need to complement them. It is worth noticing that such ontologies in turn reused other imported ontologies and, therefore, we decided to utilize also them. For instance, while there are many ontologies modeling events. We used the Event ontology because it was already imported in the Music Ontology. Similarly, for other imported ontologies such as the Time and the Friend of a Friend ontologies.

3. Methodology, audience, and scope

This section describes the methodology adopted for the design and development of MUSICO, as well as the audience of the ontology and its scope.

3.1. Methodology for ontology development

MUSICO is developed and maintained by the authors as well as other members of the emerging IoMusT research community, which is composed by leading research institutes in sound music computing and Internet of Things (A.2 and C.2). Similarly to the previously developed ontologies for the IoMusT and SMIs [22,23], MUSICO's design and development was mainly inspired by METHONTOLOGY [32] (A.6), a methodological framework comprising the following phases: (i) the specification, i.e., the identification of the audience, scope, scenarios of use, and requirements (Sections 3.2 and 5); (ii) the conceptualization of an informal model (first paragraph of Section 6); (iii) the formalization of the namespaces, classes, and properties of the ontology; and (iv) the integration of existing ontologies in a description as well as its formalization and publication using OWL2 [33] (Section 6); (v) the implementation of the ontology with an appropriate serialization language (Section 7); (vi) the maintenance of the ontology once implemented (Section 7).

Moreover, METHONTOLOGY describes three tasks, orthogonal to the six phases, which are accomplished during the lifetime of the ontology: (i) knowledge acquisition through research of related ontologies and models (Section 2.1) as well as gathering data from potential users (Section 4), to inform multiple phases of the design process, mainly conceptualization and integration; (ii) documentation of the process phases (internal) and the ontology specification (public) (Section 7); (iii) the evaluation of the ontology before its release (Section 8).

[6] https://w3id.org/iomust#
[7] https://w3id.org/smi#

3.2. Scope and audience

The role of MUSICO is to offer a data model to foster the development of intelligent musical applications to be embedded in, or used in conjunction with, musical instruments. In particular, the ontology is useful for applications within the IoMusT paradigm. Therefore, the scope of the ontology (C.1) is represented by all ecosystems forming around existing or future IoMusT technologies devised for SMIs and related musical interfaces. For the conceptual part, the target audience of the ontology (B.3) is represented by all actors and stakeholders that are involved in such ecosystems, including performers, composers, arrangers, studio producers, live sound engineers as well as musical instruments manufacturers. This is confirmed by the fact that our use cases and competency questions have been created discussing with these categories of stakeholders. Conversely, for the implementation of applications, the target audience is represented by computer scientists and developers.

4. Knowledge acquisition

The process of knowledge acquisition has been performed since the beginning of the ontology building and still today is continuously carried out. Following the results of the survey on context-aware computing reported in [4], to gather knowledge about a musician's context we focused on identity (such as the role of a musician, e.g., music student), activities (e.g., composing), as well as temporal (e.g., playing during mornings), spatial (teaching in a conservatory of music), and social (e.g, playing in group or alone) aspects. Notably, we considered both actual human musicians and software agents playing the role of a musician. The latter are particularly useful to model knowledge related to services for human musicians interacting with virtual musicians (e.g., a virtual music teacher).

Firstly, we relied on the knowledge of the first author, who is a professional musician with extensive experience in the musical domain to be represented. His view was further validated by interviewing, using semi-structured interviews, *12 professional musicians* recruited from his network: 3 composers, 5 performers, 3 music teachers, and 1 sound engineer (4 females, 8 males; mean age = 41.6, stddev = 5.8; average years of professional musical experience = 17.1). We also interviewed *2 amateur musicians*, one of them is blind and part of an orchestra of visually-impaired performers. The gathered knowledge was corroborated by insights from the second and third authors, who are amateur musicians.

Secondly, we devised a set of *uses cases* of the ontology, where the work of specific musical systems and applications is only possible thanks to the use of an ontology that models the context of a musician (see Section 4.1 below). Thirdly, we conducted a *review of the existing literature* on all aspects that could be related to a context of a musician. This included (1) existing applications of smart musical instruments (e.g., [34]) and envisioned scenarios (see [8]), (2) studies on both ontologies and other aspects of the investigated context across the dimension of interests mentioned above. The results of such a review indicated that existing ontologies neither were capable of covering the requirements of the identified use cases nor satisfied the design goal of representing concepts and relations in the context of musical activities based on computing and the network. Finally, we extensively considered *recent trends in the musical industry*, including emerging hardware products and services for musicians (with particular attention to those based on artificial intelligence).

4.1. Use cases

Hereinafter, we describe six instances of use cases for an ontology modeling the context of musicians, around which the MUSICO design is framed. The reported use cases involve systems and applications that strongly rely on the use of an ontology for the domain at hand. Notably, such systems and applications are based on the use of one or more SMIs, and may involve a cloud-based triplestore. In Section 8.3 we describe the in-use validation of the ontology by means of the implementation of one of the use cases listed below. While the other five are not yet implemented, their implementation is achievable with means similar to those used for the implemented use case. All mentioned use cases are realistic as they are strongly grounded on the results of the knowledge acquisition process, as detailed in Section 4, and are illustrative examples of how the ontology could be practically utilized.

Searching for the right musicians. A website allows musicians to search for other musicians according to their needs. The website relies on a database of musicians profiles, which gathers a large variety of information about the musician. This information becomes a set of criteria for the search. These criteria include diversity factors (e.g., gender, age, disabilities) as well as musical aspects (e.g., musical expertise level, played genres, played instruments, the names and last names of the mentors had, the places where the musician studied, the list of musicians with whom has played).

Mark wants to find online other musicians who are currently playing some music in order to play with them. The musicians he is searching for would be expert currently playing some music that has a happy mood, is of genre pop, and in G major. To perform such a search, he uses his smart guitar to record an excerpt of 30 s containing such musical features. The instrument automatically recognizes in real-time the features contained in the signal and uses them to perform a query to the website, which returns a number of musicians who are playing music that is matching those features. The website also recommends some particular musicians based on Mark's previous choices. As he wants to connect only with expert musicians who are playing instruments other than the smart guitar, he refines his search by selecting from the web interface some of the musicians listed, and then sends them an invitation to join a musical session.

Musical activities recognition. The smart musical instruments produced by the company SmartMusicKey2 are capable of understanding, from the instrument's sensors and microphones data, the type of activity a musician performs during each day (e.g., performing in concert with a band, practicing alone, attending lessons, teaching, composing). This information is stored in a cloud-based triplestore for each musician playing a smart instrument of the company worldwide. Via big data analysis techniques the company infers trends about the usage of the instrument in each musical activity and for various dimensions such as type of smart instrument and the musician's expertise level, gender, country, duration of use. The SmartMusicKey2 company then provides tailored services for each musician while conducting a given activity.

Cristina is a professional musician who every morning studies new pieces with her smart drums by SmartMusicKey2. A service connected to the smart instrument suggests her to learn a new pop song that is trendy at the moment, to be performed in her next show. The service, however, does not suggest other trendy jazz pieces because it infers that they are too difficult for Cristina as well as jazz is not a genre she plays often. The service further recommends her to read a magazine for musicians which contains an article about how to optimally learn that recommended pop piece.

Group rehearsal. An amateur rock band meets in a rehearse room every Wednesday evening to rehearse. The SMI of each band member automatically detects that its user is playing it in that location at that time together with other musicians. Through an app connected to the instrument, each musician is asked whether the activity was a rehearsal. The musicians answer positively and this information, along the temporal, spatial and social information from each instrument, is sent to a cloud database which saves it for further analysis. The app of each musician then displays the statistics related to the rehearsal activities (e.g., average duration of rehearsals, number of band members present at the rehearsal, number of repetitions of a given song or part of a song, which musician in the band performed most often an error).

The singer of the band, Pierre, analyzes every week the statistics provided by the app. He notices what are the issues encountered by the band while practicing a new song and devises some new strategies for the next rehearsal. Based on the app's data, he suggests to keep the rehearsal shorter and make pauses more often, as statistically towards the end a higher number of errors are made by the drummer as he feels more the tiredness.

Emotion-based performance. Anka is a professional smart violin soloist who is performing for an audience at the Royal Albert Hall. The soloist wears a bracelet that detects heart rate, oxygen consumption, and galvanic skin response, which are biosignals from which the user's emotion can be detected. The SMIs infers, in real-time, from both the audio signal and the biosignals what is the emotional status of the soloist at each point of the performance. On the basis of the detected emotion, the SMI wirelessly controls the stage lights, thanks to a virtual agent that implements a predefined mapping between emotions and colors. The information about Anka's emotional status is saved in a cloud-based triplestore for each performance and at regular intervals for each piece. Through an app, statistics are then provided to the soloist along with recommendations to improve her performances. Anka takes into account such statistics, which revealed that in some performances her stress level was too high and that she could not express her emotions in music optimally. The app recommends her to take a slightly longer break between a song and the other for the next performance at a large concert hall.

Social context detection. The smart drums of a professional drummer, Prateek, keep track of all the other musicians with whom the drummer plays, along with their instruments, and genres played. In particular, the smart drums can detect if the group activity is performed in a situated or remote fashion (the latter via a networked music performance system embedded in the smart drums themselves), in a duo, trio, quartet, etc. Furthermore, the smart drums understands if the drummer is playing only with musicians for rehearsals or in front of an audience, thanks to the ability to connect to other smart devices such as smartphones. All this information is collected in a cloud-based repository, and statistics about the drummer behavior are provided to him/her.

This information is useful to Prateek to relate his sources of income and the kind of performances he did. Based on this knowledge he infers that it is more economically convenient to him to perform in trio rather than in quartet. Surprisingly he also notices that the situated performances were paid less than the remote performances, and therefore he decides to play more often online. Finally, he understands that on average with some musicians more rehearsals were necessary compared with other musicians, and he decides to reduce the number of shows with them.

Intelligent music tutoring system. A smart electric guitar is capable of inferring several low-level and high-level musical features related to the way a guitarist plays (e.g., tempo, mood, chords, scales). From this information the instrument understands the expertise level of the player, monitors over time his/her progresses, and through a training program provides recommendations to improve his/her techniques.

Hyojung is a beginner smart guitarist who struggles to learn the pentatonic scales as well as the chords progressions. The instrument understands such an issues and as a result it automatically configures itself to provide specific and restricted set of musical timbres and effects chains. Secondly, a software agent plays the role of a virtual musician with whom Hyojung plays. Such a virtual musician plays a Blues backing track, over which the Hyojung can practice specific chords progressions and scales. As Hyojung improves her technique, the intelligent tutoring system suggests other backing tracks and configuration of the instrument.

5. Specification

The acquired knowledge was then analyzed to identify a set of requirements that the ontology should satisfy [35]. The resulting requirements are represented below as a list of formal requirements as well as a list of example questions that the ontology should be able to support answering [36].

5.1. Formal requirements

MUSICO should be able to:

1. Represent the concept of musician, including:
   (a) the kind of musician (i.e., either human or virtual);
   (b) the role of the musician (i.e., arranger, composer, conductor, live sound engineer, music learner, music teacher, performer, and studio producer);
   (c) the expertise level (i.e., beginner, expert, and intermediate);
   (d) the played instruments (e.g., smart guitar, smart saxophone, etc.);
   (e) the played genres (e.g., jazz, fusion, rock, metal, folk, etc.);
   (f) the moods and emotions felt or expressed while playing, (e.g., happy, sad, etc., where distinction between moods and emotions is well described in the Emotions Ontology [29]);
   (g) the relation with other musicians (e.g., a student is the pupil of his/her mentor, a musician plays in the same band of another, etc.).
2. Represent the concept of musical activity, including:
   (a) the type of musical activity (e.g., performance, rehearsal, lesson, etc.);
   (b) the time or period during which the activity occurs (e.g., the exact date and time or the period in the day, such as morning, afternoon, night);
   (c) the activity's geographical position and type of location (e.g., in terms of name of the city or the type of musical venue such as a concert hall, a conservatory of music, etc.);
   (d) the social aspects of the activity (e.g., playing alone or in group).

5.2. Competency questions

The following sample questions are meant to be asked with respect to a SMI or a broader IoMusT ecosystem based on SMIs:

1. What is the name, last name, played instrument and role of all visually-impaired female musicians living in London who are amateur and play rock?
2. Which musical genres professional musicians play more frequently when they feel happy?
3. In how many sessions the musician Cristina Ladynekt has performed with her smart microphone during a tour in 2021?
4. What are the emotions of beginner smart guitar players while learning the study number 5 of Fernando Sor's "20 studies for guitar" during lessons with Prof. Cristina Ladynekt at KMH Royal College of Music in Stockholm?
5. Which are the three virtual teachers playing piano with which smart guitar players interact most frequently while self-learning at home?

6. When is the last time the musician Sharan Giptas has rehearsed with the other members of his band "The Unicorns and Camels"?
7. How long poly-instrumentalist musicians from Tokyo play on average for recreational music making?
8. How many synchronous, displaced performances have the musicians from London performed in 2020?

Appendix B details such competency questions in SPARQL.

6. Ontology description

MUSICO has been developed incrementally through an iterative process based on continuous refinement and control of concepts and relationships. Such an iterative process followed the evolution of the knowledge acquisition phase. In the following, for the sake of clarity, we have kept the prefixes in a contracted form. To see their expanded version, please see Table A.2 in Appendix A. The very first step has been that of defining a novel namespace `musico:` to describe the core knowledge related to a musician's context. The subsequent efforts focused on the specification of the concepts that are fundamental to the domain at hand, with particular focus on the four core aspect of a context [4,31]: identity, activities, temporal aspects, spatial aspects. Fig. 1 shows a high level structural overview of the ontology.

Identity. In first instance, we categorized the musicians as either human or virtual. This crucial distinction was motivated by the fact that we wanted to represent not only human beings involved in a musical activity (e.g., composition, performance) but also software agents capable of performing a musical activity (e.g., composition via computational creativity techniques [37]). For this purpose we defined the class `musico:Musician` as a subclass of `foaf:Agent`, and within it the subclasses `musico:HumanMusician` and `musico:VirtualMusician`. The use of Friend of a Friend Ontology allows one to define many general aspects of a musician such as name, gender or age, which are useful also when representing knowledge of virtual musicians (for instance simulating a real human musician). We complemented such details about a `foaf:Person` with data properties related to disability, as this is an important factor to consider for the representation of diversity in musical contexts. Specifically, we defined the data properties `musico:has_disability` and `musico:disability_type` (the latter with the following individuals, visually-impaired, auditory-impaired, cognitively-impaired, motor-impaired). Notably, the choice of giving a user the possibility of including this privacy-sensitive information was made to enable the creation of more inclusive applications, and was the result of a direct feedback from one of the interviewed participants, who is blind. To align our ontology with the Polifonia Ontology Network, we further defined `musico:Musician` as a subclass of `pon:Music Artist`, and `musico:VirtualMusician` as a subclass of `pon:Music Algorithm`.

Subsequently, we specified the musicians into various roles. The Music Ontology already defines several roles, such as composer or conductor, as subclasses of `foaf:Agent`. However, being an ontology conceived for representing editorial data, it does not specify many other roles that are relevant to our purposes, such as a music teacher or a music learner. Therefore, new roles were added. In particular, we distinguished between studio engineers (e.g., studio producers) and live sound engineers. Moreover, for each existing or newly added role, we then specified its human or virtual counterparts. For instance, for `mo:composer` we defined its subclasses `musico:HumanComposer` and `musico:VirtualComposer`, which are also subclasses of `musico:HumanMusician` and `musico:VirtualMusician` respectively. Notably, defining who has been the mentor of a given musician is an important aspect in certain contexts. Therefore, we added the predicate `musico:is_mentor_of` (and its inverse `musico:is_pupil_of`) to link a music teacher with a music learner. In addition, we associated various data properties (with constrained values) to the concept of musician, including the expertise level (beginner, intermediate, and expert), the multi-instrumentalism level (multi-instrumentalist and single-instrumentalist), and the professional level (amateur and professional).

We then linked the concept of musician to that of musical instrument (which can then be specialized in the various `iomust:SmartInstrument` categories, e.g., `smi:SMI Electric Instrument`), via the predicate `musico:plays_instrument` (this refer to the activity of playing a real or virtual instrument depending on the human or virtual musician instance). Moreover, through the predicate `musico:plays_genre` we represented the activity of a (human or virtual) musician or a group of musicians of playing one or more musical genres [38]. For this purpose, we leveraged the class `mo:Genre` and we populated it with instances taken from the taxonomy of genres and sub-genres reported in [39] (e.g., Jazz, Folk, Rock, etc.).

Furthermore, whereas in the Music Ontology there was the concept of `mo:MusicGroup` in relation to editorial data (e.g., to represent the concept of a band such as Pink Floyd), we additionally defined other types of aggregation of musicians: `musico:MusiciansGroup` to represent a general group of musicians who perform a musical activity together, which has subclasses `musico:PerformersGroup`, which is equivalent to `mo:MusicGroup` (further specified in `musico:Orchestra`, `musico:ChamberEnsemble`, `musico:Band`), `musico:ComposersGroup` for group of composers (e.g., involved in a collaborative music composition activity), as well as `musico:TeachersGroup` and `musico:LearnersGroup` to define groups of music teachers and learners (e.g., involved in a music lesson). In addition, we utilized data properties for the class `event:Event` to represent whether an activity is conducted by only one musician (`musico:is_solo_event`) or by more than one (human or virtual) musician (`musico:is_multiagent_event`). Notably, our modeling decision was due to the Open World Assumption, because in this domain there are potentially a lot of missing data and we did not want to allow wrong inferences from the lack of data.

Activities. We defined activities as events, leveraging the Event Ontology. The Music Ontology already represents different activities, especially in relation to the roles covered by musicians (e.g., a composer is related to the event composition). These, however, needed to be complemented to represent in a more exhaustive way the set of activities a musician can conduct. Firstly, we specified the class `musico:MusicalEvent` as subclass of `event:Event` to contextualize the musical nature of the event. Secondly, we created different subclasses of `musico:MusicalEvent`, such as `musico:Lesson`, `musico:Rehearsal`, `musico:CompositionSession`, `musico:JamSession`, `musico:RecordingSession`, and `musico:RecreationalMusicMaking`. We also defined `musico:Performance` as equivalent class of `mo:Performance`, and `musico:RecordingSession` as equivalent to `mo:RecordingSession`. Thirdly, we created the class `musico:MusicalSession` as subclass of `event:Event`, and related it to the class `musico:MusicalEvent` via the object property `musico:sub_musical_event` to express the notion that a musical event is composed by one or more sessions. Notably, we introduced the concept of musical session a part of a musical event, as we aimed to reuse a common terminology in the music field that indicates with "session" a part of a musical event. To align our ontology with the Polifonia Ontology Network, we further defined `musico:CompositionSession` as a subclass of `pon:Creative Process`, and `musico:RecordingSession` as a subclass of `pon:Recording Process`.

At the core of the modeling of a musical activity there is the concept of participation: a musician participates in a musical event, and the sessions within it. To model this complex concept we relied on the class `musico:MusicianParticipation`. This class has several object properties: `musico:participating_musician`, to link it to a specific human or virtual musician who takes part in the musical activity; musico:involved_event, to link it to a specific musical event; musico:played_instrument to link it to a played musical instrument; musico:played_musical_work and musico:taught_musical_work, musico:learnt_musical_work to respectively link it to a mo:MusicalWork during the activity of playing, teaching or learning a given musical piece. Emotional aspects of a musical activity are also crucial factors of the context. In line with previous research on emotion in music [28], we distinguish between the concept of mood from that of emotion, and between moods or emotions that are expressed while playing and those actually felt by the musician. For this purpose, we added various object properties linking the concept of musico:MusicianParticipation to moods and emotions, specified as the classes mfoem:emotion_process and mfoem:mood process described in the Emotions Ontology [29]. Specifically, we distinguished by emotion and mood processes accomplished by human and virtual musicians. For musico:HumanMusician we defined the predicates musico:felt_emotion, musico:felt_mood, musico:expressed_emotion, musico:expressed_mood. For musico:VirtualMusician we considered affective computing tasks that a program involved in musical activities could perform, such as musico:displayed_emotion and musico:displayed_mood for simulated emotions and moods, as well as musico:recognized_emotion and musico:recognized_mood for recognized emotions and moods. The affective state recognition may be based on several sources of information, including the audio signal generated by a musician, signals tracked by biometric devices, or data logs from social networks. The communities of Affective Computing as well as Music Information Retrieval have developed several techniques to achieve the classification of a user's affective state (see e.g., [40]). Notably, we used different names for the properties of emotions/moods related to human or virtual musicians (i.e., expressed vs. displayed and felt vs. recognized). This design was motivated by our willingness to keep the distinction between such agents, where a software agent can only perform affective computing tasks rather than expressing or feeling emotions/moods like a human does.

Musicians use various kinds of applications and services, which help to identify and categorize a context. Therefore, we introduced the classes musico:MusicalService and musico:MusicalApplication to represents the applications and services used by musicians (such as social networks, music editing software, digital audio workstations, music streaming services, or collaborative music making online platforms). Such classes have respectively the subclasses smi:SMIService and smi:SMIApplication which relate to specific applications and services offered by smart musical instruments. For instance, an smi:SMIApplication can involve a virtual musician (e.g., a self-learning app leverages a virtual music teacher). For this purpose we used the predicate musico:has_virtual_musician to link an smi:SMIApplication with a musico:VirtualMusician.

Temporal aspects. To represent the time or period during which a musical activity occurs we used the Timeline Ontology as well as the Event Ontology, which already defines the predicate event:time to bind an event to its timing. This allows to specify temporal coordinates as temporal instants or intervals (in terms of year, day, hours, minutes, seconds, durations, etc.) as well as, through inference, to represent more general concepts such as morning, afternoon, evening, and night. Furthermore, we added to the class musico:MusicianParticipation the data property musico:is_synchronous to specify whether virtual and/or human musicians take part to the activity at the same time in which the activity is conducted or in an asynchronous way (e.g., a musician can play synchronously with other musicians online, or s/he can attend an online music lesson after it has been recorded).

Spatial aspects. To represent the place in which a musical activity occurs we distinguished between the place's geographical position and its type. Indeed, to define a context of a musical activity, it is important also to specify what kind of venue the activity occurs in. For instance, a lesson could occur in music school such as a conservatory of music, or a performance could happen in a jazz club rather than a concert hall, while rehearsals could occur at home or at a rehearsal room. To represent the geographical coordinates we leveraged the Geonames' ontology. Regarding the kind of location, we leveraged the predicate schema:location and created several subclasses of the class schema:MusicVenue, e.g., musico:OperaHouse, musico:JazzClub, musico:ConcertHall, musico:RehearsalRoom. Furthermore, we added to the class musico:MusicianParticipation the data property musico:is_situated to specify whether virtual and/or human musicians take part to the activity at the same or at a different location (for instance linked by an Internet connectivity, using a networked music performance system).

Notably, the use of the data property musico:is_situated (as well as the use of musico:is_synchronous) allows to indicate how each musician takes part in a musical activity, and through inference it is possible to determine whether an event is situated or not (and synchronous or not).

6.1. SWRL rules

With the help of the Semantic Web Rule Language (SWRL), rules can be written to infer new data and expand the knowledge graph. Four rules were defined for expanding the musician's knowledge network by suggesting new activities or people to know.

The first rule (listing 1) is based on the geographical location of the musician and the facility hosting the event; if these two are close, then the event is recommended to the musician.

```
EventRecommendation_1:
    HumanMusician(?u) ^
    MusicalEvent(?ev) ^
    event(?ev, ?pl) ^
    foaf:based_near(?u, ?pl) ->
    gets_recommended_event(?u, ?ev)
```

Listing 1: Rule 1.

With the second rule (listing 2) an event is recommended to the user if a person s/he knows is interested in attending it.

```
EventRecommendation_2:
    HumanMusician(?u) ^
    MusicalEvent(?ev) ^
    foaf:knows(?u, ?o) ^
    interested_in(?o, ?ev) ->
    gets_recommended_event(?u, ?ev)
```

Listing 2: Rule 2.

The third rule (listing 3) enables the connection of musicians who may be interested in playing together. If two musicians are situated in the same city and perform similar genres of music, the rule suggests that the two musicians may be interested in playing together. The $swrlb : notEqual$ relation is employed to ensure that the two musicians are not the same person.

```
UserRecommendation_1:
    HumanMusician(?u) ^
    HumanMusician(?o) ^
    swrlb:notEqual(?u, ?o) ^
    foaf:based_near(?u, ?city) ^
    foaf:based_near(?o, ?city) ^
    plays_genre(?u, ?gen) ^
    plays_genre(?o, ?ggen) ^
    similar_to(?gen, ?ggen) ->
    gets_recommended_user(?u, ?o)
```

Listing 3: Rule 3.

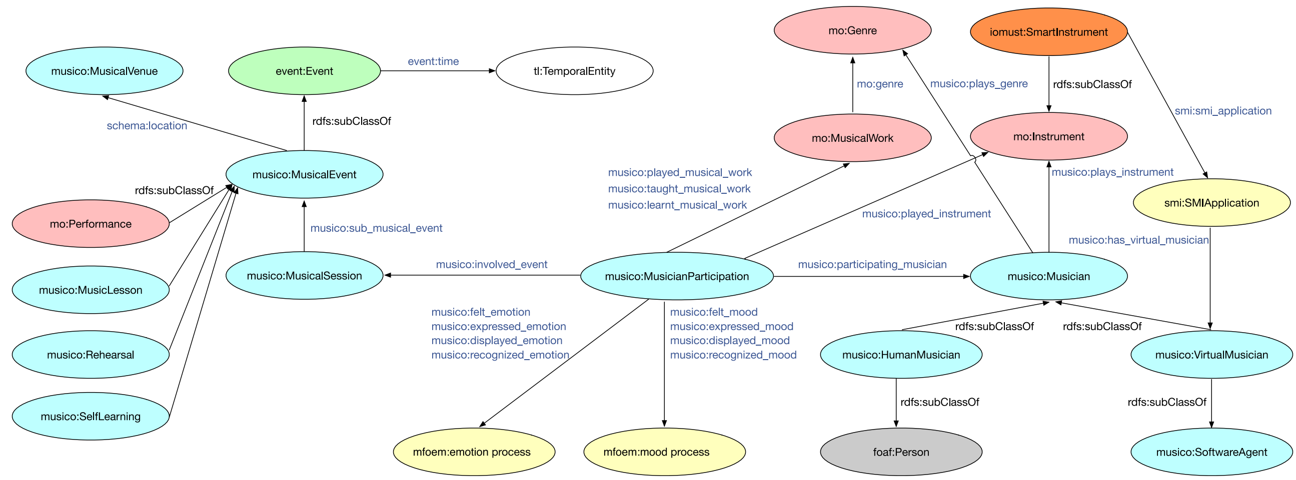

Fig. 1. High level structural overview of the ontology. The different colors for the classes relate to different namespaces. For the properties we relied on the color-coding of the Graffoo notation [41].

The fourth rule (listing 4) enables the inference of a musician's level of multi-instrumentalism. The presence of at least two different instruments in a musician's repertoire allows for the inference that the musician is a multi-instrumentalist.

```
Multi_instrumentalism_level:
    HumanMusician(?u) ^
    plays_instrument(?u, ?x) ^
    plays_instrument(?u, ?y) ^
    swrlb:notEqual(?x, ?y) ->
    multi-instrumentalism_level(?u, "multi-
    instrumentalist"^^rdf:PlainLiteral)
```

Listing 4: Rule 4.

7. Implementation and maintenance

Firstly, we have chosen the profile OWL 2 RL, in which the ontology consistency, class expression satisfiability, instance checking, etc., can be solved in a reasonable time to allow the real-time inference needed for specific scenarios of the envisioned smart musical applications (see Section 4.1).

The ontology development is accomplished in an online public git repository hosted on GitHub[8] (A.5). The issue tracking system offered by GitHub, will be used as communication channel for maintenance and future development of the ontology (C.3). MUSICO is an implementation-driven ontology, which is evaluated and evolves during its use while developing applications. As a consequence, the ontology will be growing depending on the introduction of novel applications for SMIs and IoMusT ecosystems (F.1).

The latest version of the ontology will always be accessible at the MUSICO URI, while previous versions will remain accessible using an URI scheme including the version ID (F.3). To guarantee backward compatibility, all the defined concepts will remain in the ontology and keep their current meaning. In case, at some point, the ontology maintainers decide that a concept is "not to be used any more", it will be annotated as deprecated (F.2).

To document the ontology we used the Wizard for Documenting Ontologies (Widoco) [42], which uses LODE [43] for generating ontology documentation and WebVOWL [44] for its visualization. The resulting HTML documentation is available online,[9] and is indexed with a permanent identifier.[10]

8. Evaluation

We have evaluated MUSICO using consolidated formal methods as well as by checking its fitness for our domain and purposes, similarly to what we have done in [22,23] for the IoMusT and for SMI ontologies.

8.1. Metrics and formal validation

The quality of MUSICO has been assessed using and adapting the evaluation methodology mentioned in [45]. Similarly to our previous works, we have not used all the indicated twelve metrics, while some of them required some adaptations to the specific scenario. This is because ontology engineering is often a matter of personal interpretation of the designers, and most of the validation process is conducted through experimentation with real-world data in real-world scenarios. What we considered relevant as metrics for our study falls into the class of "Knowledge coverage and popularity measures". On the other hand, as MUSICO is built up as a compound of sub-vocabularies, global metrics are considered less relevant, and were not included. The values of the utilized metrics are reported in Table 1.

Most classes and properties have been provided with a textual description (`rdfs:comment`) in English (E.7). To check the correctness of the ontology we utilized the ontology editor Protégé [46] and the Visual Notation for OWL Ontologies tool (VOWL) [47]. The logical consistency was checked by running (through Protégé) three reasoners, HermiT (version 1.4.3.456) [48], Pellet (version 2.2.0) [49], and FaCT++ (version 1.6.5) [50]. No inconsistencies were found.

8 https://github.com/lucaturchet/musico

9 https://lucaturchet.github.io/musico

10 https://w3id.org/musico#

Table 1
Ontology metrics.

Metric	Value
Number of classes	93
Number of properties:	
– *Datatype properties*	19
– *Object properties*	41
Number of individuals	0
Direct popularity	0
Inverse popularity:	
– *Ontology direct imports*	8
– *Ontology indirect imports*	27
– *Classes*	1747
– *DataType Properties*	335
– *Object Properties*	1756

To have another evaluation perspective, we submitted our ontology to the OntOlogy Pitfall Scanner! (OOPS!) online service [51], a well-known service that performs a set of checks to detect common pitfalls in ontology design based on the existing literature. The service seems to have some problems on ontologies with a substantial number of imports, so we removed the external references just to execute the validation test and ignoring the respective problems. We also removed all the errors categorized as "Minor", reporting that an ontology element (classes, predicate or datatype property) has no relation to the rest of the ontology. In addition, we ignored the warnings related to the missing comments. After this simplification on the original ontology, no pitfalls classified as "Important" or "Critical" have been detected in MUSICO.

8.2. Evaluation against requirements and competency questions

MUSICO underwent the application of the following four sets of criteria:

1. The academic community of the International Semantic Web Conference (one of the major conferences for Semantic Web research), defined in its website[11] a set of guidelines that resulted in specific evaluation criteria;
2. MIRO evaluation [24], that provides an organized list of standardized questions;
3. The competency questions reported in Section 5;
4. In-use validation by implementing an application leveraging the ontology.

Firstly, the analysis using the guidelines of the International Semantic Web Conference (which are also included partially in MIRO report) resulted in the following assessment. Regarding the *Impact* criteria, it is possible to conclude that MUSICO fulfills all the requests (the answers to the questions were largely discussed over the previous sections of this paper). Concerning the questions of the *Reusability* criteria, these are answered by the explanations given in Section 6. Notably, reusability is maximized by integrating into MUSICO well established ontologies like FOAF as well as other ontologies specific to the musical domain like the IoMusT Ontology and Music Ontology. Moreover, *Design & Technical Quality* and *Availability* criteria are appropriately fulfilled by the concepts provided in Section 7.

The competency questions in Section 5.2 are completely and successfully handled. MUSICO provides all the tools to perform semantic discoveries as complex as needed. As a consequence, the ontology provides all the tools necessary to create SPARQL queries that would answer the questions (as detailed in Appendix B).

[11] http://iswc2018.semanticweb.org/call-for-resources-track-papers/#

8.3. In-use validation

We assessed the usage of the ontology in a real IoMusT ecosystem, implementing the use case "Searching for the right musicians" reported in Section 4.1. Specifically, we developed a smartphone application called "MusicoNet", which utilizes the SPARQL queries created to address competency questions and the SWRL rules to provide automatic reasoning [52].

The application is a *social network* based on the IoMusT paradigm, which connects musicians and allows them to discover new opportunities and experiences. Each musician can sign up to the social network and create his own profile. In addition to personal information, the musician can specify the instrument and genre of music s/he plays. To complete the user's profile, it is also possible to upload short excerpts of the music they play using their individual instrument. Thanks to all this contextual information, the application can recommend the most suitable musicians to play with or the best future events to attend.

In more details, one of the features offered by the application is the ability to search for other musicians in real-time by simply recording a short excerpt with their smart musical instrument, which is then sent to the edge or cloud server hosting the social network. There, a routine based on established music information retrieval methods [53] extracts low- and high-level features such as genre, key, tempo, danceability and emotions. This data is then used to carry out a targeted search across the music excerpts linked to the profile of each musician. Those who match the search criteria will be suggested to the user, allowing him/her to start a conversation via chat and to connect to services for networked music performances (such as Elk Live [54]). Alternatively, users can manually enter the search criteria, or refine the list of retrieved musicians with further textual queries.

In addition to people, the application allows users to search for and create events. The application automatically suggests events based on the SWRL rules described in Section 6.1. The system will then keep track of the events the musician attends, so that similar events can be suggested in the future.

The app has been technically validated by means of extensive tests, which showed that a search can be performed with a triplestore of 1000 (fake) user profiles, thus demonstrating the app scalability. Moreover, an evaluation was conducted with 30 musicians (10 beginners, 10 intermediates, and 10 experts) who were provided with either a smart guitar or a smart keyboard. For this purpose, 100 profiles were created from the demographics and audio recordings of actual musicians. These related to the profiles of the 30 participants plus 70 profiles of musicians involved in our previous studies about the creation of a dataset of individual instruments (see e.g., [55]). Participants were asked to use the app to perform 10 searches. Their experience in interacting with the app was assessed via questionnaires and semi-structured interviews. Results clearly indicated that musicians highly appreciated the novelty and the concept underlying the proposed system as well as were satisfied by the provided service while using it. We found that the searches of expert musicians were generally more elaborated than those of beginners. The experts suggested adding several other musical criteria to refine the search, such as specific types of equipment of a musician (e.g., sound effects). All musicians consistently reported that the app can address their needs to expand their network, as well as for finding events and venues (such as available recording studios or rehearsal rooms). The need of supporting the search of other musicians and online resources for learning purposes was more felt by beginners and intermediates than experts. Overall, the user study demonstrated the actual need for MUSICO and its usefulness. Further details about the evaluation with users will be provided in a future publication.

9. Discussion

It is worth noticing that in modeling the ontology, we decided to reuse as many existing and community-accepted ontologies as possible. This is a well consolidated practice in many fields of Information Science, including ontology engineering. This, however, implied some strong constraints dictated from what already existed. We are aware that sometimes this leads to discrepancies in the modeling style, or the non-adherence to best practices, but we always gave priority to the reuse of existing concepts over the redefinition of the same concepts from scratch. While more recent methodologies for ontology engineering have been proposed (see e.g., [56,57]), we relied on the well established and widely used approach of METHONTOLOGY [32]. This, however, does not provide explicit guidelines for ontology reuse.

While ontology reuse aligns with standard practices in ontology engineering, many different types of reuse can be employed. For instance, the W3C recommends reuse based on ontology design patterns rather than importing entire ontologies [58]. The approach taken in MUSICO relies entirely on `owl:imports`, which is prone to issues. First, `owl:imports` does not allow for selective customization, meaning that entire ontologies are imported, potentially introducing irrelevant or incompatible concepts. Second, the transitive nature of `owl:imports` may lead to unintended dependencies, unnecessarily increasing the complexity of the resulting ontology. Third, there is a risk that reused ontologies may become unavailable over time, resulting in semantic loss and instability. Fourth, adopting the strategy of reusing existing domain representations can cause some inconsistencies. In MUSICO these relate to naming and conventions. Finally, some of the reused ontologies were selected mainly on the basis of their quality for our domain representation.

Therefore, this discussion on the trade-off between reuse and best practices aimed at making clear what are the possible implications of reusing MUSICO. We plan to address the identified issues in future works, so as to achieve a better integration and refinement.

10. Conclusions

This paper detailed the development of MUSICO, the Musician's Context Ontology, which models situational and environmental information related to musicians and their activities. The aim of the ontology is that of facilitating the development of context-aware musical applications, such as those embedded in or interfacing with the emerging class of SMIs, which are envisioned to maintain knowledge about their users and the environment and time in which they are used [8]. The ontology as well as its documentation are freely accessible online.

An extensive literature review revealed that there was no previous comprehensive data model for the domain of musicians' context. Nevertheless, MUSICO is based on existing ontologies and models, including the IoMusT Ontology [22] for the representation of Internet of Musical Things ecosystems and the Music Ontology that deals with the description of the music value-chain from production to consumption. It is worth noticing that MUSICO could be used as a reference to model other art-related domains such as dance. For instance, a dancers' context ontology would have several analogies with the knowledge represented in the present study.

The conducted evaluation showed that MUSICO is consistent, follows good practices, and its practical usage respond to actual needs by musicians. In future work, we plan to extensively utilize MUSICO in IoMusT ecosystems addressing a large variety of contexts such as those defined in this paper. Finally, as MUSICO is disseminated, more feedback is expected in the near future. These inputs will allow us to evolve the ontology based on potentially unexpected use cases as well as conduct a more in-depth evaluation.

CRediT authorship contribution statement

Luca Turchet: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation. **Jacopo Tomelleri:** Software. **Andrea Molinari:** Writing – original draft, Formal analysis, Conceptualization. **Paolo Bouquet:** Supervision.

Declaration of competing interest

• All authors have participated in (a) conception and design, or analysis and interpretation of the data; (b) drafting the article or revising it critically for important intellectual content; and (c) approval of the final version.

• This manuscript has not been submitted to, nor is under review at, another journal or other publishing venue.

• The authors have no affiliation with any organization with a direct or indirect financial interest in the subject matter discussed in the manuscript

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Appendix A. Prefixes and namespaces

Table A.2 lists the prefixes used in the present work and their corresponding expanded URI.

Table A.2
Expanded SPARQL prefixes.

Prefix	URI
`rdfs:`	http://www.w3.org/2000/01/rdf-schema#
`musico:`	http://purl.org/ontology/musico
`smi:`	http://purl.org/ontology/iomust/smi
`iomust:`	http://purl.org/ontology/iomust/internet_of_things
`mo:`	http://purl.org/ontology/mo/
`studio:`	http://purl.org/ontology/studio/
`pon:`	https://w3id.org/polifonia/ontology/ontology-network/
`mfoem:`	http://purl.obolibrary.org/obo/MFOEM.owl
`foaf:`	http://xmlns.com/foaf/0.1/
`event:`	http://purl.org/NET/c4dm/event.owl#
`time:`	https://www.w3.org/2006/time
`tl:`	http://purl.org/NET/c4dm/timeline.owl#
`schema:`	https://schema.org/docs/schemaorg.owl
`gn:`	http://www.geonames.org/ontology/ontology_v3.2.rdf

Appendix B. SPARQL queries associated to the competency questions

```
SELECT  ?firstName ?lastName ?instrument ?role
  WHERE {
    ?Musician        a/rdfs:subClassOf*              musico:HumanMusician ;
                     foaf:based_near                 ex:London ;
                     foaf:firstName                  ?firstName ;
                     foaf:lastName                   ?lastName ;
                     foaf:gender                     "female" ;
                     musico:professional_level       "Amateur" ;
                     musico:has_disability           true ;
                     musico:disability_type          "visually-impaired" ;
                     musico:plays_genre              ex:Rock ;
                     musico:plays_instrument         ?instrument ;
                     rdf:type                        ?role .
}
```

Listing 5: Query retrieveing name, last name, played instrument and role of all visually-impaired female musicians living in London who are amateur and play rock.

```
SELECT ?Genre (COUNT(?Genre) as ?num_genres_happy)
  WHERE {
    ?Musician                a/rdfs:subClassOf*           musico:HumanMusician ;
                             musico:professional_level    "Professional" ;
                             musico:in_participation      ?MusicianParticipation .
    ?MusicianParticipation   musico:involved_event        ?MusicalSession ;
                             musico:felt_emotion          mfoem:happiness ;
                             musico:played_musical_work   ?MusicalWork .
    ?MusicalWork             mo:genre                     ?Genre .
}
GROUP BY ?Genre
ORDER BY DESC(?num_genres_happy)
LIMIT 3
```

Listing 6: Query retrieving the three musical genres professional musicians play more frequently when they feel happy.

```
SELECT  (COUNT(?MusicalSession) as ?num_sessions)
  WHERE {
    ex:CristinaLadynekt       musico:in_participation      ?MusicianParticipation .
    ?MusicianParticipation    musico:played_instrument     ex:karaokeSmartMicrophone ;
                              musico:involved_event        ?MusicalSession .
    ?MusicalSession           musico:sub_musical_event     ?Performance .
    ?Performance              musico:sub_tour_event        ?Tour .
    ?Tour                     event:time                   [
                                                            a tl:Instant ;
                                                            tl:at "2021"^^xsd:gYear ;
                                                            ] .
}
```

Listing 7: Query retrieving how many sessions the musician Cristina Ladynekt has performed with her smart microphone during a tour in 2021.

```
SELECT DISTINCT ?emotion
  WHERE {
    ?Learner                 rdf:type                   musico:HumanMusicLearner ;
                             musico:expertise_level     "Beginner" ;
                             musico:plays_instrument    ex:SmartGuitar ;
                             musico:in_participation    ?LearnerParticipation .
    ?LearnerParticipation    musico:involved_event      ?LessonSession ;
                             musico:felt_emotion        ?emotion .
    ?LessonSession           rdf:type                   musico:MusicalSession ;
                             musico:sub_musical_event   ?Lesson .
    ?Lesson                  rdf:type                   musico:MusicLesson ;
                             schema:location            ex:KMHRoyalCollegeOfMusic .
    ?Teacher                 rdf:type                   musico:HumanMusicTeacher ;
                             foaf:firstName             "Cristina" ;
                             foaf:lastName              "Ladinekt" ;
                             musico:in_participation    ?TeacherParticipation .
    ?TeacherParticipation    musico:involved_event      ?LessonSession ;
                             musico:taught_musical_work ex:study5Sor20Studies .
}
```

Listing 8: Query retrieving the emotions of beginner smart guitar players while learning the study number 5 of Fernando Sor's "20 studies for guitar" during lessons with Prof. Cristina Ladynekt at KMH Royal College of Music in Stockholm.

```
SELECT ?virtualMusician (COUNT(?virtualMusician) as ?num_virtual_musicians)
  WHERE {
    ?Musician                   musico:plays_instrument      ?instrument ;
                                musico:in_participation      ?SelfLearnerParticipation .
    ?SelfLearnerParticipation   musico:involved_event        ?SelfLearningSession .
    ?SelfLearningSession        rdf:type                     musico:MusicalSession ;
                                musico:sub_musical_event     ?SelfLearningActivity .
    ?SelfLearningActivity       rdf:type                     musico:SelfLearning ;
                                schema:location              ?home .
    ?home                       rdf:type                     musico:Home .
    ?instrument                 rdf:type                     smi:SmartGuitar ;
                                smi:smi_application          ?application .
    ?application                rdf:type                     smi:SMIApplication ;
                                musico:has_virtual_musician  ?virtualMusician .
    ?virtualMusician            rdf:type                     musico:VirtualMusicTeacher ;
                                musico:plays_instrument      ?virtualInstrument .
    ?virtualInstrument          rdf:type                     smi:Piano .
}
GROUP BY ?virtualMusician
ORDER BY DESC(?num_virtual_musicians)
LIMIT 3
```

Listing 9: Query retrieving the three virtual teachers playing piano with which smart guitar players interact most frequently while self-learning at home.

```
SELECT ?DateTime
  WHERE {
    ex:SharanGiptas          musico:in_participation    ?MusicianParticipation .
    ?MusicianParticipation   musico:involved_event      ?MusicalSession .
    ?MusicalSession          musico:sub_musical_event   ?Rehearsal .
    ?Rehearsal               rdf:type                   musico:Rehearsal ;
                             musico:has_group           ex:TheUnicornsAndCamels ;
                             event:time                 ?Time .
    ?Time                    rdf:type                   tl:Interval ;
                             tl:at                      ?DateTime .
}
ORDER BY DESC(?Time)
LIMIT 1
```

Listing 10: Query retrieving when is the last time the musician Sharan Giptas has rehearsed with the other members of his band “The Unicorns and Camels”.

```
SELECT ?Musician (AVG(?Duration) AS ?avg)
  WHERE {
  ?Musician              musico:multi-instrumentalism_level  "multi-instrumentalist" ;
                         foaf:based_near                     ex:Tokyo ;
                         musico:in_participation             ?Participation .
  ?Participation         rdf:type                            musico:MusicianParticipation ;
                         musico:involved_event               ?Session .
  ?Session               rdf:type                            musico:MusicalSession ;
                         musico:sub_musical_event            ?RecreationalMusicMaking .
  ?RecreationalMusicMaking rdf:type                        musico:RecreationalMusicMaking ;
                         event:time                          ?Time .
  ?Time


}
GROUP BY ?Musician
```

Listing 11: Query retrieving how long poly-instrumentalist musicians from Tokyo play on average for recreational music making.

```
SELECT (COUNT(DISTINCT ?Performance) as ?count)
  WHERE {
    ?Musician                a/rdfs:subClassOf*          musico:HumanMusician ;
                             foaf:based_near             ex:London ;
                             musico:in_participation     ?MusicianParticipation .
    ?MusicianParticipation   musico:involved_event       ?MusicalSession ;
                             musico:is_situated          false ;
                             musico:is_synchronous       true .
    ?MusicalSession          musico:sub_musical_event    ?Performance .
    ?Performance             rdf:type                    musico:Performance ;
                             event:time                  [
                                                           a tl:Instant ;
                                                           tl:at "2020"^^xsd:gYear ;
                                                          ] .

}
```

Listing 12: Query retrieving how many synchronous, displaced performances have the musicians from London performed in 2020.

Data availability

Data will be made available on request.

References

[1] M. Weiser, The computer for the 21st century, Sci. Am. 265 (3) (1991) 94–105.
[2] M. Satyanarayanan, Pervasive computing: Vision and challenges, IEEE Pers. Commun. 8 (4) (2001) 10–17.
[3] L. Atzori, A. Iera, G. Morabito, The internet of things: a survey, Comput. Netw. 54 (15) (2010) 2787–2805.
[4] C. Perera, A. Zaslavsky, P. Christen, D. Georgakopoulos, Context aware computing for the internet of things: A survey, IEEE Commun. Surv. Tutor. 16 (1) (2014) 414–454.
[5] T. Strang, C. Linnhoff-Popien, A context modeling survey, in: Workshop on Advanced Context Modelling, Reasoning and Management At UbiComp 2004 - the Sixth International Conference on Ubiquitous Computing, 2004, pp. 1–8.
[6] G. Pierra, Context representation in domain ontologies and its use for semantic integration of data, in: Journal on Data Semantics X, Springer, 2008, pp. 174–211.
[7] X.H. Wang, D.Q. Zhang, T. Gu, H.K. Pung, Ontology based context modeling and reasoning using OWL, in: IEEE Annual Conference on Pervasive Computing and Communications Workshops, IEEE, 2004, pp. 18–22.
[8] L. Turchet, Smart Musical Instruments: vision, design principles, and future directions, IEEE Access 7 (2019) 8944–8963.
[9] L. Turchet, C. Fischione, G. Essl, D. Keller, M. Barthet, Internet of Musical Things: Vision and Challenges, IEEE Access 6 (2018) 61994–62017.
[10] D. Bogdanov, M. Haro, F. Fuhrmann, A. Xambó, E. Gómez, P. Herrera, Semantic audio content-based music recommendation and visualization based on user preference examples, Inf. Process. Manage. 49 (1) (2013) 13–33.
[11] P. Knees, M. Schedl, B. Ferwerda, A. Laplante, User awareness in music recommender systems, Pers. Human-Comput. Interact. (2019) 223.
[12] Y. Raimond, S. Abdallah, M. Sandler, F. Giasson, The music ontology, in: Proceedings of International Society for Music Information Retrieval Conference, 2007.
[13] G. Fazekas, M. Sandler, The studio ontology framework, in: Proceedings of the International Society for Music Information Retrieval Conference, 2011, pp. 24–28.
[14] T. Wilmering, G. Fazekas, M. Sandler, AUFX-O: Novel Methods for the Representation of Audio Processing Workflows, in: The Semantic Web, Proc. of the 15th International Semantic Web Conference, in: Lecture Notes in Computer Science, vol. 9982, Springer, Cham, 2016, pp. 229–237.
[15] P. Proutskova, D. Wolff, G. Fazekas, K. Frieler, F. Höger, O. Velichkina, G. Solis, T. Weyde, M. Pfleiderer, H.C. Crayencour, et al., The jazz ontology: A semantic model and large-scale RDF repositories for jazz, J. Web Semant. 74 (2022) 100735.
[16] V. Carriero, J. de Berardinis, A. Meroño-Peñuela, A. Poltronieri, V. Presutti, The music meta ontology: A flexible semantic model for the interoperability of music metadata, in: Ismir 2023 Hybrid Conference, 2023.
[17] J. de Berardinis, V.A. Carriero, N. Jain, N. Lazzari, A. Meroño-Peñuela, A. Poltronieri, V. Presutti, The polifonia ontology network: Building a semantic backbone for musical heritage, in: International Semantic Web Conference, Springer, 2023, pp. 302–322.
[18] P. Choffé, F. Leresche, DOREMUS: connecting sources, enriching catalogues and user experience, in: 24th IFLA World Library and Information Congress, 2016, pp. 1–20.
[19] S.S.-s. Cherfi, C. Guillotel, F. Hamdi, P. Rigaux, N. Travers, Ontology-based annotation of music scores, in: Proceedings of the 9th Knowledge Capture Conference, 2017, pp. 1–4.
[20] A. Poltronieri, A. Gangemi, The music note ontology, in: Proceedings of the 12th Workshop on Ontology Design and Patterns, 2021.
[21] A. Allik, G. Fazekas, M. Sandler, An ontology for audio features, in: Proceedings of the International Society for Music Information Retrieval Conference, 2016, pp. 73–79.
[22] L. Turchet, F. Antoniazzi, F. Viola, F. Giunchiglia, G. Fazekas, The internet of musical things ontology, J. Web Semant. 60 (2020) 100548.
[23] L. Turchet, P. Bouquet, A. Molinari, G. Fazekas, The smart musical instruments ontology, J. Web Semant. (2022) 100687.
[24] N. Matentzoglu, J. Malone, C. Mungall, R. Stevens, MIRO: guidelines for minimum information for the reporting of an ontology, J. Biomed. Semant. 9 (1) (2018) 6.
[25] L. Ding, L. Zhou, T. Finin, A. Joshi, How the semantic web is being used: An analysis of FOAF documents, in: Proceedings of the 38th Annual Hawaii International Conference on System Sciences, IEEE, 2005, pp. 1–10.
[26] Ò. Celma, X. Serra, FOAFing the music: Bridging the semantic gap in music recommendation, J. Web Semant. 6 (4) (2008) 250–256.
[27] J. Hobbs, F. Pan, An ontology of time for the semantic web, ACM Trans. Asian Lang. Inf. Process. 3 (1) (2004) 66–85.
[28] P. Juslin, J. Sloboda, Handbook of Music and Emotion: Theory, Research, Applications, Oxford University Press, 2011.
[29] J. Hastings, W. Ceusters, B. Smith, K. Mulligan, The emotion ontology: enabling interdisciplinary research in the affective sciences, in: International and Interdisciplinary Conference on Modeling and using Context, Springer, 2011, pp. 119–123.
[30] K. Janowicz, A. Haller, S.J. Cox, D. Le Phuoc, M. Lefrançois, SOSA: A lightweight ontology for sensors, observations, samples, and actuators, J. Web Semant. (2018).
[31] G. Abowd, A. Dey, P. Brown, N. Davies, M. Smith, P. Steggles, Towards a better understanding of context and context-awareness, in: International Symposium on Handheld and Ubiquitous Computing, Springer, 1999, pp. 304–307.
[32] M. Fernández-López, A. Gómez-Pérez, N. Juristo, METHONTOLOGY: from ontological art towards ontological engineering, in: Proceedings of the Onto-Logical Engineering AAAI-97 Spring Symposium Series, American Association for Artificial Intelligence, 1997.
[33] B. Motik, P. Patel-Schneider, B. Parsia, C. Bock, A. Fokoue, P. Haase, R. Hoekstra, I. Horrocks, A. Ruttenberg, U. Sattler, M. Smith, OWL 2 web ontology language: Structural specification and functional-style syntax, W3C Recomm. 27 (65) (2009) 159.
[34] L. Turchet, J. Pauwels, C. Fischione, G. Fazekas, Cloud-smart musical instrument interactions: Querying a large music collection with a smart guitar, ACM Trans. Internet Things 1 (3) (2020) 1–29.
[35] K. Siegemund, E.J. Thomas, Y. Zhao, J. Pan, U. Assmann, Towards ontology-driven requirements engineering, in: Workshop Semantic Web Enabled Software Engineering at 10th International Semantic Web Conference, 2011.
[36] M. Grüninger, M.S. Fox, Methodology for the design and evaluation of ontologies, in: Workshop on Basic Ontological Issues in Knowledge Sharing, 1995, pp. 6.1.–6.10.
[37] F. Pachet, The continuator: Musical interaction with style, J. New Music Res. 32 (3) (2003) 333–341.
[38] J. Aucouturier, F. Pachet, Representing musical genre: A state of the art, J. New Music Res. 32 (1) (2003) 83–93.
[39] F. Pachet, D. Cazaly, A taxonomy of musical genres., in: Content-Based Multimedia Information Access Conference, RIAO, 2000, pp. 1238–1245.
[40] J.S. Gómez-Cañón, E. Cano, T. Eerola, P. Herrera, X. Hu, Y.-H. Yang, E. Gómez, Music emotion recognition: Toward new, robust standards in personalized and context-sensitive applications, IEEE Signal Process. Mag. 38 (6) (2021) 106–114.
[41] R. Falco, A. Gangemi, S. Peroni, D. Shotton, F. Vitali, Modelling OWL ontologies with graffoo, in: The Semantic Web: ESWC 2014 Satellite Events: ESWC 2014 Satellite Events, Anissaras, Crete, Greece, May 25-29, 2014, Revised Selected Papers 11, Springer, 2014, pp. 320–325.
[42] D. Garijo, WIDOCO: a wizard for documenting ontologies, in: International Semantic Web Conference, Springer, 2017, pp. 94–102.
[43] S. Peroni, D. Shotton, F. Vitali, The live OWL documentation environment: a tool for the automatic generation of ontology documentation, in: International Conference on Knowledge Engineering and Knowledge Management, Springer, 2012, pp. 398–412.
[44] S. Lohmann, V. Link, E. Marbach, S. Negru, WebVOWL: Web-based visualization of ontologies, in: International Conference on Knowledge Engineering and Knowledge Management, Springer, 2014, pp. 154–158.
[45] M. Fernández, C. Overbeeke, M. Sabou, E. Motta, What makes a good ontology? A case-study in fine-grained knowledge reuse, in: A. Gómez-Pérez, Y. Yu, Y. Ding (Eds.), The Semantic Web, Springer Berlin Heidelberg, Berlin, Heidelberg, 2009, pp. 61–75.
[46] M.A. Musen, the ProtégéTeam, The protégé project: A look back and a look forward, AI Matters 1 (4) (2015) 4–12.
[47] S. Lohmann, S. Negru, F. Haag, T. Ertl, Visualizing ontologies with VOWL, Semant. Web 7 (4) (2016) 399–419.
[48] R. Shearer, B. Motik, I. Horrocks, HermiT: A highly-efficient OWL reasoner, in: Proc. OWLED 2008, vol. 432, 2008, p. 91.
[49] B. Parsia, E. Sirin, Pellet: An owl dl reasoner, in: Third International Semantic Web Conference-Poster, vol. 18, Publishing, 2004, p. 2.
[50] D. Tsarkov, I. Horrocks, FaCT++ description logic reasoner: System description, Autom. Reason. (2006) 292–297.
[51] M. Poveda-Villalón, A. Gómez-Pérez, M.C. Suárez-Figueroa, Oops!(ontology pitfall scanner!): An on-line tool for ontology evaluation, Int. J. Semant. Web Inf. Syst. (IJSWIS) 10 (2) (2014) 7–34.
[52] L. Turchet, T. Jacopo, R. Alessandro, MusicoNet: A Social Network for Musicians Based on the Internet of Musical Things and People Paradigm, in: Proceedings of the 5th IEEE International Symposium on the Internet of Sounds, IEEE, 2024, pp. 1–8.
[53] D. Bogdanov, N. Wack, E. Gómez Gutiérrez, S. Gulati, P. Herrera Boyer, O. Mayor, G. Roma Trepat, J. Salamon, J. Zapata González, X. Serra, Essentia: An audio analysis library for music information retrieval, in: Proceedings of the International Society for Music Information Retrieval Conference, 2013, pp. 493–498.
[54] L. Turchet, C. Fischione, Elk audio OS: an open source operating system for the internet of musical things, ACM Trans. Internet Things 2 (2) (2021) 1–18.

[55] L. Turchet, D. Stefani, J. Pauwels, Musician-AI partnership mediated by emotionally-aware smart musical instruments, Int. J. Hum.-Comput. Stud. 191 (2024) 103340.
[56] E. Blomqvist, K. Hammar, V. Presutti, Engineering ontologies with patterns–the extreme design methodology, in: Ontology Engineering with Ontology Design Patterns, IOS Press, 2016, pp. 23–50.
[57] S. Peroni, A simplified agile methodology for ontology development, in: OWL: Experiences and Directions–Reasoner Evaluation: 13th International Workshop, OWLED 2016, and 5th International Workshop, ORE 2016, Bologna, Italy, November 20, 2016, Revised Selected Papers 13, Springer, 2017, pp. 55–69.
[58] V.A. Carriero, M. Daquino, A. Gangemi, A.G. Nuzzolese, S. Peroni, V. Presutti, F. Tomasi, The landscape of ontology reuse approaches, in: Applications and Practices in Ontology Design, Extraction, and Reasoning, IOS Press, 2020, pp. 21–38.