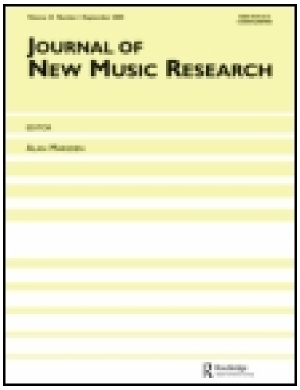

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Music Processing Technologies for Rescuing Music Archives at Teatro alla Scala and Bolshoi Theatre

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Abstract

In this paper we characterize special features of music archives concerning how to preserve and organize them by means of computer technologies. We consider two representative case studies: the Music Archive at Teatro alla Scala and Bolshoi Theatre. We consider all the kind of materials involved – i.e., audio tapes, music sheets, photos, videos, etc. – with particular emphasis on audio media and scores.

Both qualitative and quantitative aspects of these materials are considered in order to allow us to define a basic scheme for designing a computerized processing of information within a music database framework.

1 Musical archive content

There is a large number of music archives which could be considered for preserving and digitization projects. Historical and commercial archives are generally considered to be the most urgent to be processed. In this paper we try to outline the kind of problems related with preserving and the general architectures of computer based systems for music digital archives.

Music archives are made of a number of different media, that deal with musical content i.e., audio media and music sheets. Other common media involved are: photos, videos, metadata describing compositions, performances, and similar.

In the digital domain, audio media are commonly represented as discrete signals while page sheets are generally represented as digital images. Both of them have their own specific digital formats and standards; see Haus and Pighi (1996). Furthermore, both of them can be described at symbolic level by proper codes. So, we have to consider the following standard codes:

a) *digital audio*: CD-DA & DVD Audio PCM (sampling frequency at 44.1, 48, 88.2, 96, 192 KHz; 16 and 24 bits quantization words), AIFF, and MP3 files;
b) *digital music sheets*: PDF, TIFF, and JPEG files;
c) *symbolic codes*: MIDI, NIFF, and SMDL files.

Audio media include:

- a1) various analog and digital master open-reel and cassette tapes (mono/stereo; ¼, ½, 1 inch; various tape speed);
- a2) various analog and digital multitrack open-reel and cassette tapes.

Music scores include:

- b1) handwritten original scores;
- b2) commercially available published scores;
- b3) elaboration of previously published scores (such as personalization of orchestral scores by conductors, who generally have special directives for dynamics and expression, of great cultural value for study and comparison of interpretation and performance styles).

Furthermore, organizing music scores into a digital archive is further complicated by the existence of several music texts related to the same composition, such as the complete orchestral score, the parts for each instrument, the singer-piano reduction used during rehearsals, and additional versions containing annotations made by conductors and/or performers over the years.

All these versions have to be preserved and described within an integrated music information environment.

Both audio and score materials could have heterogeneous quality levels with respect to the state of conservation and the way they were originally produced.

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Symbolic codes are usually not present in music archives, so they have to be written by hand or, as we describe below, automatically generated by computer.

2 A new technology for musical content processing

The processing of musical content implies the availability of systems which are able to:

- convert audio media and music sheets in the digital domain;
- extract symbolic music information from both audio and score digital files;
- extract indexes for efficient retrieving of musical content;
- store digital audio, digital score images, music symbolic information and indexes within an integrated music database environment;
- browse within both audio and score music data by content.

Such a technology consists of a set of processing units devoted to the analysis/processing/synthesis of music information. Each processing unit can be a software and/or a hardware device. Furthermore, each processing unit can operate either in interactive or realtime mode. The most innovative feature is the approach here summarized, which allows the musician to work with music information within a multimedia environment (music databases + internet music content browsing) in which all the musical representation forms – such as audio signals, timbral models and characteristics, scores, abstract structures and forms – are integrated.

Basic processing units could be the following:

SAS:	*Symbolic based Audio Segmentation* segmentation of audio recordings based on score-like codes
input:	linear digital audio data; score-like symbolic codes
processing:	automatic mapping into score-like codes of “note” information within complex audio data
output:	score “spine” structure with start-end flags added within audio data
ASG:	*Audio-to-Symbolic Generation* score-like codes generation from audio recordings
input:	linear digital audio data
processing:	generation of score-like symbolic codes based on music features’ extraction from linear digital audio data
output:	score-like symbolic codes
OMR:	*Optical Music Recognition* score-like codes recognition from printed scores
input:	digitized score pages
processing:	recognition of music notation within digital score pages; the symbolic codes generated allows the user to electronically process and publish complex scores for both single instrumental parts and the whole orchestral score
output:	score-like symbolic codes
SS:	*Symbolic Segmentation* segmentation of score-like symbolic codes
input:	score-like symbolic codes
processing:	recognition of generative music fragments and their transformations within scores; generation of music structural models
output:	score-like symbolic codes (fragments); music structural models
ASI:	*Audio/Symbolic Integration* integration between symbolic and digital audio codes into the LIM enhanced NIFF code
input:	symbolic codes; digital audio codes; score “spine” structure with start-end flags within audio data added
processing:	interleaving of symbolic and digital audio codes into the LIM enhanced NIFF code
output:	LIM enhanced NIFF symbolic codes
SSM:	*Symbolic Similarity Measure* similarity measures of score-like music indexes
input:	score-like symbolic codes (fragments); library of musical metric tools; parametric queries by the user
processing:	pattern matching among music fragments applying music metrics to get similarity measures
output:	similarity measures based on the metric tools used
MCQ:	*Musical Content Query* queries by musical content (fragments such as digital audio data, MIDI, and NIFF codes) to multimedia archives
input:	MIDI symbolic codes (fragment); NIFF symbolic codes (fragment); digital audio codes (fragment); standard string queries enriched by musical content;
processing:	quick research by content based on the indexes generated by the SAS + ASG + SS modules and the measures get from the SSM module
output:	table of audio/music media retrieved ordered by descending similarity values

Setting up musical archive schemas is a complex activity in that, unlike conventional database environments, these environments are characterized by an extraordinarily large amount of image and audio data stored in a variety of formats and characterized by tightly relationships. Multimedia data are inherently different from conventional ones; see Ferrari and Haus (1998).

The main difference is that information about the content of multimedia data is usually not encoded into attributes provided by the data schema (like traditional structured data). Rather, text, image, video, and audio data are typically unstructured. Therefore, specific methods to identify and represent content features and semantic structures of multimedia data are needed. Another distinguishing feature of multimedia data is their large storage requirements. Moreover, the content of multimedia data is difficult to analyze and compare, in order to be actively used during query processing and related reporting. For this reason, we have designed and developed the technology summarized in this paper for processing musical and multimedia data such as digital sounds, scores, photos, videos, etc.

The basic functionality consists in the possibility to retrieve all the pieces of music scores and/or audio files which contain a particular sequence of notes (or a sequence of notes similar to a given one). Thus, to keep query processing efficient we have developed an approach based on audio and score segmentation. The idea is to automatically extract the more semantically meaningful fragments of both audio and score before inserting them into a database. Such fragments are then used as indexes for all the music files related; see Frazzini et al. (1999). The segmentation algorithm is based on the observation that most compositions (quite all) have some source patterns (i.e., brief sequences of notes) to which a great part of the piece can be brought back by means of several music functions. This function can be: a transposition, a repetition, a mirror inversion, a retrogradation, or other transformations or even combinations of some of them. The source patterns are usually the melodies of the music scores, that is, those that are usually remembered by a person.

The essential high level data structure of a music piece is a timed list called "spine" whose nodes are made of time representation of notes (pitch and duration couples). All other information about the score and the audio recordings of performances have to be suitably linked to the spine nodes. We have implemented the general idea of spine generating a "timed spine" which enhances the NIFF standard descriptive capability, adding to NIFF codes the spine information coupling audio and symbolic score; see Haus and Longari (1998). The essential note information that must be coded in the spine can be extracted from the files in each of the above mentioned formats.

3 Preserving music archives and retrieving musical content within multimedia databases

Four main steps are needed for doing the task of preserving music archives and retrieving musical content within them:

I) preservation of the original media i.e., restoration of the original media and then conversion of the original music information into standard digital formats;
II) structuring subsymbolic (audio and image), symbolic (score), and string (metadata i.e., musicmedia descriptors) music information;
III) time and note based music information indexing;
IV) querying and retrieving music information by metadata (traditional) and musical content (innovative).

Unfortunately, most of the media within music archives have not been well preserved and are actually deteriorating at a quick pace. For this reason, the first step in any preserving project is the restoring of media so that they can be well transferred into the digital domain by suitable digitization processes. The most relevant analog music media are audio tapes for sound and paper sheets for score pages.

The basic idea for preserving audio tapes' content is that audio media have to be restored at their best while audio content has to be preserved as they are without any restoring processes applied. Restoring audio is a lossy process.

The audio preserving process consists of many tasks and activities, quickly summarized as follows:

- cleaning of analog audio tapes;
- heat treatment for those tapes that have softened due to age;
- digitization of tapes tracks;
- mastering of two/three copies of an optical disc (CD-R or DVD-R) for each original recording;
- classification of the original recordings and of the new ones by means of suitable attributes which are entered in a music database.

Here follows a short explanation of the techniques mentioned above. While many tapes need to be cleaned by hand, turn by turn, with a special liquid, those which have suffered from softening of the oxide coating and have absorbed moisture during their long term storage require a special heat treatment if they are to be restored to playable condition – without squeaking, nor sticking to the guides and heads of the recorder – and transferred to digital form. This treatment consists in putting the tapes into a heated oven or incubator at a temperature of 45°C–55°C for about three days. Once the tapes reach a satisfactory quality, their content is digitized at a standard sampling rate and quantization word, and stored on computer hard disks. The resulting digital audio files are edited and structured as digital tracks that correspond to single musical pieces. Meaningless heads and tails are removed. The main goal of this step is to keep the original information exactly "as it is," postponing choices for a possible restoration – hence, extra noises are also carefully preserved. The digital tracks are copied on CD-R or DVD-R optical discs, for each of which there are at least two original copies for backup.

The basic idea for preserving music scores is that paper sheets have to be scanned and digitally stored for maintain-

Fig. 1. Queries window by strings and audio fragment.

ing graphic information as is, retrieving and using it when needed without consumption for the original paper document.

Then musical content has to be automatically recognized within digital images by means of an OMR (Optical Musical Recognition) process. Unfortunately, commercially available products for OMR have a limited reliability, particularly for complex scores, high density of symbols, non standard symbols; furthermore, commercially available products work with either proprietary codes (they have formats not in the public domain) or MIDI codes which are not satisfying for musicological and publishing applications: not all the music information obtained by OMR can be translated into the MIDI format.

There are a number of critical problems such as very high and very low notes with respect to the staves, changeable distance between the staves, systems ("accollature") with changeable dimensions, etc. So, the cost of the OMR is very high due to the amount of human work needed for make symbolic scores correct.

While these activities take place, information is collected about the content of the tapes, both from the artistic and the technical point of view. In addition, all information acquired during cleaning and heating, digitalization and mastering, contributes to the definition of music metadata (100 descriptors approximately) concerning the original recordings and the new media (CD-R and DVD-R), is entered in a multimedia database which would be object-oriented, distributed and multiplatform.

Once audio, page sheets, and symbolic scores are put into a digital multimedia archive, one can consider all these materials at his disposal simply by querying. The environment for querying music information provides an integrated support for both standard and content-based queries. Content-based queries allow the retrieval of both audio and scores based on *melodic similarity* – see Polansky (1996) – a feature defined as *melody retrieval*. Thus, melody retrieval allows a search for audio and scores containing a given theme, or a sequence of notes similar to that theme.

Thanks to the musical query environment, a user can formulate both traditional queries such as: "*Retrieve all the scores written by Mozart*," or melodic queries such as: "*Retrieve all the scores containing a particular sequence of notes (or a sequence of notes whose melodic content is similar to a given one)*." Both traditional and advanced selection criteria can be combined. A window by which the user can submit queries on music information could be as the one shown in Figure 1.

The matching between the music input and the music information stored into the digital archive is performed in

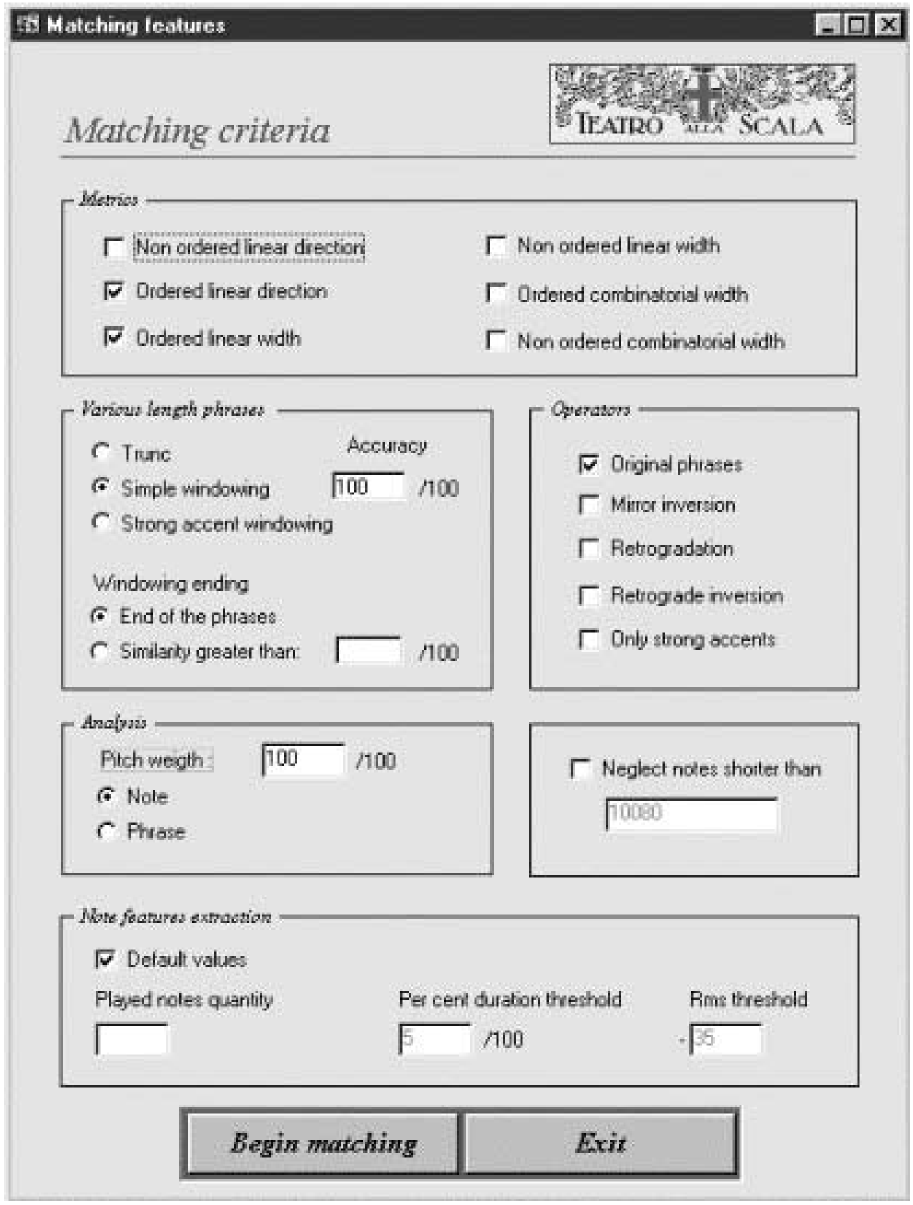

Fig. 2. Similarity metrics window: here the user defines his own criteria for classifying music information retrieved.

several steps. The input can be either an audio signal or an audio file or a score fragment, played by the user on a keyboard or sung or whistled into a microphone connected to the computer. From the audio files, note-like attributes are extracted by converting the input into a symbolic code, i.e., the concatenation of pitch and duration of each input note. Such step is performed by the ASG functional module. A number of works has been done on this topic; see the works by Ghias et al. (1995), McNab et al. (1996) and Pollastri (1998).

Quantification of the similarity between fragment and source patterns of a given piece of music is determined according to a library of six different metrics, based on the work by Polansky. Music metrics can be specified with respect to the direction – i.e., ascending/descending – and the width of the interval. These features can be evaluated either by considering adjacent notes – linear – or coupling any note to each other within sequences – combinatorial. By combining direction/width, linear/combinatorial, and ordering/non-ordering of sequences, eight metrics are obtained. In this library, combinatorial direction metrics are not considered, because they do not give any appreciable improvement to the search.

Musicians can define ad-hoc searching strategies for music retrieval using the environment shown in Figure 2, by combining metrics with different weights. Non-experts are given a default combination of metrics, so that musical content is classified with a well-balanced combination. Furthermore, the weight of pitch vs. duration in the matching process can be controlled. A set of operators can be used

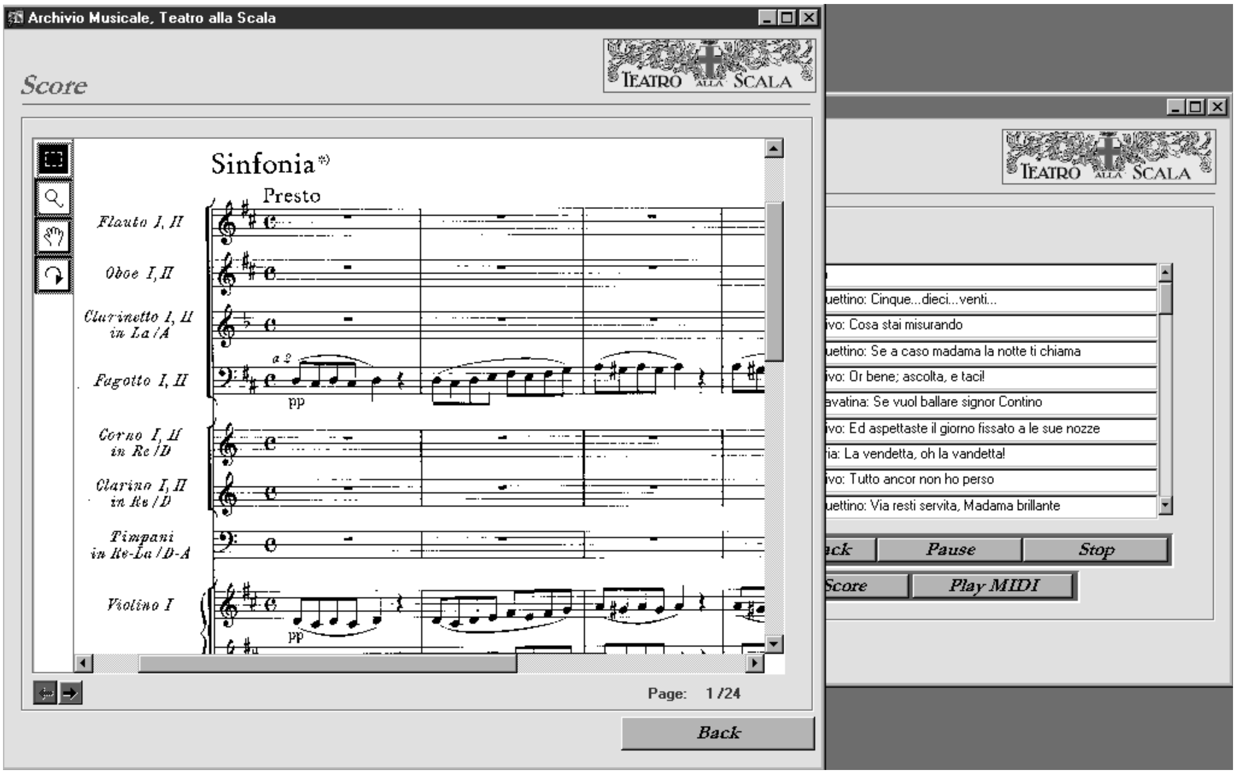

Fig. 3. An example of retrieval results after a query by audio fragment: optical media within the archive, sound and score are found and classified with respect to the similarity metrics defined by the user.

for retrieval to take into account logical closeness of related music fragments, such as when a fragment can be obtained from another with pitch transposition, retrogradation, mirror inversion, or a combination of the three.

The returned music files – audio, page sheets, and symbolic scores – are then presented to the user, together with their similarity degree with the input. The user can then select a music score, or one of its versions, from the list, observe its graphical representation, excerpts (see Figure 3), while simultaneously playing the music.

4 Two case studies: the musical archive projects at the Teatro alla Scala and Bolshoi Theatre

The music technology described in this paper has been partially and successfully adopted within two projects for rescuing theatre music archives, the former for the *Teatro alla Scala* in Milan, and the latter for the Bolshoi Theatre in Moscow.

The *Teatro alla Scala* of Milan is probably one of the best-known musical temples of the world. Although the Teatro alla Scala is often associated with operas, concerts and recitals, it also possesses a large historical archive of great significance, consisting of the *Musical Archive*, the *Photographic Archive*, the *Video Archive*, the *Costume Archive*, the *Scenographic Archive* and the *Properties Archive*.

The Musical Archive includes audio recordings – the *Phonic Archive* – and music scores – the *Score Archive*. Audio recordings have very heterogeneous content, ranging from first nights to standard performances, passing through final and general singer rehearsal, ballet masters, and so on, that cover a period of almost fifty years; see Haus et al. (1998).

Most of this material is either in paper form or stored in a variety of media such as disks, tapes or CD-R's. Clearly, its availability in digital form would be of great value to people doing research within the theater itself or outside of it, since a digital database would allow remote query of the content of the archive – for instance through the WEB – and provide information on the activities at the Teatro alla Scala.

For these reasons, a group of international sponsors has founded in 1997 a project with the aim to recover, restore and preserve the heritage of the Teatro alla Scala, thanks to a complete digitization of its archived materials, as well as to the creation of an on-line database to allow fast query and retrieval. The archive includes more than 5000 hours of music, 800 000 photos, 3000 hours of video, 5000 music scores, 60 000 costumes, 90 000 scene objects, 15 700 fashion-plates, 3600 sketches, and metadata concerning 4000 nights and all the related music media.

From a quantitative viewpoint, the audio component of the project will be approximately 5 terabytes; the other components (scores, photos, videos, etc.) will be approximately

100 terabytes. Audio and most probably also other multimedia data will be taken out of the database, but obviously linked within the database. Some of them – the ones concerning events under production – will be kept online by CD-R and DVD-R juke-boxes, the others are stored offline and indexed online.

The scientific direction of the project has been entrusted to the *Laboratorio di Informatica Musicale* (LIM) of the Computer Science Department at the University of Milan. The project has started with the digitization of the Teatro alla Scala tapes, while at the same time LIM began to apply for the first time the technology described in this paper as the *Musical Archive Information System* (MAIS), to store and retrieve audio material and music scores; see Haus (1998a), Haus (1998b), Ferrari and Haus (1999).

In 1999 a new project, the *Digital Asset Management* (DAM) project, was started, with the aim of including into MAIS all additional data from storage rooms, archives and warehouses. Furthermore, in 2000 a third project has been realized, the website of the theatre. The three projects are scientifically coordinated by LIM and consists in an integrated internal/external environment which includes:

– intranet services specialized for internal archives and production teams;
– internet website for giving information, sell tickets, music education, and e-commerce.

All the Scala software has been implemented in an Oracle 8i multiplatform distributed object-oriented environment; see Record (1998).

Then, a subset of MAIS has been used in a similar project conducted by LIM for the Bolshoi Theatre in Moscow. The goal was to rescue a "best" selection of 250 historical tapes approximately.

So, tapes restoring and digitization onto CD-R and a simpler database application has been developed. Tables 1 and 2 show the operas more often represented as documented by tapes of respective archives of the two theatres.

Both projects have been conceived and designed around an elementary logic unit called *night*, being the whole life of theatres centered around this concept. Conceptually, all main activities of theatres can be divided into the following three groups, defined in function of their temporal relations with the staging of a night:

1. the activities for the preparation of a night;
2. the actual staging of the night;
3. the conservation and exploitation of the items used during the night or produced for it.

The activities for the preparation of a night include:

I) retrieval and realization of properties, scenographies and costumes for the night;
II) retrieval and realization of musical material: orchestral scores, single instrument scores, audio recordings of previous productions of the same music pieces;
III) rehearsals necessary for the night.

Table 1. Operas more represented within the musical archive at the Teatro alla Scala.

Author	Title	Number of tapes
Giacomo Puccini	La Boheme	81
Giuseppe Verdi	La Traviata	67
Giacomo Puccini	Madama Butterfly	59
Giuseppe Verdi	Don Carlos	51
Wolgang Amadeus Mozart	Don Giovanni	49
Francesco Cilea	Adriana Lecouvreur	41
Gaetano Donizetti	Lucia di Lammermoor	41
Giacomo Puccini	Manon	40
Gioacchino Rossini	Guglielmo Tell	36
Carl Maria Von Weber	Oberon	36
Richard Wagner	Parsifal	36
Giuseppe Verdi	Rigoletto	35
Giacomo Puccini	Turandot	33
Gioacchino Rossini	La Cenerentola	32
Giuseppe Verdi	Aida	31

Table 2. Operas more represented within the musical archive at the Bolshoi Theatre.

Author	Title	Number of tapes
Wolfgang Amadeus Mozart	Requiem	10
Giacomo Puccini	Madama Butterfly	9
Alexander Borodin	Prince Igor	9
Piotr I. Tchaikovsky	Pike Dame	8
Giuseppe Verdi	Aida	7
Giuseppe Verdi	Otello	7
Giacomo Puccini	Turandot	7
Piotr I. Tchaikovsky	Eugene Onegin	6
Giacomo Puccini	La Boheme	6
Michail Glinka	Ivan Susanin	5
Gaetano Donizetti	Lucia di Lammermoor	5
Giuseppe Verdi	Il Trovatore	5

During the staging of a night, a number of items are produced, such as audio recordings, photos, and videos. MAIS has been designed for various sets of archives, each of which can store different types of items, produced or used during the staging of nights. Items coming from preparation and staging are put in their own specific archives, classified and stored. Every archive has its own methods to access the items it contains, since query methods depend on the media considered.

Both the first and the third have great historical value. Thousands of these documents are available and need to be preserved, and organized for efficient enjoyment. Furthermore, computer methods allows the Archive to enhance the quality of its products, and reduce the costs of many activities. For example, within musical archives' activities, the printing of transposed parts.

5 Perspectives

Future lines of research concern:

– generalization of the ASG module for automatic symbolic codes extraction (i.e., NIFF, ANSI SMDL, MPEG4 SASL) from graphic score files (i.e., TIFF, JPEG);
– generalization of the ASI module for automatic links generation between digital audio (i.e., PCM CD-DA, MP3) and score codes at many granularity levels (i.e., notes, bars, themes, pages, timing) within the cross environment orchestral scores, single instrument scores, multitrack audio recording, and orchestral stereo audio recording;
– generalization of the SS module for automatic generation of thematic indexes extracted from digital audio and music scores for music database applications.

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