CELLULAR AUTOMATA IN XENAKIS' MUSIC.
THEORY AND PRACTICE

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This paper is dedicated to Agostino Di Scipio, Peter Hoffmann and Horacio Vaggione.
The English version, edited here, has not been revised.

ABSTRACT

Cellular automata are developed since some decades, belonging to the field of abstract automata. In the beginning of the 1980s, they were popularized in relationship with the study of dynamic systems and chaos theories. They were also applied for modelling the evolution of natural systems (for instance biological ones), especially in relationship with the idea of auto-organization. From the end of the 1980s since nowadays, several composers begin to use cellular automata. Xenakis must have been one of the first (or the first), as he used them, probably for the first time, in *Horos* (1986), so as to produce harmonic progressions and new timbre combinations. His use of cellular automata seems to be limited. This paper has three aims: 1. To try to understand the reasons why Xenakis used cellular automata. This will mean a discussion of the idea of "automaton", characterized as a model of autonomy (as opposed to the model of the "command"); 2. To analyze three instances of musical implementations of cellular automata in *Horos*; 3. To discuss the notion of "theory" specific to Xenakis. Based on the analysis of scores and of sketches (Archives Xenakis, Bibliothèque nationale de France), the analysis of musical implementations of cellular automata in *Horos* will show that Xenakis acts as he is always acting when he is appealing to one or another form of formalization: he uses them to produce a result, allowing himself *bricolage* (either in the construction of the tool itself, either in the results produced by the tool). In other terms, his use of cellular automata is mediated through manual interventions.

1. INTRODUCTION

In the preface to the second American edition of *Formalized Music* (1992), Xenakis devote a whole paragraph to cellular automata and to the use of them that he made in his music:

> "Another approach to the mystery of sounds is the use of cellular automata which I have employed in several compositions these past few years. This can be explained by an observation which I made: scales of pitch (sieves) automatically establish a kind of global musical style, a sort of macroscopic "synthesis' of musical works, much like a 'spectrum of frequencies, or iterations', of the physics of particles. Internal symmetries or their dissymmetries are the reason behind this. Therefore, through a discerning logico-aesthetic choice of 'non-octave' scales, we can obtain very rich simultaneities (chords) or linear succession which revive and generalize tonal, modal or serial aspects. It is on this basis of sieves that cellular automata can be useful in harmonic progressions which create new and rich timbric fusions with orchestral instruments. Examples of this can be found in works of mine such as *Ata*, *Horos*, etc." [39: XII].

Knowing that this preface is relatively short, the length of this paragraph shows the importance that Xenakis lends to cellular automata. Indeed, they can be considered as one of his "theories", and we know that there are relatively few xenakien theories (see [24]). Moreover, it seems that it is his last theory. Speaking in 1989 about his compositions of the 1980s, he said: "In all these years I've been working on the theoretical construction of sieves […] Apart from that the only new procedures I've used is the so-called cellular automata" (Xenakis *in* [33: 199]). But we have to be careful, as, until today, the music of his last period has not been extensively studied.

Peter Hoffmann is the first specialist who studied cellular automata in Xenakis' music [12: 145-152; 13: 124-126]. He showed the relationship of cellular automata to the idea of an "automated art" and to chaos theories, and he analyzed an extract of *Horos*. Benoît Gibson [9: 166-168], James Harley [11: 176-178] and myself [25, 26] are three other

specialists, who have studied that subject. The fact that, for the moment, only few Xenakis' specialists have shown interest in his use of cellular automata is quite understandable. First, as I said, the field of Xenakis' late works remains largely to be explored. And second, Xenakis himself has commented this theory in very few extracts of his writings. There is no developed article of him devoted to this subject. Except the quoted paragraph from *Formalized Music*, there are, to my knowledge, only three other references, belonging to two interviews: Restagno [18: 61] and Varga [33: 182-184, 199-200]. I will quote them later.

This paper has two main goals. First, after mentioning what could have been Xenakis' source on cellular automata, I will try to search for the reasons why he developed an interest for them. There are general reasons: his love of a turbulent, wild nature; the idea of automaton seen as a model for autonomy. There are also musical reasons: harmonic progressions and sonorities. Then, I will study his use of cellular automata in *Horos*. This study will be the occasion to deal with a typical xenakien problem: the relationship between theory and practice. What is "theory" for Xenakis is an important question: is it just a tool for formalization, and for producing sonorities? Is it *theoria* in the Greek sense of the word? And, of course, we will see that – as it happens with all his "theories" – in his concrete use of cellular automata, Xenakis takes liberties with his model, and introduces "licences", "gaps" (*écarts* in French), manual interventions; in other terms, his use of cellular automata is mediated through *bricolage*. The conclusion of the paper will raise a last question: to what extent do we find cellular automata in Xenakis' late music?

2. CELLULAR AUTOMATA AND XENAKIS' GENERAL AND MUSICAL INTEREST

2.1. Cellular automata and Xenakis' sources

		0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
bar 10	1												1											
	2											1	1	1										
	3										1	4		4	1									
	4							1	2	2	1	2	2	1										
	5							1			2	2	2	2	2		1							
	6						1	1			4	4	4			1	1							
	7					1	4	4	1		1	2	1		1	4	4	1						
	8				1	2	4	4	2	4			4	2	4	4	2	1						
	9			1						4				4						1				
	10			1	1	1													1	1	1			
	11		1	4		4	1											1	4		4	1		
	12		2	2	1	2	2	1									1	2	2	1	2	2		1
	13			2	2	2	2		1						1			2	2	2	2			4
	14		4		4	4			1	1					1	1			4	4		4		
	15			1	1	1		1	4	4	1			1	4	4	1		1	1	1			
	16		1	4		4	4	2	4	4	2	1		1	2	4	4	2	4	4		4	1	
bars 14-15	17		2	2	1	1							4						1	1	2	2		1
	18	4		2		4	1												1	4		2		4
	19		4	4	4	2	2	1									1	2	2	4	4	4		
	20	1	2			1	2		1								1	2	1		2	1		
	21	1							1	1			1	1										1
	22								1	4	4	1			1	4	4	1						
	23					1		2	4	4	2	1		1	2	4	4	2	1					
	24					1							4						1					
	25			1	1	1												1	1	1				
	26			1	4		4	1								1	4		4	1				
	27		1	2	2	1	2	2	1							1	2	2	1	2	2	1		
	28	1		2	2	2	2	2		1						1	2	2	2	2				1
	29		4			4	4	4			1	1				1	1		4	4	4		4	
	30			1	1	2	1		1	4	4	1		1	4	4	1		1	2	1	1		
	31		1	4					4	2	4	4	2	4	2	4	4	2	4			4	1	
	32	?	2	2					4				1					4				2	2	1
	33	?		4								1	1	1						4				4

Figure 1. Reconstruction of the cellular automaton used in *Horos*, bars 10 and 14-15 (code number 4200410).

sum	0	1	2	3	4	5	6	7	8	9	10	11	12
value	0	1	4	0	0	2	4	0	1	4	0	0	2

Figure 2. Transformation of the sums with code number (200410)4200410.

"The components of a cellular automaton are mathematical 'cells', arranged in one dimension at a sequence of equally spaced points along a line or in two dimensions on a regular grid of squares or hexagons. Each cell carries a value chosen from a small set of possibilities, often just 0 and 1. The values of all the cells in the cellular automaton are simultaneously updated at each 'tick' of a clock according to a definite rule. The rule specifies the new value of a cell, give its previous value and the previous values of its nearest neighbors or some other nearby set of cells" [35: 194]. Let's take the example shown in **figure 1** (as we will see, it is one of the automata used in *Horos*). This automaton starts from a "seed" (i.e. a single point), and "grows": the vertical numbers show the successive steps of the automaton, at time 1, 2… 33. The possible values are not only 0 and 1, but they are very few: if you look at all the figure, you will only find the following values: 0 (empty cell), 1, 2, 4. So, you can read the evolution (the "growth") of the automaton as such: at time 1, it starts with value 1 in column 11; at time 2, we have the values 1, 1, 1 in columns 10, 11, 12; at time 3, we have the values 1, 4, 0, 4, 1 in columns 9 to 13; etc. The rule, which specifies the way the evolution happens, says that:

1. The value of a cell at time $t+1$ equals the value of the cell at time t plus the values of the two neighbouring values (left and right)

2. There is a transformation of this sum, which is realized through the "code number" of the automaton. Here, the code number is 4200410. It has to be read from right to left, and it specifies that: if the sum (step 1) equals 0, the value of the cell will be 0; if the sum equals 1, the value will be 1; if the sum equals 2, the value will be 4; etc. **Figure 2** shows all possible transformations (as the possible sums are going till the number 12, the whole code number is: 2004104200410).

Cellular automata belong to the mathematical theory of automata, which is "a branch of the theory of control systems" [6: 289]. "The theory of automata was born in the mid-twentieth century in connection with finite automata, which are mathematical models of nervous systems and electronic computers" [6]. The first cellular automata were developed in the 1940s and 1950s by John von Neumann [see Weisbuch, 1989: 38]. During the following decades, they remain "curiosities", like for instance the 1970 "Game of Life" elaborated by John Conway. During the beginning of the 1980s, thanks to the development of computers, they began to develop very quickly; they were "popularized" and they find applications in several scientific fields (see for instance [8]). Till today, the numerous studies of Stephen Wolfram of that period (for instance: [34, 35, 36]) remain references.

"Cellular automata are discrete dynamical systems with simple construction but complex self-organizing behaviour" [36]. So, they helped the development of the new scientific field emerging in the end of the 1970s, which deals with dynamical systems, chaos theories, and, more generally, with what is called today "the sciences of Complexity". Indeed, "cellular automata are mathematical models for complex natural systems containing large numbers of simple identical components with local interactions". [36]. Look for instance at the graphical representation of two cellular automata (**figure 3**). To take the title of a Xenakis' piece of 1983, we can easily imagine them as *lichens*.

**Figure 3. Two cellular automata. Wolfram (1984c).**

Today, the use of cellular automata in music begins to be very common. If you search in the web, you will find several sites with different applications. There are even applications to sound synthesis (see [17]). In the 2004' International Computer Music Conference, several authors presented musical implementations with cellular automata (see [17b]: papers from Dale Millen, Peter Beyls, Dave Burraston, Kam Wah Wong). Musicologists also begin to use cellular automata for music analysis (for instance, Marc Chemillier [3] analyzed in that way an extract of 1971 Ligetis' *Melodien*[1]). But in the mid 1980s, the musical community was probably not aware about cellular automata! Thanks to his scientific curiosity, Xenakis is probably the first composer to have used them.

We can put forward the hypothesis that Xenakis' source about cellular automata is an article of Stephen Wolfram published in *Scientific American* of August 1984 [[35]][2]. Xenakis had a subscription to this review, and he had already drawn his inspiration from it (for instance: a 1976 article about supernovæ was introduced in the programme of the *Diatope*; in *Keqrops*, he used a specific group that he found in an article of 1985[3]). In the Archives Xenakis, Bibliothèque nationale de France, the *Scientific American's* issue with Wolfram's article is missing (that is also the case with other issues), so this hypothesis will remain a hypothesis. The strongest argument for this hypothesis is the fact that we find in this article the automaton with the code number 4200410, used by Xenakis (see **figure 4**; note that the original is in colour), and it is important to remind that the values of a cellular automaton are "often just 0 and 1", which is not the case of this automaton.

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[1] I am grateful to Mihu Iliescu who turned my attention to that article.

[2] Peter Hofmann [2002: 124] is the first specialist who put forward this hypothesis. I am glad to confirm it.

[3] See Archives Xenakis, Bibliothèque nationale de France, Dossiers œuvres 30/8: we can find there this article ("The Enormous Theorem") from the *Scientific American*, with Xenakis' annotations.
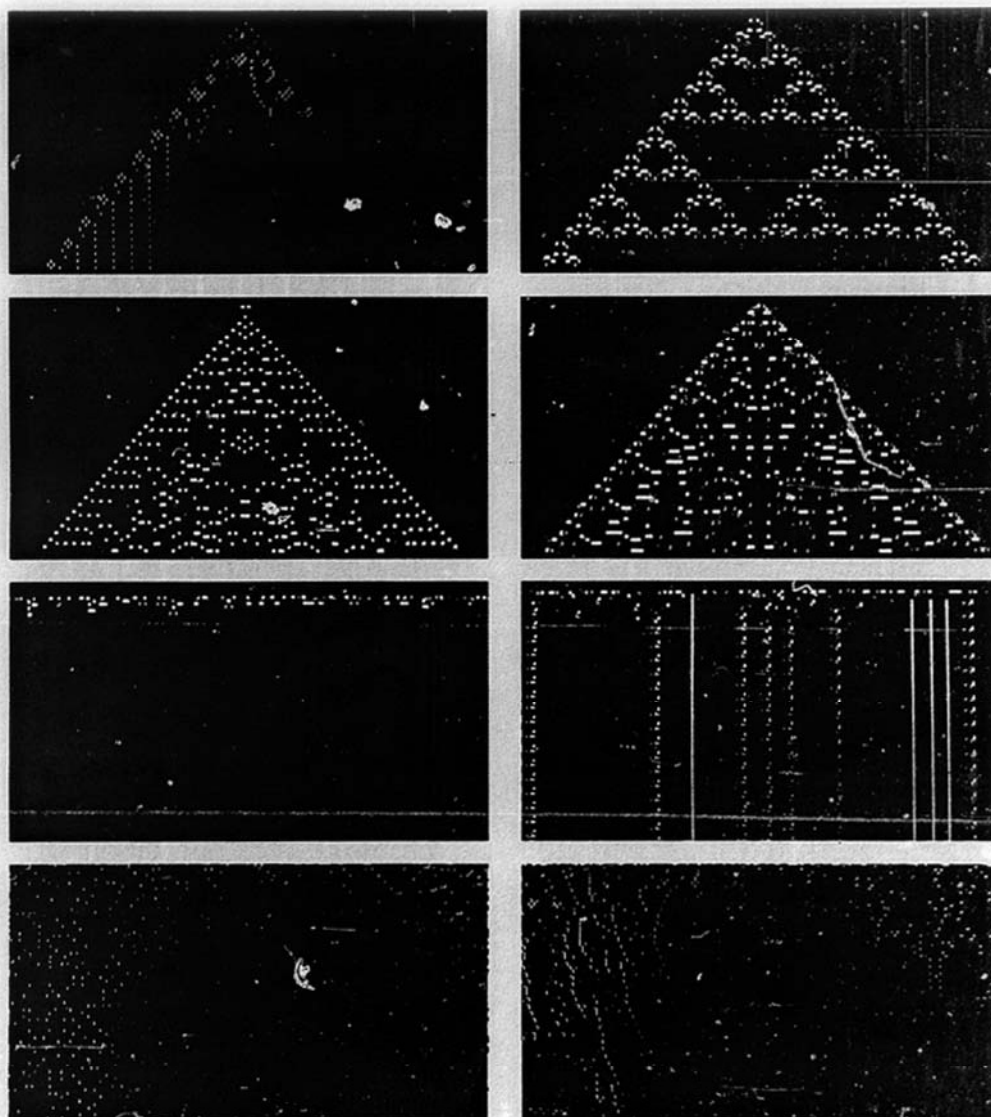
2213310₄	4200410₄	■ =0
331240₄	2024310₄	■ =1
1100400₄	2231000₄	■ =2
131210₄	3211310₄	■ =3
		□ =4

COMPLEX BEHAVIOR can develop even in systems with simple components. The eight cellular automata shown in the photographs are made up of lines of cells that take on one of five possible values. The value of each cell is determined by a simple rule based on the values of its neighbors on the previous line. Each pattern is generated by the rule whose code number is given in the key (*see illustration on page 197*). The patterns in the upper four photographs are grown from a single colored cell. Even in this case the patterns generated can be complex, and they sometimes appear quite random. The complex patterns formed in such physical processes as the flow of a turbulent fluid may well arise from the same mechanism. Complex patterns generated by cellular automata can also serve as a source of effectively random numbers, and they can be applied to encrypt messages by converting a text into an apparently random form. The patterns in the lower four photographs begin with disordered states. Even though the values of the cells in these initial states are chosen at random, the evolution of the cellular automata gives rise to structures of four basic classes. In the two classes shown in the third row of photographs the long-term behavior of the cellular automata is comparatively simple; in the two classes shown in the bottom row it can be highly complex. The behavior of many natural systems may well conform to this classification.

Figure 4. Wolfram, 1984b: 199.

Wolfram's article is not devoted to cellular automata, it has a general title: "Computer Software in Science and Mathematics". It deals with the use of computer in mathematics, and in science. It shows that this use can be fertile, especially for the simulation of complex systems (remind that, at that time, the idea of "complexity" was not yet firmly established). The article associates this idea to the expression "experimental mathematics", an expression used by Xenakis in the preface of *Formalized Music*[4]. The article takes as examples random walks (already used, as it is well known, by Xenakis; but it deals also with "self-avoiding random walks", which were perhaps also used by Xenakis[5]) and cellular automata, and concludes with the question of the computational irreducibility. The more complex cellular automata are computational irreducible: there is no "algorithm that could work out the behavior of these automata faster than the automata themselves evolve" [35: 198]. Knowing that a computer can easily draw the evolution of these automata, then they can serve to simulate evolution of complex systems much more difficult to draw. The extract devoted to cellular automata takes half of the article, with a lot of illustrations. It starts with the following statement, where there is a reference to "fluid turbulence": "Several examples have been given of systems whose construction is quite simple but whose behavior is extremely complicated. The study of such systems is leading to a new field called complex-system theory, in which the computational method plays a central role. The archetypal example is fluid turbulence, which develops, for example, when water flows rapidly around an obstruction. […] It is suspected there is a set of mathematical mechanisms common to many systems that give rise to complicated behavior. The mechanisms can best be studied in systems whose construction is as simple as possible. Such studies have recently been done for a class of mathematical systems known as cellular automata" [35: 194].

2.2. Xenakis' general interest for cellular automata

Why did Xenakis take a great interest in cellular automata? Their novelty and their mathematical elegance and simplicity (like the group theory) played probably an important role. If we search for more general reasons, we can enumerate at least two.

The first reason is related to the "fluid turbulence", which has just been quoted. In one of his few references to cellular automata, after having explained the way they function, Xenakis says: "They are very simple rules which can create structures on very large surfaces. It's related to the nature of fluids, for instance. For me the sound is a kind of fluid in time – that's what gave me the idea to transfer one area to the other. I was also attracted by the simplicity of it: it's a repetitious, a dynamic procedure which can create a very rich output" (Xenakis *in* [33: 200]). Indeed, in the middle of the 1980s, cellular automata have already been applied to hydrodynamics. In a technical article of 1985, we can read: "At a microscopic level, the cellular automata are discrete approximations to molecular dynamics, and show relaxation towards equilibrium. On a large scale, they behave like continuum fluids, and suggest efficient methods for hydrodynamic simulation" [37]. **Figure 5** shows a simulation of a fluid turbulence with a cellular automaton.
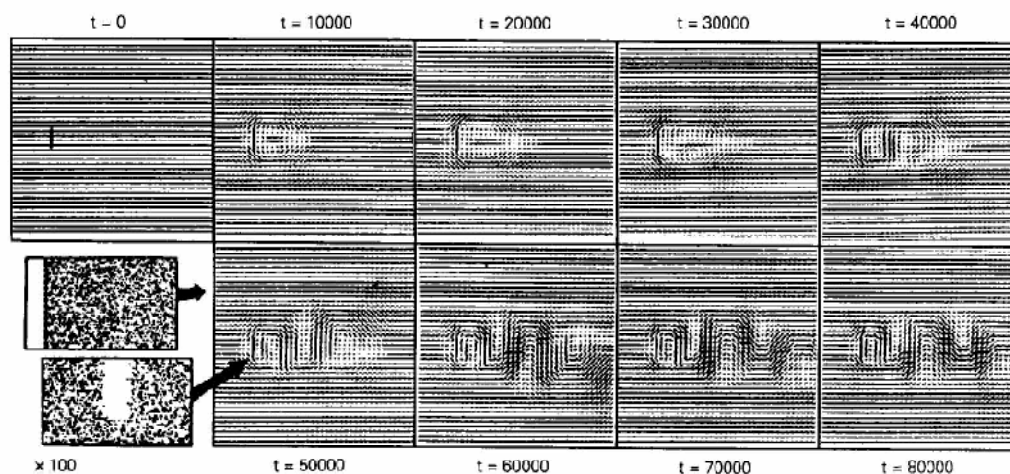
Figure 5. Simulation of a fluid turbulence with a cellular automaton. Wolfram, 1985.

The ideas of fluid and turbulence are of course related to a more general idea, very important for Xenakis: nature. As it is well known, references to nature are very frequent in Xenakis' work. Recalling the steps that had led him to stochastic composition, he says: "The first step was the control of mass events and the recognition of laws which govern nature" (Xenakis *in* [33: 76]). In a sense, for Xenakis there is no duality of the kind "nature vs. culture". The

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4 "Today, there is a whole new field of investigation called 'Experimental Mathematics', that gives fascinating insights especially in automatic dynamic systems, by the use of math and computer graphics" [39: XII]. "Experimental mathematics is an exploratory technique made possible largely through the use of computer" [35: 198].

5 "Self-avoiding random walks" are random walks where "the successive steps […] must not cross the path taken by any previous steps". Wolfram adds that they can be simulated by Monte Carlo method [35: 192-194]. In some works from the second part of the 1980s, Xenakis maybe used self-avoiding random walks to create melodies. I make this hypothesis because in the Archives Xenakis we find for these works list of probabilistic numbers corresponding perhaps to pitch coordinates, with references to "Monte Carlo". This hypothesis has to be explored!

"cosmos" or "universe" (ultimately: nature) is for him the only existing thing. This is why his music often appears as naturalist. But it is important to note that the kind of nature he is referring to is the one supplied by modern science. It is far removed from, say, the naturalistic views proper to Classicism or Taoism – Nature as Harmony. This is fundamental to understand Xenakis' "naturalism". The nature he is referring to is the one of thermodynamics, of probabilities, of Brownian movements, etc[6]. It was then normal that he expresses an interest in chaos theories, which were popularized only in the end of the 1970s and on. For him, there was nothing new: "They open up new horizons, although for me, the results are novel aspects of the equivalent compositional problems I started dealing with about thirty-five years ago", is he saying in the preface of the second edition of *Formalized Music* [39: XIII]. It is in the same text that the idea of chaos is related to cellular automata: as it has already been said, cellular automata can simulate complex, chaotic natural events.

The second motivation that certainly led Xenakis to cellular automata is the idea itself of "automaton". It is well known that Xenakis took a great interest in automata. There are numerous articles where he expresses this interest. In what remains from his library (Archives Xenakis), there are two books, both from the end of the 1960s, dealing with the mathematical theory of automata. In the first [1] there are handwritten annotations in the chapter "Finite automata". In the second [10], there are no annotations, but there is, inside it, a handwritten sheet of paper with notes on automata from the Antiquity, on the general notion of automaton by Descartes, on living automata (reference to Goethes' *Faust*), and to the mathematical theory of automata.

This idea is related to "formalization", which has several meanings in Xenakis' thought and practice. One of its meanings is the idea of "mechanism", very important for Xenakis on the 1960s. Recently, Sharon Kanach has argued that the first proposed title for the first French edition of *Musiques formelles* was *Mécanisme d'une musique* [14: 203]. In the book, Xenakis used the word "mechanism" when dealing with stochastic composition with computers: "[…] everything that is rule or repeated constraint is part of the mental machine. […] A musical work can be analyzed as a multitude of mental machines. A melodic theme in a symphony is a mold, a mental machine, in the same way as its structure is. These mental machines are something very restrictive and deterministic, and sometimes very vague and indecisive. In the last few years we have seen that this idea of mechanism is really a very general one. It flows through every area of human knowledge and action, from strict logic to artistic manifestations. Just as the wheel was once one of the greatest products of human intelligence, a mechanism which allowed one to travel farther and faster with more luggage, so is the computer, which today allows the transformation of man's ideas" [38: 164; English translation: 39: 132]. And of course, from the idea of mechanism we can easily go to the idea of "black box", which underlies the algorithmic model, where you have an input, transformations, and an output.

All this is well known, and I just wanted to show the possible direction: automaton → black box. *But* this is only one possible direction! In our postmodern civilization, which is drawing to an end, where the idea of automation is embodied in repressive technologies (pseudo virtual wars, web surveillance…), we tend to confuse, to identify the post war II radicalization of the idea of automaton with other ideas developed through the same period: the information theory, the development of computers as universal machines, etc. – and, ultimately, we tend to reject it, opposing to it what remain of humanity: freedom, inspiration, etc. And yet, the idea of automaton is not so unequivocal. Francisco Varela [32: 209-211] has shown that, in the beginning of all that history, *two* ideas confront each other. The first was developed by von Neumann (who thought the computer as a universal machine): it is the idea of the *command*, and, to simplify, the idea of the black box. Norbert Wiener, the founder of cybernetics, who believed in the idea of autonomy, developed the second. This opposition has a political aspect: von Neumann participated in the development of A- and H-bombs and, during the Cold War, recommended a preventive nuclear attack against USSR; in the same period, Wiener was judged unpatriotic. The idea of the "command" is clearly related to the military model, while the idea of "autonomy" is interested in "the generation, the affirmation of its own identity, the internal regulation, the internal definition" (of a system) [32: 7]. The problem is that the first idea has prevailed… But there is no reason to identify the idea of the automaton with the idea of the information flow (of the black box, of the "command"; of a military drone, for instance!): in reality, if we take into account the etymology of the word, its relationship with the second idea is much more clear.

I think that Xenakis' idea of automaton is related to the idea of autonomy. Let's read a long quotation, where I underline two small sentences. Speaking about the step from *Achorripsis* to the *ST* program, he says:

> "Cela correspond à cette idée de base qui est d'unifier et de faire une sorte d'automate sonore qui marcherait tout seul une fois que vous mettez la prise de courant. Et cela correspond […] à une préoccupation […] immémoriale de l'homme. Quand on fabriquait à Alexandrie des automates, c'était un peu ça ; des machines à vapeur ou des clepsydres […] Les machines antiques, c'était cela. Ensuite, à travers le Moyen Âge aussi, il y a eu des tentatives d'imiter la vie d'une manière automatique. *Qu'est-ce que cela veut dire 'automate' ? Qui marche tout seul.* Et dans la tête d'Aristote, cela voulait dire : au hasard. […] Et ensuite, la même préoccupation fondamentale se trouve chez les alchimistes du Moyen Âge et se retrouve en résumé dans le *Faust* de Goethe, qui termine la première partie avec la fabrication par Wagner de l'*homunculus*, le petit bonhomme, qu'il sort de la fiole. […] Et dans le domaine de la musique, cela correspond à des principes comme celui de la fugue. […] Donc le problème de l'automate est un problème fondamental en composition musicale, mais aussi dans le domaine artistique en général. *C'est ce qu'on appelle l'unité d'un organisme*" (Xenakis *in* [4: 65-67]).

"Qu'est-ce que cela veut dire 'automate' ? Qui marche tout seul" ("What means 'automaton'? Something that works all on his own"); "C'est ce qu'on appelle l'unité d'un organisme" ("It is what we call the unity of an organism"): here is clearly expressed the idea of autonomy. Of course, most of Xenakis' musical automata seem nearer to the model of the "command", of the black box. It is perhaps the case with the *ST* program. Maybe it is the case with some very formalized works, manually composed, like *Herma* or *Nomos alpha*. And it is probably the case of the *GENDYN*

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[6] For a discussion of the idea of nature by Xenakis, see [27].

program, although it uses dynamic systems. As we know, the development of dynamic systems, chaos theories, etc. reinforced the idea of autonomy – for instance, it is in parallel with their development that part of cognitive sciences begun to question the computationalist paradigm ("the brain as a computer", a paradigm which is subject to the idea of the "command"), and to develop the paradigm of the emergence ("the brain as a neuronal network", a paradigm which is nearer to the idea of autonomy). But, if we follow Agostino Di Scipio's analysis, the *GENDYN* program does not take this direction[7].

It is difficult to discuss these questions without detailed analysis. We can only add that Xenakis himself was not totally satisfied with the *ST* program[8], and probably neither with the *GENDYN* program. But we can put forward the hypothesis that part of his interest for cellular automata results from the fact that they accomplish the idea of the automaton as an autonomous system: they are better means to fulfil the idea of autonomy, than the stochastic models used in the *ST* program or in the *GENDYN* program (and than the ensemble theory of *Herma* or the group theory of *Nomos alpha*, at least in the way they are used). I based this hypothesis on the fact that, in scientific implementations of cellular automata[9], we find, behind them, the model of the autonomy. It is the case of Varela's works in the field of neurobiology, where he developed the idea of *autopoïesis*, and used cellular automata as examples to clarify it [32: 49-53, 217-22]. The philosophical ideas behind the notion of "autopoïesis" are, first, the fact that a living system does not have something like a Subject (in the philosophical sense): it grows from the interaction of simple components, and the "meaning" is an "emergence" (a "bring forth", a *hervorbringen*, in the language of phenomenology). And second that this growth happens in the interaction between the system and his environment, which, in a way, is part of the system itself. These precisions are important because a part of the terminology of cellular automata could remind the well known, for musicians, model of organicism: they "grow", some of them begin with a "seed", etc. But the 19th century musical organicism is very different: it needs a Subject, it develops itself against its environment. In some cases, it leads to monstrous outgrowths.

Knowing that Xenakis' music is rooted in the aesthetic of the Subject, when examining his musical implementations of cellular automata, the question will be: do these implementations fulfil the idea of autonomy?

2.3. Xenakis' musical interest for cellular automata

All these discussions need further developments – here, they have been just outlined. But let's now search the musical reasons of Xenakis' interest for cellular automata. Xenakis himself has given very clearly two reasons.

> "The method [cellular automata] helps in deciding how to go from the notes of one chord to those of another within a rational, perceptible structure. […] Let's say you have a grid on your screen, with vertical and horizontal lines forming small squares, that is, cells. They are empty. It's for the composer (whether working with pictures of with sounds) to fill them. How? One way is through probabilities, for instance by using the Poisson distribution, as I did 30 years ago in *Achorripsis*. There's also another way, with the help of a rule that you work out for yourself. Let's suppose the vertical lines represent a chromatic scale, or semitones, quarter-tones and so on. Any kind. You start at a given moment, that is, at the given vertical line, at a given pitch – in other words, a cell – and you say: here's a note played by an assigned instrument. What's the next moment going to be? What notes? In accordance with your rule, the cell which has been filled gives birth to say, one or two adjacent cells. In the next step each cell will create one or two notes. Your rule helps to fill the entire grid. These are the cellular automata" (Xenakis *in* [33: 199-200]). " […] It is on [the] basis of sieves that cellular automata can be useful in harmonic progressions" [39: XII].

So the first reason is to create harmonic progressions. Take **figure 1** and make a rotation of 90° to the right, and then read again Xenakis' description: we have chords progressions in time. The description says that the pitches can be taken in a chromatic continuum. But the second sentence says that they are taken in a sieve. The few extracts where I have found cellular automata use sieves – and that is normal, as, at that time, Xenakis used sieves. As we know, with sieve theory, Xenakis choose notes to elaborate a scale. But it does not give the means to create melodic lines or harmonic progressions, if of course they are not linear progressions (for instance: scales), which is a common case. Until today, the Xenakis created these lines or progressions have not been studied in detail. We could suppose that, sometimes, he did it manually. But he probably used also mechanical procedures[10]. Cellular automata are such a mechanical procedure.

The second reason has already been quoted:

> "It is on this basis of sieves that cellular automata can be useful in harmonic progressions which create new and rich timbric fusions with orchestral instruments" [39: XII]. "Naturalmente puoi ottenere, con lo stesso principio, anche una propagazione di colori; basta identificare il suono di una determinate cellula con un determinato timbro e procedere" (Xenakis *in* [18: 61]).

Look again at **figure 1**, and pay attention to the possible values of the cells (0, 1, 2, 4). As we will see, they can be associated to family instruments of the orchestra. It is the reason why this automaton has more that just 0, 1 as values.

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7 Di Scipio [5], after dealing with *Analogique A et B*, *Concret PH* and the *GENDYN* program, writes: "Before *Gendy3*, where the macro-level controls are no more determined directly by the composer but by a 'composing' program that triggers and initializes lower-level synthesis processes, Xenakis' mechanism can hardly be seen as an actual instance of 'automatic art' freed of human interference. However, even in the case of *Gendy3* or *S.709*, the stochastic laws anyway prevent the mechanism itself from establishing a truly self-organizational dynamics". [5: 83].

8 Answering to a question about the clarity of the macroform, Xenakis says: "Dans toute la série *ST* […], le programme […] est pour beaucoup dans la formation macroscopique. Je veux dire que les choses ne sont pas aussi automatiques que j'ai l'air de le dire. Même si on les rend automatiques, il faut des ajustements, il faut des coups de pouce – et c'est ce que j'ai fait – avec le programme. C'est-à-dire que […] l'organisation de la macroforme en relation avec la microforme […] est faite avec une certaine désinvolture. Elle aurait pu être différente et aurait donné un résultat différent. Mais c'était une façon de voir que j'avais à l'époque, et que je reconnais maintenant qu'il y a beaucoup de façons d'ailleurs, bien sûr, tout en restant soumis à cette idée de base: faire une famille d'œuvres, représentée par un programme machine, telle que l'ensemble soit régi par un nombre aussi petit que possible de principes et de règles" (Xenakis *in* [4: 71-72]).

9 And also in some musical implementations: it seems to be the case of Miranda's works [17].

10 See the previous footnote about "self-avoiding random walks".

Furthermore, we can add that the harmonies themselves are sonic synthesis, or, more exactly, specific filterings (in the sense of electronic music) of a global timbre: being a stratification of the register, a sieve itself can be conceived as a (macroscopic) sound synthesis[11].

3. CELLULAR AUTOMATA IN *HOROS*

3.1. *Horos* and cellular automata

Horos, which is very representative of Xenakis' late style, was achieved in summer 1986[12], and was premiered on October 1986, in Japan. To limit myself to the reasons why cellular automata could have been used in *Horos*, I will say that, in that piece (like in others from this period), Xenakis takes particular interest in the orchestration. The word has here a double sense. First, it means the research of new combinations of timbre. So the use of cellular automata is understandable (second musical reason). It also means a kind of geometrical work on orchestral blocs, where the first musical reason can also play an important role. Indeed, *Horos* seems to follow a specific plan, which can be seen as the way its macroform is organized. There is a progression leading from static homophony of only 4 same instruments (first chord of bar 1) to a kind of polyphony of the *tutti* with a lot of divisions (final bars, 121-129). This progression is not linear, it is made with interpolations, i.e. a section can go to an evolution phase previous to the evolution phase where was the previous section. Between the two extreme evolution phases, there are several phases. The determination of a specific phase of evolution is the result of the combination of the evolution of two factors: a) density: going from a single family instruments with few divisions to the *tutti* with a lot of divisions; b) homophony/polyphony: going from static homophony (combinatorial repetition of a few chords) to polyphony. For instance, intermediate phases can be: relative dynamic homophony (combinatorial repetition of several chords) in the *tutti* with few divisions (bars 40-42); heterophony in some instruments (bars 109-120). Then, the first mentioned musical reason to use cellular automata is clear. If they are used to create harmonic progressions: a) they allow to create sections where density is in constant change; b) they remain in the frames of homophony, but with constant changes of the chords, defining then a very dynamic homophony.

I will analyze three instances of cellular automata in *Horos*. This analyze is possible of course with the help of the score, but also with the help of documents of the Archives Xenakis[13] – the second and third instances are not analyzable without the help of these documents. These documents consist in narrow and long printed sheets of paper, from the small pocket computer of Xenakis, where he programmed calculations of cellular automata[14].

3.2. Bars 10-15 and 16-18

"It is in this piece [*Horos*] that I used the cellular automata to determine the succession of chords. Bars 10 and 16, for instance, are areas created in this way, calculated with my pocket computer" (Xenakis *in* [33: 182-184]). **Figure 6** shows bars 10-18. The sieve used during this section is shown in **figure 7** (upper numbering). It has the famous sound connotation of many of Xenakis' sieves from the late 1970s and on, the Javanese one from a *pelog* scale, characterized, by Xenakis, as the interlocking of two fourths[15] (here: pitches 8-11, 12-15 and 14-17). This sieve is very often used in *Horos* – but there are also other sieves –, sometimes extended as far as the deepest and/or higher register.

Figure 7. Sieve of *Horos*' bars 10-18 (upper numbering) and 67-71 (lower numbering).

11 "The structure of the melodic scale is very important, not only in melodic patterns – melodies – but also in producing chords of a different timbre. If you take a given range, and if the structure of the scale is rich enough, you can stay there without having to resort to melodic patterns – the interchange of the sounds themselves in a rather free rhythmic movement produces a melodic flow which is neither chords nor melodic patterns. […] They give a kind of overall timbre in a particular domain" (Xenakis *in* [33: 145]). [21: 86-96] and [22: 135-138; English translation: 163-165] develop these questions.
12 See the indication in the score, Éditions Salabert.
13 Dossiers œuvres 33/4.
14 There is a big conservation problem with these printed sheets, as we can see in **figure 8**.
15 "I want to tell you about something which has been very important for my evolution: my study of Javanese music, and of the scale called *pelog* in particular, which is based on a very powerful interlocking of two fourths" (Xenakis *in* [33: 144]).

Figure 6. *Horos*: bars 10-18. Éditions Salabert.

3.2.1. Bars 10 and 14-15

In bar 10, you can read a very strange annotation for a musical score: (4200410). If you have read this discussion about cellular automata, you will recognize the code number of a cellular automaton, the one presented in **figure 1**. **Figure 8a** shows Xenakis' printed sheets of paper with the results of the calculations for this cellular automaton. We can read the following handwritten annotations: "Japon 86", "(4200410)": it is the automaton which begins in bar 10. It uses symbols and not numbers. There is another document of the Archives (a printed sheet for another automaton) where Xenakis gives, in a handwritten annotation, the equivalences:

- symbol of a lozenge = 1
- o = 2
- symbol of a dense "e" = 4
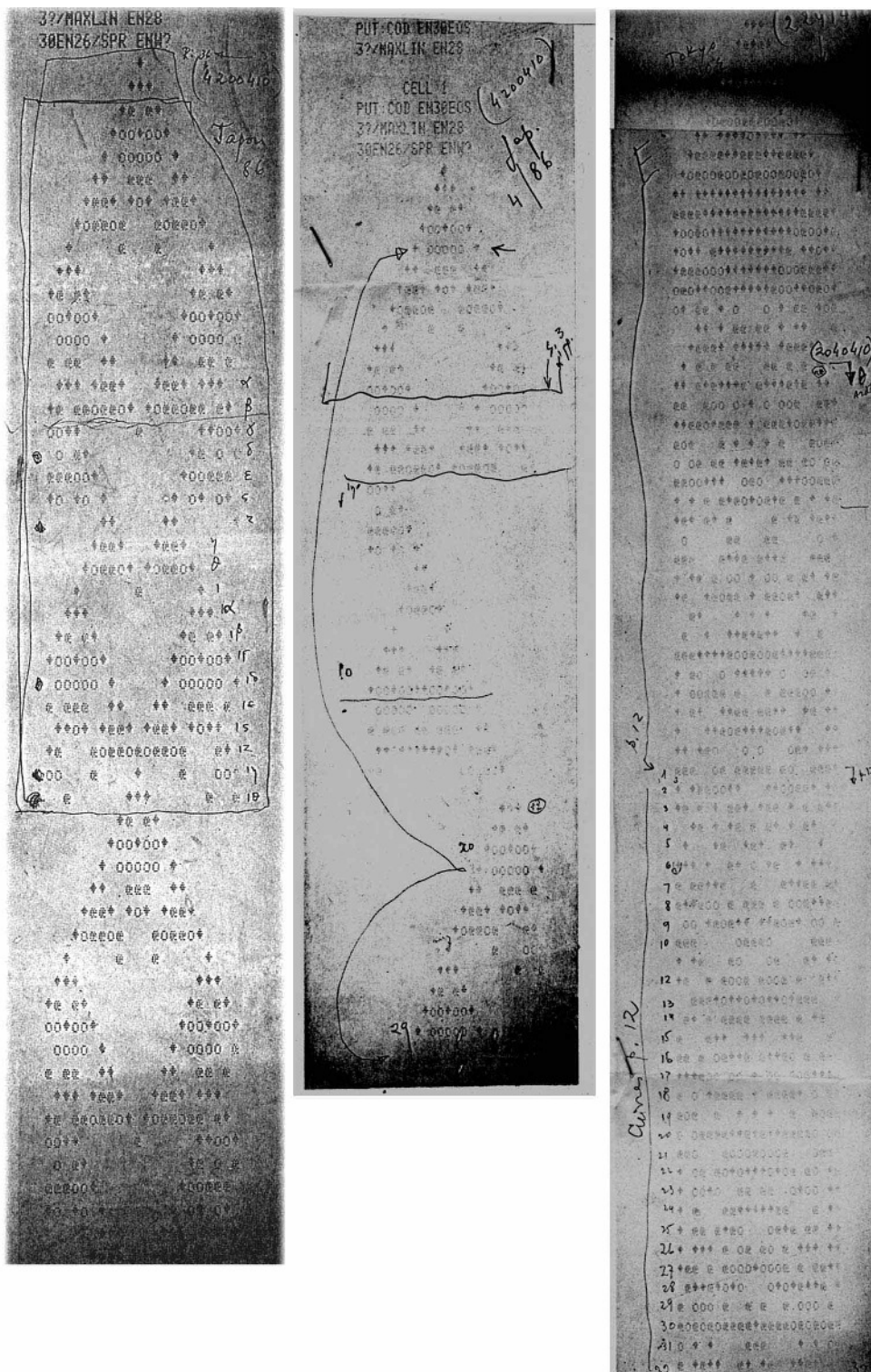
(and, of course, empty cell = 0).

**Figure 8. Printed sheets of paper from Xenakis pocket computer for *Horos'* cellular automata:
a) (left) bars 10 and 14-15;
b) (middle) bars 16-18;
c) (right) bars 67-71.**

Archives Xenakis, Bibliothèque nationale de France.

Figure 1, already commented for introducing cellular automata, reconstruct this automaton, with its numerical values. Two precisions are important to understand the precise automaton of Xenakis:

- column 22: its values do not intervene in next line calculations
- column 0: as we can see from **figure 8a**, it is added manually by Xenakis.

As we can see in **figure 8a** or in **figure 1**, this automaton, which starts from a "seed", is fractal: it has obvious symmetries. Peter Hoffmann [13: 125] states that it belongs to the third of the fourth classes of cellular automata as classified by Wolfram[16]. Moreover, in Xenakis' implementation, this automaton will begin to repeat itself at time 32.

Musically, you can already read this automaton: the columns correspond to the pitches given in **figure 7** (upper numbering); the lines correspond to time divisions. As this automaton is fractal, we have harmonic progressions with very interesting symmetrical progressions in densification or dedensification. As for the instrumental distribution, it is easy to understand it from the score:

- 1: brass instruments
- 2: wind instruments
- 4: strings

Inside each family, the distribution seems to be done manually, and only in regard to practical considerations (possible register and quantity of notes). As about this second musical reason to use cellular automata, this automaton gives also here fast changes and symmetries.

The automaton starts in the beginning of bar 10 (and not in the 5th chord as we could think while reading Xenakis' indication of the code number in the score). Xenakis put the 16 first steps of the automaton in bar 10, in regular semiquavers. We have there a homophony but with constant change of the chords, and which plays with the density (it contrasts then with bars 1-10). So, as about the general formal plan of the piece, this phase corresponds to an evolution phase rather advanced: in fact, this sound not like a homophony, but like a very strange and free note to note counterpoint, with "holes". There are some errors that I have surrounded in the score. There are very natural. Xenakis probably worked directly from the printed sheet to the score itself. Try to do it, you will see that you will make much more errors that him[17]!

In bars 11-13, the automaton stops, probably because the music goes back to a previous evolution phase, which is between the phase of bars 1-9 and the phase of bar 10. In bars 1-9, we had: a) a static homophony (combinatorial repetition of a few chords); a linear progression from 4 same instruments to the *tutti* with a lot of divisions. Bar 10, as it has been said, represent an advanced phase (very dynamic homophony). In bars 11-13: b) we have 10 chords with no repetition; b) but the motion is slow down, and only winds and brasses are playing.

In bars 14-15, the automaton continues, but in irregular rhythms, and in slower motion: we have 15 chords in two bars. So it can be seen as an intermediate evolution phase between bars 11-13 and bar 10. And this movement leads to the 31st step of the automaton[18].

3.2.2. Bars 16-18

As the previous automaton would now begin to repeat itself, Xenakis quit it. But he continues with cellular automata in bars 16-18. Probably for making some continuity, he does not use a different automaton. He uses the same one, as we can see in **figure 8b**. In theory, it is exactly the same automaton, starting from the same "seed". But it practice, it is not the same, because the right border is not the same: one column is added (the values of which, as in the previous automaton, do not intervene in the next line calculations). So there is one more pitch in the sieve, number 23 of **figure 7**, upper numbering (but the deep D does not appear anymore). **Figure 9** reconstructs the automaton evolution (in the extreme left column are indicated the time steps). This automaton is the same as the previous until time step 12. As we can guess from **figure 8b**, Xenakis does not read this automaton from the beginning. In reality, he does not read it in a linear way: he makes *bricolage*. He proceeds in the following way:

a) chords 32-59 correspond to time steps 17-44

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16 The first three have attractors, which are respectively: limit points (the cellular automata of that class evolve after a finite number of time steps from almost all initial states to a unique homogeneous state), limit cycles (in that class, there are "filters" which generate separated simple structures from particular, typically short, initial site values sequences), and chaotic ("strange") attractors (the evolution of this class from almost all possible initial states leads to aperiodic, chaotic patterns); the fourth class automata "behave in a more complicate manner" [36].

17 In detail:
-chord 7: a) the D# of va should be one octave lower; b) the pitch of v.I should be D and not D#
-chord 13: the pitches of vc and cb should not exist
-chord 14: the pitch of va should be E
-chord 15: the pitch of tb should be F#
Only in chord 13 we could speak about a voluntary change, as column 1, corresponding to the pitch played there, is added manually. Note that there are no errors in instrumentation.

18 The few errors, also surrounded in the score, are:
-chord 18: the pitch of the cb should be the deep D of the sieve
-chord 20: the pitch of the fg should be a Db
-chord 21: the deep D of the sieve is missing in the strings
-chord 27: in the hb: a) the E should be a D#; b) the Gb should be a G
-chord 28: a) the deep D of the sieve is missing in the strings; b) the pitch of the cl should be read in F key
-chord 29: a B is missing in the strings
-chord 30: the high G and G# are missing in the trumpet.

b) chords 60-66 correspond to time steps 6-12[19].

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
1	—											1												
2	—										1	1	1											
3	—								1	4		4	1											
4	—							1	2	2	1	2	2	1										
5	—						1		2	2	2	2	2		1									
6	60					1	1			4	4	4			1	1								
7	61				1	4	4	1			1	2	1		1	4	4	1						
8	62			1	2	4	4	2	4					4	2	4	4	2	1					
9	63			1						4				4						1				
10	64		1	1	1													1	1	1				
11	65	1	4		4	1												1	4		4	1		
12	66	2	2	1	2	2	1										1	2	2	1	2	2	1	
13	—		2	2	2	2		1										2	2	2	2	2		*1*
14	—	4		4	4			1	1					1	1			4	4	4		4		
15	—		1	1	1		1	4	4	1				1	4	4	1	1	2	1	1			
16	—	1	4		4	4	2	4	4	2	1		1	2	4	4	2	4				4	1	
17	32	2	2	1	1							4						4				2	2	*1*
18	33		2		4	1															4			*4*
19	34	4	4	4	2	2	1																	
20	35	1	2		1	2		1																
21	36							1	1															
22	37						1	4	4	1														
23	38						1	2	4	4	2	1												
24	39				1							1												
25	40		1	1	1						1	1	1											
26	41		1	4		4	1			1	4		4	1										
27	42	1	2	2	1	2	2	1	1	2	2	1	2	2	1									
28	43		2	2	2	2	2			2	2	2	2	2		1								
29	44	4		4	4	4		4	4		4	4	4			1	1							
30	45		1	1	2	1	1	1	1	1	1	2	1		1	4	4	1						
31	46	1	4											4	2	4	4	2	1					
32	47	2	2											4					1					
33	48			4														1	1	1				
34	49																	1	4		4	1		
35	50																1	2	2	1	2	2	1	
36	51																1	2	2	2	2	2		*1*
37	52													1	1			4	4	4		4		
38	53													1	4	4	1	1	2	1	1			
39	54												1	2	4	4	2	4				4	1	
40	55											1						4				2	2	*1*
41	56										1	1	1								4			*4*
42	57							1	4			4	1											
43	58						1	2	2	1	2	2	1											
44	59						1		2	2	2	2	2		1									

Figure 9. Reconstruction of the cellular automaton used in *Horos*, bars 16-18.

Despite of the new border and this heterodox reading of the automaton, there are of course similarities with the previous automaton: a) chords 32-46: we have the same pitches than the deep pitches of chords 17-31; b) chords 48-54: it is close to the high pitches of chords 10-16; c) chords 57-66 = chords 3-12. In fact, if someone would not have at his disposal **figure 8b**, he could have analyzed the harmonic progression of bars 16-18 with reference to the previous automaton, and to a lot of *bricolage* (in this case, the analyst *bricolage* would be attributed to Xenakis!).

3.3. Bars 67-71

The third instance of cellular automata is given by the Archives' document shown in **figure 8c**, which uses the same numerical values 0, 1, 2, 4. Here, Xenakis is making *bricolage* in the calculation itself. In the printed sheet of paper of **figure 8c**, we can read two handwritten annotations, giving two code numbers: 2241410 and 2040410 (**figure 10** gives the sum transformations with these two codes). Indeed, this printed sheet is a *mixing* of these two automata. It starts with the first, and then, at time step 17 (and not 20 as indicates the handwritten annotation for 2040410), it continues with the second. **Figure 11** gives the reconstruction of this mixing with its numerical values. In bold, at time step 17 are shown the changes with the second automaton. Xenakis change the code numbers probably because the first one, already in time step 12, has led to saturation. The new code number is close to the previous: the only difference is that it introduces two more 0s, thus allowing a dedensification.

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19 The errors in bars 16-18 are fewer than in bars 10 and 14-15:
-chord 32: the high D of the sieve is missing in the winds
-chord 33: the pitch of the va should be read in G key
-chord 34: the pitch of the vc should be a A#
-chord 44: the pitch of the cor should be read in G key
-chord 45: the pitch of the tp should be a A
-chord 53: the pitch of the hb should not exist
-chord 59: the pitch of the cor should be played by the winds
Note that we find here the two only errors in instrumentation (chords 53 and 59) for the whole section (bars 10 and 14-15, 16-18).

sum	0	1	2	3	4	5	6	7	8	9	10	11	12	code number
value	0	1	4	1	4	2	2	0	1	4	1	4	2	2241410

sum	0	1	2	3	4	5	6	7	8	9	10	11	12	code number
value	0	1	4	0	4	0	2	0	1	4	0	4	0	2040410

Figure 10. Transformation of the sums with code numbers 2241410 and 2040410.

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
1												1											
2											1	1	1										
3										1	4	1	4	1									
4								1	2	2	4	2	2	1									
5							1	1	2	1	1	1	2	1	1								
6							1	4	4	4	4	1	4	4	4	4	1						
7							1	2	4	2	2	4	4	4	2	2	4	2	1				
8					1	1			1	1	1	2	1	1	1	1		1	1				
9				1	4	4	4	4	1	1	4	4	4	1	1	4	4	4	4	1			
10			1	2	4	2	2	4	2	2	4	2	4	2	2	4	2	2	4	2	1		
11		1	1		1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1		1	1
12		4	4	4	4	1	1	1	1	1	1	1	1	1	1	1	1	1	4	4	4	4	1
13		1	2	2	4	2	1	1	1	1	1	1	1	1	1	1	1	2	4	2	2	1	4
14		1	2	1	1		4	1	1	1	1	1	1	1	1	1	4		1	1	2	1	1
15		1	4	4	4	2	2	2	1	1	1	1	1	1	2	2	2	4	4	4	1	1	
16		2	4	2	1	1	2	2	4	1	1	1	1	1	4	2	2	1	1	2	4	2	1
17		2	1		4	4	**0**	1		2	**0**	**0**	**0**	2		1	**0**	4	4		1	2	4
18				1	1		1		4	4			4	4		1		1	1				4
19			1	4	4	4	1		1	1	1	1	1		4	4	4	1					
20			1		4		4		4	4				4	4		4		4		1		
21		1	1		4	1	4	1	1	1	4		4	1	1	1	4	1	4		1	1	
22		4	4			4	2	2		2			1		2	2	4			4	4	4	1
23		1	1	4	4	2	1	4	4	4			1	4	4	4	1	2	4	4	1	1	4
24		4	2	4				4		1			1		1		4			4	2	4	1
25		2		2	4		4	4		1	4	1		4		4	4		4	2		2	4
26		4	4	2	2	1	1	1			2	4	2			1	1	1	2	2	4	4	4
27		1		1		4		4	1	4	2	1	2	4	1	4		4		1		1	4
28		1	4	1		4	1		4					4		1	4		1	4	1	1
29			2						4	4				4	4						2		1
30		4	4	4				4	1	1	4		4	1	1	4			4	4	4	
31		1		1	4		4		2	2			1		2	2		4		4	1	1	4
32		1	4			1	4	2	4	4		1		4	4	2	4	1				4	1	1
33				4	1					1		1		1					1	4		4	1
34			4			1		1	1	4	1	4	1	1			1				4		
35		4	4	4	1	1	1	1	4	2	2	4	2	2	4	1	1	1	1	4	4	4	
36		1		4	2			2		1	1	1	1	1		2			2	4		1	4
37		1		2	2	4	4	4		4				4		4	4	4	2	2		1	1
38		1		4	1			1	1	4	4		4	4	1	1			1	4		1	1
39		1				1	1	4	2	4	1	1	1	4	2	4	1	1				1	1
40		1	1		1	4	2				2		2				2	4	1		1	1	1
41	1	4	4	4			2	4		4	4	4	4	4		4	2			4	4	4	1
42	2	1		1	4	4	2	2	1	1				1	1	2	2	4	4	1		1	4
43	3	1	4		4			1	4	4	1		1	4	4		1		4			4	1	1
44	4			1	4		1		1	4			4		4	1		1		4	1			1
45	5		1				1	4			1	4	1			4	1				1		
46	6	1	1	1				4	1		2		1	4			1		1	1	1	1
47	7	4		4	4	1	1	4			4				4	1	1	4	4			4	1
48	8	4	1	1	4	2	2		4		4	4		4		2	2	4	1	1	4	4
49	9		2	2		1	4	2	4	1	1		1	1	4	2	4	1		2	2		4
50	10	4	4	4							2	4	4	4	2					4	4	4
51	11	1		1	4				4	2				2	4				4	1		1	4
52	12	1	4			4		4	2	2	4		4	2	2	4		4			4	1	1
53	13			4	4	4	1	2	1	1	2	1	2	1	1	2	1	4	4	4	0	0	1
54	14		4	1		4		4	4	4		4	4	4	4		4	1	4			
55	15	4				4	1	1			1	1	1			1	1	4				4	
56	16	4	4		4		2	4	1	1	4		4	1	1	4	2		4		4	4	4
57	17	1	1		4	2	2		2	2			1		2	2		2	2	4	1	1	4
58	18	4		2		1	4	4	4			1		4	4	4	4	1		2		4	1
59	19	4	2	4			4			1		1		1			4			4	2	4	4
60	20	2		2	4	4	4		1	1	4	1	1	4	4	4	2		2		2		4
61	21	4	4	2					4	2	2	2	4	2	2	4				2	4	4	4
62	22	1		2	4		4	2	1	2	1	1	1	2	1	2	4		4	2		1	4
63	23	1		2	2	1	2			4	4		4	4			2	1	2	2		1	1
64	24	1		4				4	4	1	1	1	1	4	4			4			4	1	1
65	25	1		4	4		4	1	4	2			2	4	1	4		4	4		1	1
66	26	1		1	1	1		4		2	4		4	2		4		1	1	1	1	1	1
67	27	1	4	4				4	4	2	2	2	1	2	2	2		4		4	4	1	1
68	28		4	1	1	4	1	2	1	2				2	1	2	1	4	1	1		4	1
69	29	4		2	2	2		4			4		4			4		2	2	2		4	
70	30	4	2	4	2	4	2	4	4	4	4	1	4	4	4	4	2	4	2	4	2	4	4
71	31	2		1	1					4	4	4							1			2	4
72	32	4		1	4	1	1				4	1		1	4				1	1	4	1	4

(Leftmost column annotation: "bars 67 - 71" alongside rows 41–44.)

Figure 11. Reconstruction of a mixing of automata (beginning with code number 2241410 and going at time step 17 with code number 2040410). The end corresponds to *Horos*' bars 67-71.

The only relationship that I have found with the score is from time step 41 and on. It is given by two other handwritten annotations in **figure 8c**: a) "cuivres p. 12"; b) numbering of the 32 last time steps. **Figure 12** shows bars

67-72 (p. 12) from the score, where, in the brasses, we can examine the way this automaton work in its musical transcription. The sieve used here is the main sieve of *Horos*: see lower numbering of **figure 7**.

Figure 12. *Horos*: bars 67-72. Éditions Salabert.

We have first to note that, here, the automaton is not used for the orchestration. So the second musical reason to use automata disappears. Second, the *bricolage* in the way the automata is used for pitches is very important:

- chords 1-6: there is no *bricolage*
- chords 7-12 and 24: *metabolè* (in the same sieve): the lower pitch is not anymore the A, but the D (pitch 3 of **figure 7**)
- chord 13 and 15: new *metabolè* (in the same sieve): the lowest pitch is the E (pitch 4 of **figure 7**)
- chords 14 and 25-26: inversion: we have to read the sieve from the higher pitch to the deeper, starting with pitch 24 of **figure 7**
- chords 16-18: new inversion: we have to read the sieve from the higher pitch to the deeper, starting with pitch 25 of **figure 7**
- chords 19-21 and 28-29: going back to the reading from the deepest pitch, but with a new *metabolè* (in the same sieve): the lowest pitch is the F# (pitch 5 of **figure 7**)
- chord 22: new inversion: we have to read the sieve from the higher pitch to the deeper, starting with pitch 23 of **figure 7**

- chord 27: new inversion: we have to read the sieve from the higher pitch to the deeper, starting with pitch 21 of **figure 7**

    - chords 23 and 31-32: ?

    - chord 30: very special: all the cells are filled in the automaton. Xenakis takes the pitches from the middle of the register.

The reason of this *bricolage* is obvious. The brasses can play only 16 notes, but there are 22 possible pitches in the automaton. So, for going to highest pitches, Xenakis makes sometimes a *metabolè*, and sometimes he reads the automaton in inversion.

Note also that, to conclude this section, Xenakis makes another *bricolage*. He needs 16 chords more for the brasses. Instead of going on with the automaton, he makes a combination of some of the previous chords[20]. Maybe the reason to do so is for going back to a previous evolution phase in regard to the formal plan (a lesser dynamical homophony).

3.4. Theory and practice

We have seen that, in his musical implementation of cellular automata, Xenakis introduces a lot of changes, and "intervenes" consistently. This is always the case when he uses formal procedures: stochastics, symbolic logic, game theory, group theory, sieve theory, dynamic stochastic synthesis. All the Xenakis' specialists, when working in the field of the concrete analysis of works using formal procedures, have noted that the composer takes liberties with the formal models, and introduces "licences", "gaps" (*écarts* in French)[21]. In other terms, his use of formalization is mediated through manual interventions. These interventions, as we have seen with cellular automata, affect not only the musical implementation of the formal system, but also its construction[22]. They must not be confused with the errors, which can happen during the musical transcription of the system[23]. Some recent composers, who have also dealt with the question of formalization, and who, in a way, are in line with Xenakis with believing that formalization has not to be applied mechanically, have theorized the notion of manual interventions. I am thinking in particular to Horacio Vaggione's music and musical-theoretical thought. In a very important article on formalization – in the field of composition, but also in the field of musical analysis –, Vaggione says: "Science, regardless of its deductive or empirical nature, tends at least ideally towards an equivalence of process and result. Music shows no tendency of this kind, for the rigor of the generative process does not guarantee the music coherence of the work" [31: 268]. It is why Vaggione is calling for the interaction between the "formal" and the "informal"[24].

To characterize in this paper the nature of these manual interventions, I used the French word *bricolage*. I take it in the sense of Claude Lévi-Strauss' *La pensée sauvage*, which can throw light on Xenakis' specific way to do manual interventions. Lévi-Strauss says that *bricolage* is a kind of intermediate phase between the mythical (or magical) thought and the rational (scientific) one[25] (the adjective "intermediate" must not be understood in an evolutionary sense: we can replace it with the word "mediation"). What is peculiar to *bricolage*, and opposes it to rational thought, is the nature of its tools and the way they work: "Le bricoleur est apte à exécuter un grand nombre de tâches diversifiées ; mais, à la différence de l'ingénieur, il ne subordonne pas chacune d'elles à l'obtention de matières premières et d'outils conçus et procurés à la mesure de son projet : son univers instrumental est clos et la règle de son jeu est de toujours s'arranger avec les 'moyens du bord', c'est-à-dire un ensemble à chaque instant fini d'outils et de matériaux, hétéroclites au surplus" [15: 31]. With Xenakis, the idea that his *bricolage* is made through a "univers instrumental clos" (a "closed instrumental universe") is not true if we are thinking to his whole instrumental universe: he always tried to extend this universe (it's what he has done in the middle of the 1980s by using cellular automata). But this is true if we limit ourselves to a specific formal system he used. If, during its musical implementation, he realizes that it is not working as he wishes, he does not search for another instrument, more adapted, or for its systemic correction. Il "s'arrange avec les 'moyens du bord'". Furthermore, this instrumental universe consists in "outils et matériaux hétéroclites" ("heterogeneous tools and materials").

These two *bricolage*'s features have been illustrated while analysing Xenakis' implementations of cellular automata. For instance, the *bricolage* of *two* automata in the third instance shows clearly that the tools are heterogeneous. And, of course, the fact that cellular automata are used inside a general formal plan to produce specific evolution phases (dynamic harmonic progressions), while other phase evolutions use other techniques, is also characteristic of this heterogeneity. As about the fact that the tools are not "coherent" to a predetermined system, that, during their implementation, for musical reasons, Xenakis choose to make manual interventions in their limited world instead of searching for their systemic redefinition, it was also shown: the *bricolage* of two automata is here also an example; the

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[20] Note that the second chord of bar 72 has not been used before – it can be analyzed as the superposition of chords 20 and 12, but with differences.

[21] The bibliography on this subject is very vast. See [19].

[22] A very detailed analysis of the way the "system" is constructed and implemented through manual interventions in *Nomos alpha* is given in [20: 407-510].

[23] Of course, very often, the distinction is not obvious (see for instance the previous footnote on the errors of *Horos*' bar 10). I just want to say that all "gaps" between the values that stipulate the system and the values that we find in the score are not the result of manual interventions. The errors are due to the fact that the musical transcription of the system is manual (see the discussion on *Horos*' bar 10 errors).

[24] For comments on Vaggione's musical-theoretical thought and on this interaction, see [28].

[25] "Une forme d'activité subsiste parmi nous qui, sur le plan technique, permet assez bien de concevoir ce que, sur le plan de la spéculation, put être une science que nous préférons appeler 'première' plutôt que primitive : c'est celle communément désignée par le terme de *bricolage*" [15: 30]. In Lévi-Strauss' thought, art, in general, is characterized by *bricolage*: "L'art s'insère à mi-chemin entre la connaissance scientifique et la pensée mythique ou magique ; car tout le monde sait que l'artiste tient à la fois du savant et du bricoleur : avec des moyens artisanaux, il confectionne un objet matériel qui est en même temps objet de connaissance" [15: 37].

very heterodox musical transcription of this mixed automaton shows the same; and also the way the second instance automaton is musically read.

Because of these two features, with *bricolage*, the "résultat […] sera toujours un compromis entre la structure de l'ensemble instrumental et celle du projet. Une fois réalisé, celui-ci sera donc inévitablement décalé par rapport à l'intention initiale (d'ailleurs, simple schème), effet que les surréalistes ont nommé avec bonheur 'hasard objectif'" [15: 35]. It is why, if we take cellular automata as a "theory", we have to examine it *always* in regard to a *practice*. This "theory" could indeed lead to very different practices. Furthermore, the theory itself is made *through* practice.

With these elements – generalized to all Xenakis' formal tools –, we can try to answer to the initial question: what is "theory" for Xenakis? In regard to what musical tradition calls "theory", I think that the word is difficult to use with Xenakis' formal tools. For instance, the theory of tonal music is, in a certain way, independent from tonal music (from concrete pieces). Of course, nowadays musicology tends to show that this independence is lesser than what thinks the dogmatic theory of harmony. But tonal theory remains an autonomous field, except if we do not believe anymore in theory. In that sense, Xenakis' theories are not theories. Because of *bricolage*, we can apprehend them only as tools to produce interesting sonorities. Making them theories, independent of practice, can only lead to the observation that they are not coherent! It is what the mathematician readers of *Formalized Music* are always saying. It is what Wolfram could have said about Xenakis' uses of cellular automata: "reading" a cellular automaton by beginning in a certain time step and, after few steps, going to previous time steps, means the destruction of the automaton…

Does it mean that, with Xenakis, we have to abandon the word "theory"? If we limit ourselves to the tradition of musical theory, there is a great temptation to abandon it[26]. In that sense, we would not speak about stochastics, sieves, etc. as theories, except for convenience. Besides, Xenakis himself did not use very often the word in that sense, with the notable exception of sieves theory. The only period where he was interested in that meaning of the word theory was during the first half of the 1960s, in articles like "Towards a Metamusic" or "Towards a philosophy of music" [39].

And yet, there is another use of the word "theory" that fits to Xenakis. The etymological meaning: *theoria*, "view". Indeed, Xenakis theories are "views": ways of viewing the world, *Weltanschauungen* — but not with the metaphysical connotation of this expression. For instance, stochastics introduce in music the view of a probabilistic nature, characterized by massive, violent phenomena. Symbolic logic and group theory correspond to a structuralist view, where human brain is supposed to work with "structures". Etc. And cellular automata, as it has been said, represent his final view of the idea of "automaton".

3.5. Xenakis' implementations of cellular automata and the idea of autonomy

These reflections lead as back to the question of Xenakis' model of "automaton". When dealing with this idea, the final question was: do Xenakis' musical implementations of cellular automata fulfil the model of *autonomy*, as opposed to the model of the "command"? After analysing these implementations, the answer is obvious: no. And the reason is also obvious: because of *bricolage*[27]. Xenakis' manual interventions are very important; sometimes they destroy the nature of cellular automata. And, of course, they are far away from the idea of something that works alone, of an automaton, from which an autonomous meaning emerges.

A last feature of *bricolage* is its "poetic aspect": "La poésie du bricolage lui vient […] de ce qu'il ne se borne pas à accomplir ou exécuter ; il 'parle', non seulement avec les choses […], mais aussi au moyen des choses : racontant, par les choix qu'il opère entre des possibles limités, le caractère et la vie de son auteur. Sans jamais remplir son projet, le bricoleur y met toujours quelque chose de soi" [15: 35]. Indeed, with Xenakis' implementations of cellular automata, we learn more about the way he is working (the way he makes *bricolage*) than about cellular automata!

But this does not mean that we are in the model of the "command". This is where the distinction between the two meanings of the word "theory" is important. If cellular automata are comprehended as "theory" in the first sense (as independent, in the musical level, of a practice), then they are working as black boxes: they are only used to produce interesting sonorities, and it is why there are a lot of manual interventions. But if they are comprehended as *theoria*, something remains from the model of autonomy to which they are related by their nature.

Finally, we can say that we have a kind of compromise, between the philosophy of the Subject (here: manual interventions) and the model of autonomy (here: the nature itself of cellular automata). The mixing between the philosophy of the Subject and the model of the "command" is the most terrible one: the old idea of the automaton is drove to pseudo virtual wars, web surveillance, and so on. While the mixing between the reject of the philosophy of the Subject and the model of autonomy just begins to be explored (in music, it is the case with composers like Agostino Di Scipio: see [29]), Xenakis' mixing is maybe a way to temper the philosophy of the Subject which, as it has been said, can lead to monstrous outgrowths.

4. CONCLUSION

Last question: to what extent do we find cellular automata in Xenakis' work?

First, let's examine the question in *Horos*. I have shown three instances of cellular automata. Are there other instances? In the printed sheets of paper corresponding to two of the three analyzed instances, there are handwritten

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[26] It was always François-Bernard Mâche's position, who says that Xenakis' theories are principally "justifications". See for instance [16: 20].
[27] Another important reason is the fact that they are implemented in very local instances (in regard to the total scale of *Horos*).

annotations that correspond perhaps to their use for different extracts of *Horos*: in **figure 8a**, the time steps 15-33 are numbered from 1 to 19 ("α" to "ιθ"); in **figure 8c**, the time steps from 11 until the extract analyzed have the inscription "E". But I have not found any correspondence with the score. Furthermore, there are in the Archives four other printed sheets of paper with automaton calculations. They have different code numbers (none of them corresponds to the examples of codes numbers in the article of Wolfram). One has, like the analyzed automata, three possible values, but the three others have four possible values. I have neither here found a correspondence with the score. Note that in these sheets, three have no handwritten annotations. So one hypothesis could be that Xenakis made the calculations, but was not enough satisfied to apply them. Especially, the fact that there are four possible values is problematic: to which instrumental family could correspond the fourth value? The only sheet that has a handwritten annotation indicates: "Début *Horos* Tokyo". But it does not correspond to the beginning ("début") of *Horos*.

The fact that most probably there are no other instances of cellular automata implementations in *Horos* should not be surprising, in regard to the score. We have seen that, as about the first musical reason to use them (harmonic progressions), they correspond to dynamic progressions. Now, the only dynamic progressions in *Horos* are in fact the sections which use the three analysed cellular automata. The only other section with dynamic harmonic progression is bars 11-13 (between bar 10 and bars 14-15, which compose the first automaton instance): we have 10 chords with no repetition. So maybe here another automaton is used.

The most curious thing concerning cellular automata is bars 97-108. Xenakis refers to this section as a fluid turbulence: "The patterns appear gradually out of phase. First the woodwinds, then the strings play more or less the same pattern. They are ascending, then descending but out of phase, that is, not starting at the same time. The time unit, however, is identical. This produces a kind of turbulence inside the flow, going up or down or reversing inside. It should be like a liquid" (Xenakis *in* [33: 184]). We have seen that cellular automata are perfect models for fluid turbulence. But Xenakis uses in this section manual writing techniques (so as to produce phase discrepancies).

Now, let's examine other Xenakis' compositions. *Horos* is, more than probable, the "first" piece to implement cellular automata. He says: "*Horos* was the first piece where I put them to use" (Xenakis *in* 33: 199]). What about next pieces? We have two contradictory statements:

- the already quoted extract of *Formalized Music*: "Another approach to the mystery of sounds is the use of cellular automata which I have employed in several compositions these past few years. […] Examples of this can be found in works of mine such as *Ata*, *Horos*, etc." [39: XII]

- a statement in his interview with Restagno: "La tecnica degli 'automi cellulari' l'ho impiegata soltanto in *Horos*" (Xenakis *in* [18: 61]). Of course, we have to take into account the fact that this interview was published in 1988, and maybe realized in 1987.

My own provisional conclusion is that, *if we limit ourselves* to the cellular automata implementations shown in *Horos*, the truth is located between these two statements, but very close in fact to the second one – it is why I used brackets when saying that *Horos* was the "first" piece to use cellular automata. There are two facts that allowed me to come to this conclusion.

I have examined all compositions between *Horos* and 1990, excluding of course the pieces which use no pitches or which use no harmonic progressions (*Kassandra*, *Taurhiphanie*, *Rebonds*, *Voyage absolu des Unari vers Andromède*, *Okho*)[28][29]. The first fact is that, in the Archives, we find no other printed sheets of papers on cellular automata calculations. Of course, this fact is not enough strong: probably a lot of sketches have been lost.

Second, I analysed the scores, searching for the necessary conditions corresponding to the need to use cellular automata. These conditions are, if we limit ourselves to *Horos*' implementations:

1. Timber combinations. But as we have seen from the third cellular automaton instance in *Horos*, this condition has not to be fulfilled (in this instance, Xenakis uses an automaton with a single instrumental family, and inside of this family the distribution is manual).

2. Dynamic homophony. This suppose:

a) constant variation of density. But from the same instance, we have seen that this condition has neither to be fulfilled (in this instance, the density is always 16 pitches)

b) then, the only remaining conditions are:

- non-chromatic (inside a sieve) pitches

- constant change of chords (and not combination of a few or even of several chords)

- changes that are not in linear progression, i.e.: a) where the melodic lines are not playing scales; b) where the changes are not in linear ascending or descending movement.

In examining the scores between *Horos* and 1990, even if the conditions are limited to 2.b, we can see that there are in fact *very few* extracts fulfilling these conditions!

In detail, the potential extracts are:

1. *Akea*: bars 1-8, piano part. *Akea* was probably composed just after *Horos* or even in parallel. There is some material coming directly from *Horos* (see [9: 273]). In the Archives, there is no file with sketches. But, in one of the third of the three printed shown sheets from *Horos* (**figure 8c**), we have the handwritten annotation: "θ arditti". Knowing that the piece was premiered by the Arditti string quartet (and Claude Helffer), I searched for a correspondence with the above-mentioned bars. The sieve is the main sieve of *Horos*, extended in the deep and in the

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28 Note that *Keqrops*, usually given as composed after *Horos*, was probably composed before *Horos*: in the score, we have the indication 5-1-1986; see also Xenakis *in* [18: 61].
29 The only existing analysis of pieces between *Horos* and 1990 are: on *A r.* [30], on *XAS* [2], and on *Tetora* [7].

high pitches. In bar 3, the first chord corresponds perfectly to the 24th time step of this automaton, and the second chord to the 27th step. Then, with of lot of *bricolage* (from the analyst) we can try to find other correspondences.

2. *Jalons*: bars 40-41.

3. *Tracées*: bars 4-8 (winds and piano), 9-12 (strings), and 16-18 (strings). But this small and wonderful piece uses very often material from other pieces. The first mentioned extract (bars 4-8) is already used in *Idmen A* and *Alax* [9: 274]).

4. *XAS*: bars 31-32, and 73-80.

5. *Ata*[30]: bars 121, 126, 131, 133. Here, the chord progressions fulfil also the conditions 1 (timbre combinations) and 2a (constant variation of density). But there are literally taken from *Horos*! In bars 121, 126 and 131, Xenakis reads respectively *Horos'* bar 14, 10 and 17 in retrograde motion; in bar 133, we have *Horos'* bar 16. Note also that, in this piece, there is also other recycling of *Horos'* material.

6. *Échange*: bars 12-13, 16-19, and 43-56.

7. *Épicycle*: bars 52-59.

8. *Kyania*. This piece uses a lot of material from other pieces (see [9: 276] and [23]). And we find, in bar 48, a retrograde reading of the *Horos'* bar 10 automaton (already recycled in *Ata*).

And now, here is a final element to this discussion on cellular automata in Xenakis' music. The composer has said:

> "Nel campo della fisica gli 'automi cellulari' sono un fatto piuttosto recente. Seguendo regole molto semplici sei in grado di dar vita a un percorso che si sviluppa progressivamente. Immagina di avere uno spazio diviso in cellule di forma rettangolare. Tu cominci a occupare una cellula e di qui procedi sviluppando, come se quella prima cellula ne generasse altre diagonalmente, verticalmente o lateralmente; applicando queste regole di propagazione ottieni, quelli che si chiamano gli 'automi cellulari'. Se immagini di trasferire lo stesso principio in campo musicale ti rendi conto, per esempio, che *una linea melodica* assomiglia a un tipo di produzione del genere di quello che abbiamo descritto. Puoi dunque generalizzare il principio e applicarlo a un'intera orchestra ottenendo degli accordi, ciascuno dei quali dipende dal precedente secondo una certa regola. Naturalmente puoi ottenere, con lo stesso principio, anche una propagazione di colori; basta identificare il suono di una determinata cellula con un determinato timbro o procedere" (Xenakis *in* [18: 61]; the italics are mine).

If we have to imagine that Xenakis used cellular automata to produce melodic lines, then, the exploration of his cellular automata implementations has just begun…

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30 In the score, there is a mistake for the numbering of the bars after bar 124.

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