Journal of
Virtual Worlds Research
jvwresearch.org ISSN: 1941-8477

Lantern
Part 2/2

August 2014
Volume 7, No. 3

Volume 7, Number 3
Lantern part 2/2
August 2014

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Journal of Virtual Worlds Research
jvwresearch.org ISSN: 1941-8477

Volume 7, Number 3
Lantern (2)
August, 2014

Two Decades of Evolutionary Art Using Computational Ecosystems and Its Potential for Virtual Worlds

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Abstract

We analyse works of digital art that use a technique from artificial life (ALife) called computational ecosystems (CEs). These are systems running on computers where agents are organized in a hierarchical structure (of a food-chain) and trade token units (of energy and biomass) as a way of promoting community dynamics. We analyse a collection of forty (40) papers communicating works developed in the last two decades. We classify each of these works according to an adapted taxonomy. We then produce a study of cumulative analysis to outline patterns and common features which might define the field. We conclude on the diversity and heterogeneity of the practice, to assert CEs as a multimedia generative tool useful in the construction of bio-mimicking ecosystems as well as in the animation of non-player characters (NPCs) with human-like behaviors in virtual words.

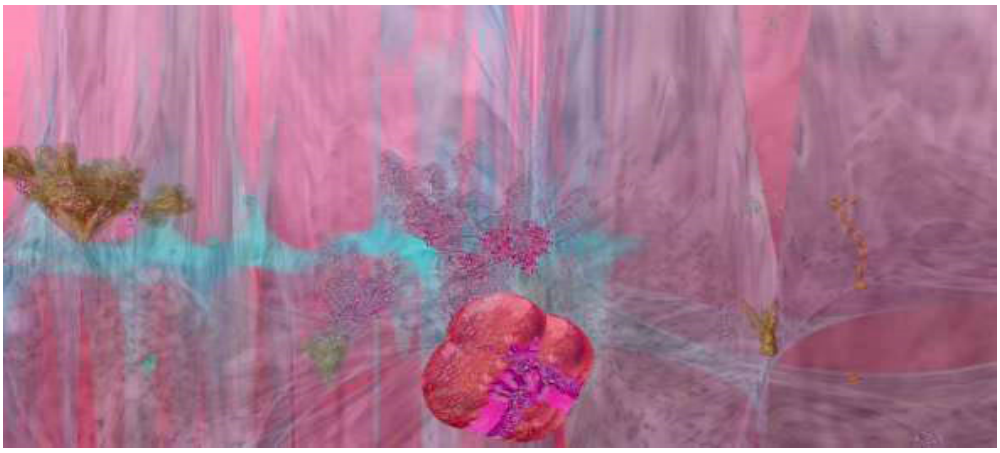

Figure 1: Still image from xTNZ (Antunes & Leymarie, 2008), a CE in which evolving creatures see their physical features (shapes, textures and sounds) evolve over generations by means of Mendelian genetics and Darwinian natural selection. © Antunes & Fol Leymarie, 2008

1. Introduction

The development of computational systems with communities of agents forming ecosystems is a practice with an already established tradition in the artificial life (ALife) community (Dorin, 2005; Bisig & Unemi, 2010). Computational ecosystems (CEs) run on computers simulating interactions of individual agents mimicking life in nature (Figures 1 and 2). In a classical CE, agents are organized in a hierarchical structure (of a food-chain) and trade token units (of energy and biomass) as a way to promote community dynamics. CEs are used either to understand complex adaptive natural systems when modelling carbon-based contexts (Watson & Lovelock, 1983; Lenton & Lovelock, 2001),[1] or as a technique to generate heterogeneous and spontaneous behaviours in artificial/digital agent-based environments (Bentley & Corne, 2002).

CEs support dynamic computerised environments which operate in a logic of autonomy, with self-organization and emergence phenomena (the apparition of new unforeseen structures). In the following we provide an in-depth overview of the landscape of the arts developed using this technique, in order to identify methods of production that may contribute towards the development of novel virtual words. We make an ontological distinction between CEs and virtual worlds such as Second Life and Worlds of Warcraft, which are, according to Mark Bell, "persistent environments based on computer networks and whose dynamics are driven by (human) users mediated by visual representations or avatars" (Bell, 2008).

ALife art practice already has a rich history, in particular since the mid-1990s, with innovative works such as Technosphere (Prophet, 1996) or A-Volve (Sommerer & Mignonneau, 1994), which captured the attention of the art world into the then new emergent practice. This new art practice has matured through the last two decades, and embraced a number of disciplines at the confluence of aesthetic ideas with science and technology, including: kinetic art, generative art, evolutionary art, and systems aesthetics. The art forms that we will be addressing in this paper make use of a CE as their

[1] In ecology, CEs can be considered part of the sub-domain of "agent and individual based models" (Railsback & Grimm, 2012).

structural basis. CEs, as we will see, play important roles as generative engines in diverse artistic contexts such as audio-visual installations (Dorin, 2012), music (Eldridge & Dorin, 2009) or choreography of avatars in virtual worlds (Antunes & Leymarie, 2012).

Metacreations (Whitelaw, 2004), *Virtual Worlds* (Bornhofen et al., 2012), *Creative Evolutionary Systems* (Bentley & Corne, 2002) and *The Art of Artificial Evolution* (Romero et al., 2007) are key texts in this area of knowledge. The first is an in-depth critical account of art created with ALife systems, which surveys the theoretical discourses of important works, covering also aspects of the development of CEs. The three other titles provide collections of texts on evolutionary art and virtual worlds, and are mostly technically oriented. In the later (Romero et al., 2007) in a chapter by Alan Dorin, art based on using CEs is described. Dorin provides a global overview, characterizing the praxis. Our research complements the previous works by mapping out this field, and in particular, it extends Dorin's own work, by virtue of providing a detailed systematization and objective classification of the art practice using CEs. We study this theme and the various contexts in which works are presented, as well as consider their formal attributes, and the user experience. Doing so we outline patterns and common features which might help to refine and better characterise the field, and grasp the uniqueness and creative potential of this praxis. The core of the paper is a survey and analysis of artworks based on CEs, pointing out ideas that can benefit the more generic domain of virtual worlds.

1.1 The three Main Genres of Evolutionary Art

The use of CEs in ALife art production is part of an aesthetic domain designated as Evolutionary Art (EvoArt). This is a form of artistic expression characterized by the instrumentalization of Darwinian processes of evolution by combining the principle of natural selection with the rules of Mendelian genetics, in order to promote the creation of artefacts obeying a new aesthetic.

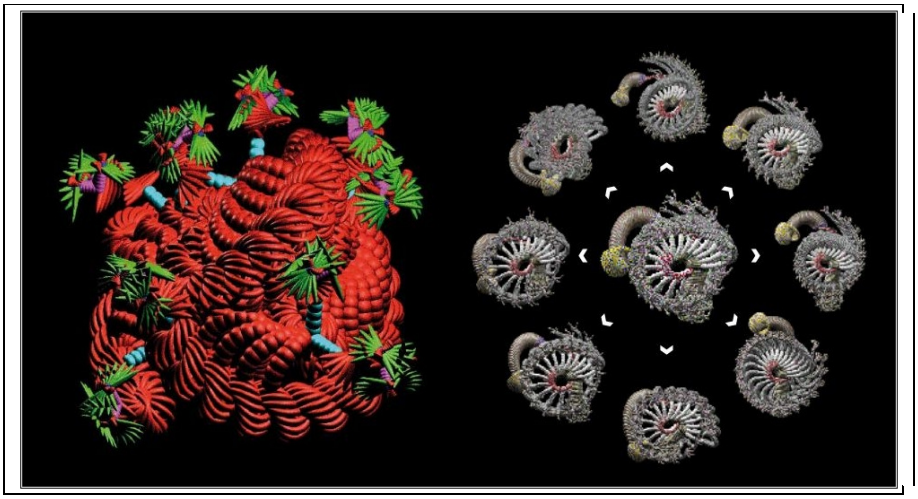

Figure 2: William Latham uses a grammar of morphological operators and trans-formations to encode the information contained in the "genomes" of his artefacts (Todd, Latham, 1992). An interactive process of selecting successive genomes generates a series of images (here in 3D) based on a process of recombination and mutation of the genes. At each generative step, the artist selects the preferred of these new images to serve as progeny for the next iteration. On the left is shown one outcome of an EvoArt session: PlantForm (© Latham, 1989) and on the right is illustrated one evolutionary step in another session where the central parent, once selected by the artist is used to create 8 new descendants (© Latham, 1991).

1.2 The 1st Genre: Gtype-Ptype

EvoArt established its roots upon a methodological approach borrowed from Computer Science. In the classic procedure of genetic algorithms, a syntactic element is transformed into its semantic representation. With traditional EvoArt, similarly, an encoded blueprint (the genotype - Gtype) is converted to its iconic or audible (or multi-media) representation (the phenotype - Ptype). A community evolves through processes derived from Mendelian genetics. The 'best' in a pool of individuals are chosen to procreate or further evolve. In the process they will blend their successful Gtypes in a new pool of individuals which will replace the old ones. With genetic algorithms the fitness criteria determining which individuals are to be kept are problem-dependent. With traditional EvoArt it is a human operator who operates this selective pressure known as the Interactive Genetic Algorithm. The complexity of this process of conversion from Gtype to Ptype is open to artistic creativity and the linearity and distance involved in this process of transformation differ widely amongst artists. The diversity of the outcomes this methodology entails is illustrated for example by computational evolutionary art pioneers Latham and Sims: William Latham produces 3D morphologies based on a process of shape deformation (Figure 2), while Karl Sims generates abstract imagery based on a language of mathematical and visual operators (Whitelaw, 2004; Lambert, Latham & Leymarie, 2013).

1.3 The 2nd Genre: Computational Ecosystems

Another established way the Gtype-Ptype metaphor has been explored is by applying it to whole populations of interacting autonomous agents defined by CEs. As mentioned earlier, CEs are communities formed by multiple autonomous individuals, which are organized in hierarchical food-chains and who trade amongst them units of energy.

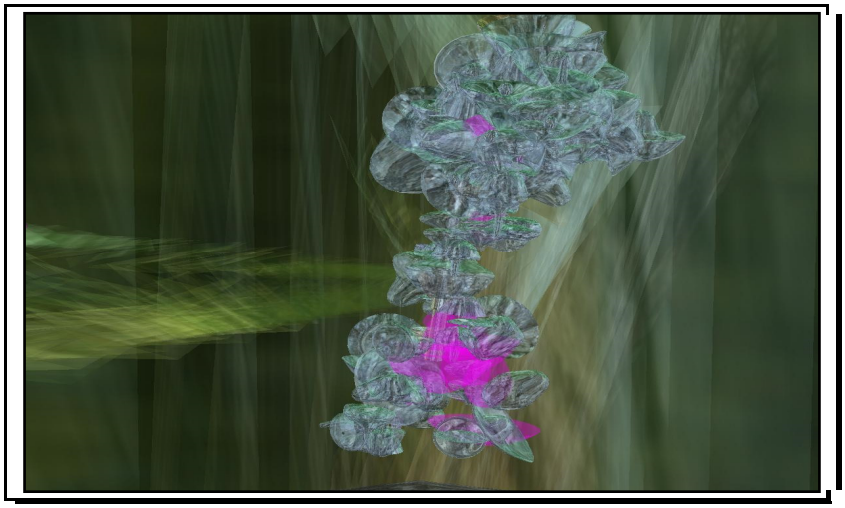

Figure 3: Still image from Senhora da Graça (Antunes & Leymarie, 2010): an evolutionary ecosystem exploring the biological phenomenon of epigenetics, where parametric variables of the system affect the physical traits of the creatures. © Antunes & Fol Leymarie, 2010.

As with the Gtype-Ptype genre, individuals are first represented and structured by the information initially written in their Gtypes, which is later transformed into some phenotypic representation. In addition to this translation process, the autonomy of the individuals, which is so characteristic in CEs,

generates an interesting dynamics of self-organization and emergence with cyclic changes of density. Each of the agents in the community emulates a simplified form of the life cycle of generic carbon-based life forms. In a regular CE, genetic characteristics such as the size or speed of the agents pass from parents to children when individuals replicate, in a process that emulates sexual reproduction. The selective pressure is expressed in how well the individuals perform in the system, in order to perpetuate their genetic heritage. Energy might be required for the activities of these individuals, such as moving, running, or simply breathing. The population competes for energy and space, and this dynamic of energy transfer occurs in predatory acts. When the energy level of an individual becomes too low, it is considered dying and removed from the community.

CEs used in EvoArt explore processes of self-organization and emergence as main mechanisms to generate heterogeneity and novelty in the artistic works (Figures 1 and 3). Gtypes may also be directly sonified or visualized. Wakefield and Ji, for instance, produce sounds directly from the transcription of the Gtype data (Wakefield & Ji, 2009).

1.4 The 3rd Genre: CEs Dynamics – Ephemeral Events, Internal States

We propose that there exists also a third genre, this one characterized by artists who are interested in the ephemeral states of the system and the dynamics generated by its individuals, where the system's internal states translate into actions performed by agents. In *Unfinished Symphonies – songs from a 3 ½ world*s, we can read: "the rhythm list increases when the creature eats a tree and decreases as it ages or fails to find food". Then, referring to another work: "Each creature starts its life as a soprano […] having only one body segment and a high pitched voice. When it reaches puberty, it becomes an Alto with one extra body segment and a slightly lower voice. Altos are also able to bear children. Later in life, the alto transforms into a Tenor and then later still becomes a Bass" (Berry et al., 2001). Another example is provided by the soundscapes produced by Eldridge and Dorin. These are granular compositions where timbre and pitch depart from the spatial aggregation of the individuals in the virtual environment (Eldridge & Dorin, 2009). Antunes and Leymarie take advantage of the internal dynamics and the ephemeral states generated by CEs to generate choreographies and animate dancers (Antunes & Leymarie, 2012) and groups of conversational humanoids (Antunes, 2012; Antunes & Leymarie, 2013).

Before we present and discuss our survey's results, we describe next the methodological aspects.

2. Methodology

2.1 Domain of the survey

To initiate this study we went through the proceedings of the main scientific conferences covering these genres of work, including: *EvoMusArt*, *Generative Art*, *Genetic Evolutionary Computation Conference*, the *IEEE Congress on Evolutionary Computation*, and *Artificial Life*. We also looked at a collection of established books with surveys on ALife art or EvoArt, including: *The Art of Artificial Evolution* (Romero et al., 2007), *Metacreations* (Whitelaw, 2004), *Creative Evolutionary Systems* (Bentley & Corne, 2002) and *Virtual Worlds* (Bornhofen et al., 2012b). Finally we looked at art magazines such as *Art Forum* and journals such as the *International Journal of Arts and Technology* and the *Journal of Virtual Worlds Research*. From these we have selected a sample of forty papers. Our aim was not of producing an exhaustive scrutiny of the field, but rather to have a sufficient sample of important works, from which we could derive with good confidence interesting conclusions. On the one hand, this sample should cover the full spectrum of activities with regards to artistic styles and uses of the CE framework, and on the other hand, it should be sufficiently well distributed throughout the

twenty years of our set time frame (1993-2013). We followed two main selection criteria: the art-criterion and the CE-criterion. The first constrained the selection to works that have been presented or discussed as artistic projects, ideally exhibited in a gallery, museum or an art festival or shown/distributed on the internet. The second criterion constrained the selection to instances where the artificial beings that populate the world emulate aspects of biological life forms. This includes works where individuals are: represented by Gtype-seeds, or exchange energy or mass, or emulate metabolic cycles (these might include birth, growing morphologies, reproduction and death). Ideally, works should include all these factors, but due to the variety of approaches this criterion was loosened to the presence of at least one of these.

2.2 Surveyed Works

The list of selected works (in reverse chronological order) follows:

1- *CodeForm*, 2012 (McCormack, 2014); 2- *SwarmArt*, 2012 (Al-Rifaie & Bishop, 2012); 3- *Untitled*, 2012 (Bornhofen, Gardeux & Machizaud, 2012a); 4- *Where is Lourenço Marques?*, 2012 (Antunes & Leymarie, 2012); 5- *Time of Doubles*, 2012 (Ji, 2012 & Wakefield, 2012); 6- *Pandemic*, 2012 (Dorin, 2012); 7- *Vishnu's Dance of Life and Death,* 2011 (Antunes & Fol Leymarie, 2012); 8- *EvoEco*, 2011 (Kowaliw, McCormack & Dorin, 2011)]; 9- *Cycles*, 2012 *(*Bisig & Unemi, 2010); 10- *Senhora da Graça*, 2010 (Antunes & Leymarie, 2010); 11- *Sonic Ecosystems*, 2010 (Bown & McCormack, 2010); 12- *Constellation*, 2009 (Dorin, 2009b); 13- *Habitat,* 2009(Dorin, 2009a); 14- *Untitled experiment (Niches)*, 2009 (McCormack & Bown 2009); 15- *Fluid Space,* 2009 (Ji & Wakefield, 2009; Ji, 2012); 16- *Quorum Sensing*, 2008 (Chen & Hoyami, 2008); 17- *Filterscape*, 2008 (Eldridge, Dorin & McCormack, 2008); 18- *Infinite Game,* 2009 (Ji & Wakefield, 2009; Ji, 2012); 19- *Colour Cycling*, 2008 (Eldridge *et al*., 2008); 20- *xTNZ,* 2008 (Antunes & Leymarie, 2008); 21- *Funky Forest*, 2007 (Watson & Gobeille, 2007); 22- *E-volver*, 2006 (Driessen & Verstappen, 2014); 23- *Plague,* 2006 (Dorin, 2006); 24- *Ambient Light,* 2006 (Annie Spinster, 2014); 25- *Lifedrop*, 2005 (Heudin, 2012); 26- *Meniscus*, 2003 *(*Dorin, 2003); 27- *Black Scholes*, 2001 (Hoile, 2014; Demos, 2012); 28- *Eden*, 2001 (McCormack, 2001); 29- *Biotica*, 2001 (Brown *et al*., 2001); 30- *Living Melodies*, 2001 (Dahlstedtd & Nordahl, 2001); 31- *Listening Skies*, 2001 (Berry *et al.*, 2001); 32- *Iki Iki*, 2001 (Sommerer *et al.*, 2001); 33- *Life Spacies*, 2000 (Sommerer & Mignonneau, 2000); 34- *Garden of Chances*, 2000 (Hutzler, 2000); 35- *Nerve-Garden*, 1998 (Damer *et al.*, 1998); 36- *The Nagual Experiment*, 1998 (Annunziatto, 1998); 37- *Relazioni Emergenti*, 1996 (Annunziato & Pierucci, 2000); 38- *Technosphere*, 1996 (Prophet, 1996); 39- *EIDEA*, 1995 (Mitchell & Lovell, 1995); 40- *A-Volve*, 1994(Sommerer & Mignonneau, 1994).

2.3 Variables and Taxonomy

To describe the selected works we modified a taxonomy from Carvalhais (Carvalhais, 2010) who recommends classifying works of generative art via an adaptation of Aesperth's taxonomy for cybertexts (Aarseth, 1997). Our taxonomy includes detailed aspects of the physical implementation of the works in a public exhibition space, while some redundant aspects to the nature of CEs (such as the existence or not of dynamism in the works) are removed. We have divided the variables to consider for classification into three groups: (i) to describe contextual properties; (ii) to capture the user experience; and (iii) to describe formal properties.

2.4 Contextual Variables

Context: This refers to the main context of the work, to its function. Does the artwork tell or narrate, inform or document, does it *visualize*, *sonify*, *monitor*, *mediate*, *transform*, *collect* or *store* an event, process or story?

Referentiality: Many works in EvoArt are self-referential or reflect upon *life;* however, a significant number also reflect about *societal*, *political*, *economic* or *environmental* processes.

Autonomy: This variable describes the focus of the work in terms of input. Is the work independent from external influences (autonomous) or does it need external sources of input like the meteorological information required by EIDEA (data-driven), or user-input designing and adding new creatures. Accepted values are: *autonomous*, *data-driven*, and *user*.

2.5 User Experience (Interactivity)

We consider now variables describing levels and types of interactivity of a CE.

Perspective: This binary parameter identifies the level of commitment of the audience with respect to the emergence of the work's outcome or storyline. When the audience plays a direct role in the narrative, the work is considered *personal* and *impersonal* otherwise.

User Functions: Members of the audience may observe, explore, activate, control, select, navigate, participate, or leave traces. These interactions are classified as one of three possibilities: *interpretative* (observe), *explorative* (explore, navigate, select) or *configurative* (activate, control, leave trace, and participate).

Linking: This variable denotes the existence of devices and processes that make a CE reactive to interactions with the audience. Accepted values are: *none*, *explicit*, or *implicit*. *Explicit* stands for works where there is a direct involvement of the user, usually via a haptic device such as a mouse, touch screen, tablet or pod. *Implicit* is when the body or its physical presence in space is captured with the help of non-interfering devices such as infra-red cameras.

Modes: Modalities of perception engaging the user are captured by this variable, including the: *visual*, *haptic*, *aural*, *movement* and *procedural* modes. *Movement* may include subtle dynamic events such as finger gestures or eye gaze. *Procedural* refers to the cognitive dimension of the experience, where in contrast to the other modes, a rational understanding of the processes involved in the construction of the work is implied. For example, Technosphere (Prophet, 1996) builds on the illusion of an "out-there" abstracting the processes involved in its construction, whereas in works such as Cycles (Bisig & Unemi, 2010) this procedural dimension beyond what is seen is emphasized by means of a more abstract form of representation using lines and simple geometric forms in an aesthetics popularized by computer screensavers, which enhances (makes explicit) the presence of the medium and its processes. Modalities of smell and taste could potentially be included here, but this is unnecessary in our study as, to the best of our knowledge, no recent work explores such territories.

Determinability: This binary indicator specifies if different interactions from the audience with the same artefact may result in similar experiences or not. This variable is subordinate to the user-function, as unique experiences exist in the explorative and dynamic modes. Accepted values are "yes" or "no". Given the subjectivity involved in accessing what are "similar" experiences, we opted to just classify as determinable those works presented in still format, as "drawings" as McCormack puts it (McCormack & Bown, 2009).

Access: We assume the whole of the artefact is available at all times (*e.g.* during an exhibit period), but its access can be *controlled* or *random.* A *controlled* situation is illustrated for example by Listening Skies (Berry et al., 2001) where the user creates a "listener" from which point of view the world will be perceived, or by Meniscus (Dorin, 2003) where the user changes the water level, thus conditioning and controlling the outcomes. A *random* situation is illustrated by xTNZ (Antunes & Leymarie, 2008) where the whole of the virtual environment can be explored in an unconstrained fashion.

Class: This variable is used to indicate the *computational class* of the work: (1) producing static non-transient outputs; (2) producing static transient outputs; (3) exhibiting complex behaviours. An example of a static non-transient output is a static image. A static transient output defines works that keep changing over time but not in a structural way. Works with complex behaviours are locally structured, partially predictable, and will exhibit random behaviour changes in surprising and unexpected ways.

2.6 Formal Variables

The final set of variables is used to describe the formal properties of the artefacts and how they are presented in public.

Format: This describes the physical manifestation of the artefact including what format was chosen to present a CE to the public. The "format" can take one of six meanings: (i) *installation* denotes works designed to transform the perception of space by surrounding (embedding) the user; (ii) *sculpture* denotes objects that are observed as a self-contained arrangements of forms; (iii) *video* and (iv) *interactive-video* stand for works where the artefact is presented in a minimalistic technical form with the help of a projector; (v) *software-application* works are experienced in the intimacy of the computer; (vi) *still-imagery* stands for printed works of digital photography.

Composition: The second formal variable describes the mode of representation used in the composition, depending if visuals and/or sounds explicitly stand for some external entity and if the work is a collection of *representational* elements or is *abstract*.

Visual Form: This descriptor is used to indicate how individuals are represented visually in the ecosystem. To cover the wide range of approaches, this category accepts a graded scale of values. Individuals can be represented by *dots*, *lines*, *surfaces*, *volumes* or *ephemeral/translucent* forms.

Depth: This binary parameter is complementary to the visual form and indicates the presence of foreshortening in the representation. Two values are accepted to denote bi-dimensional (*2D* or *flat*) or three-dimensional (*3D* or *volumetric*) representations.

Color: Works may be *monochromatic* or multi-*coloured*. Monochromatic works are few, and include black and white as well as grey-level pieces.

SFX: Special effects (SFX) indicate the level of graphical sophistication, such as surface details, texture mixing, or the use of smooth elementary units and solid objects versus complex ones. Accepted values are "yes" or "no" (*i.e.*, complex or simple).

Sonification: There are multiple alternatives for the use of sound. The main dichotomy is between pre-recorded and synthesized (in real-time) sounds. A sonification effect can be composed of *preselected* elements, which might be played for instance as screams by individuals. Alternatively, sounds produced may be *granular*, *i.e.* synthesized and played simultaneously by different units of a CE, which is typical of swarming and particle-based approaches.

Display: The CE is ultimately a system running on a computer. This (almost always) requires a visualisation. The technology used to present the CE to the public is captured by this descriptor: *frontal-projection*, *retro-projection*, *computer-screen or touch-screen*.

Scale: This variable describes the size relationship of the individuals from the virtual population with respect to the human body. Accepted values are: m*icro* for small sizes (typically less than 0.1 meter), *human* for sizes similar to the human body and parts (up to 3 meters); and *macro* for other larger sizes (*e.g.* at architectural/urban scales).

2.7 Summary

We have presented a set of variables based on the taxonomy introduced by Carvalhais to classify generative artworks (Carvalhais, 2010). Some of the original categories were removed – *i.e.* Dynamics and Transiency – since they are redundant in the context of CEs. Some others had their name changed to better clarify their relation to CEs: Individual was changed to Visual Form, Sound to Sonification Blending to SFX, shape to surfaces, transparencies to ephemeral. The nineteen selected variables are as follows:

1- Context (narrate, inform, visualize, sonify, monitor, mediate, transform, collect, store); 2- Referentiality (life, societal, political, economic, environmental); 3- Autonomy (autonomous, data-driven, user); 4- Perspective (personal, impersonal); 5- User Functions (interpretative, explorative, configurative); 6- Linking (none, explicit, conditional); 7- Modes (visual, haptic, aural, movement, procedural); 8- Determinability (yes or no); 9- Access (random, controlled); 10- Class (1 (static non-transient), 2 (static transient), 3 (complex)); 11- Format (installation, sculpture, video, interactive-video, sw-app (software-application), still (imagery)); 12- Composition (representational, abstract); 13- Visual Form (dots, lines, surfaces, volumes, ephemeral); 14- Depth (2D, 3D); 15- Colour (mono (chrome), multi (coloured)); 16- SFX (yes (complex), no (simple)); 17- Sonification (pre-selected, granular); 18- Display (frontal (projection), retro (projection), (computer-) screen, or touch); 19- Scale (micro, human, macro).

3. Results and Characterization

The following tables show the classification for the three main variable types: Contextual, Interactivity, and Formal. These tables were produced from a close inspection of: project websites, papers describing the implementations, and other material when available (*e.g.* blogs, reviews). A quick look at the tables shows a great heterogeneity of agendas and outcomes. We discuss below the content of each table in turn. Note that WisLM (Antunes, 2012 & Antunes & Leymarie, 2013) and Technosphere (Prophet, 1996) appear twice in each table as they have been exhibited both (a) in galleries and (b) on the internet; also, Time of Doubles (Ji, 2012; Wakefield, 2012) is a later and enhanced version of Infinite Game (Ji & Wakefield, 2009; Ji, 2012), and similarly with Pandemic (Dorin, 2012) in relation to Plague (Dorin, 2006); note also that tables are organised by date of publication, from most to least recent.

3.1 Contextual Variables

First, we consider the contextual aspects of the 40 projects surveyed as listed in Table 1. Summations of variable values are illustrated in Figure 4.

Table 1: Contextual classification of the 40 surveyed works

Work	Context	Referentiality	Autonomy
CodeForm (1)	vis+sonify	societal	user
Swarm-art (2)	vis+sonify	life	user
Bornhof (3)	visualize	life	autonomous
WisLM (a) (4)	vis+mediate	political	autonomous
WisLM (b) (4)	vis+mediate	political	autonomous
Time of Doubles (5)	vis+sonify	life	user
Pandemic (6)	vis+sonify	life	user
Vishnu's (7)	visualize	societal	autonomous
EvoEco (8)	visualize	life	user
Cycles (9)	visualize	life	user
SraGraca (10)	visualize	environmental	autonomous
Sonic Ecosystems (11)	vis+sonify	life	autonomous
Constellation (12)	visualize	life	autonomous
Habitat (13)	vis+sonify	life	autonomous
Niches (14)	visualize	life	autonomous
Fluid Space (15)	vis+sonify	life	user
Quorum Sensing (16)	visualize	life	user
Filterscape (17)	sonify	life	autonomous
Infinite Game (18)	vis+sonify	life	user
Colour Cycling (19)	visualize	life	autonomous
xTNZ (20)	vis+sonify	societal	user
Funky Forest (21)	vis+sonify	environmental	user
E-volver (22)	visualize	life	user
Plague (23)	vis+sonify	life	user
Ambient Light (24)	visualize	life	user
Lifedrop (25)	visualize	life	autonomous
Meniscus (26)	vis+sonify	life	user
Black Scholes (27)	visualize	economic	data-driven
Eden (28)	vis+sonify	life	user
Biotica (29)	vis+sonify	life	user
Living Melodies (30)	sonify	life	autonomous
Listening Skies (31)	vis+sonify	life	user
Iki Iki (32)	visualize	life	user
Life Spacies (33)	visualize	societal	user
Garden of Chances (34)	vis+monitor	environmental	data-driven
NerveGarden (35)	visualize	life	user
Nagual Experiment (36)	visualize	life	autonomous
Relazioni Emergenti (37)	vis+sonify	life	user
Technosphere (a) (38)	visualize	societal	user

Work	Context	Referentiality	Autonomy
Technosphere (b) (38)	visualize	societal	user
EIDEA (39)	vis+son+monitor	environmental	data−driven
A-volve (40)	visualize	life	user

The first aspect that emerges from the diagrammatic summary (Fig. 4) is that CEs operate *autonomously* within an aesthetic that is largely focused around *visualizations* of processes of *life*. A close inspection of Table #1 reveals that the internal dynamics of the processes of life, such as the spread of diseases in Pandemic (Dorin, 2012) or niche-formation in Relazioni Emergenti (Annunziato & Pierucci, 2000), and self-referentiality, such as the abstract compositions resulting from processes of natural selection in Galatema (Lioret, 2012), dominate largely representing nearly 70% of the referentiality spectrum. Together, environmental, societal, political and the economy are themes which represent only about a third of the spectrum. This should not be too surprising if we take into consideration the historical agenda of ALife which has often been used in science to demonstrate biological phenomena and offer suggestions on how such phenomena may arise and function. CEs in particular have been used to draw conclusions about complex adaptive systems. As Whitelaw underlines: ALife art is engaged in the pursuit of an agenda, where visualizing and emphasizing life and its processes, are a top priority (Whitelaw, 2004). This situation indicates potential avenues to explore in the future by artists wanting to demarcate themselves from the main themes of previous works.

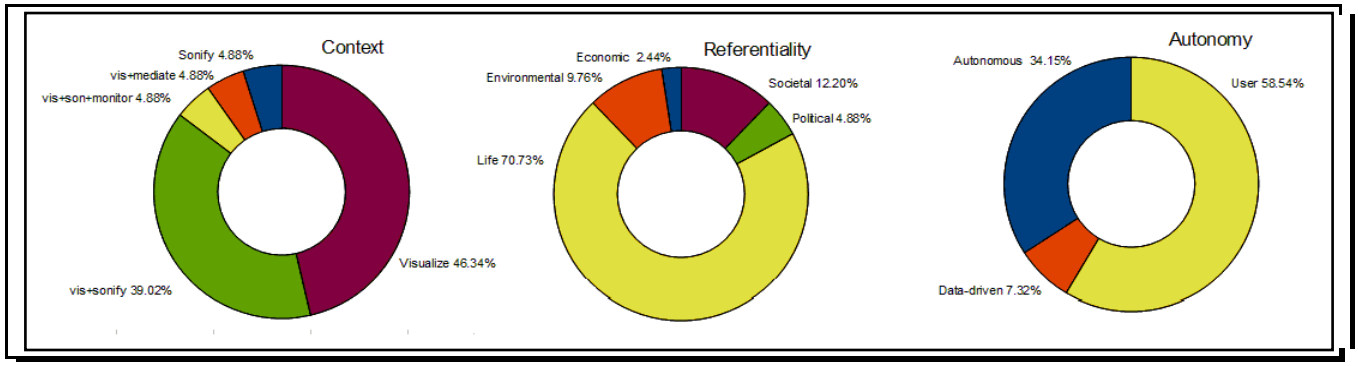

Figure 4: Diagrammatic summary of the context of the works.

Looking into the specifics of projects from the point of view of the Context variable, it is not too surprising to find that most works operate in the visual realm (95%), and almost half of them make use of the aural dimension (45%). More recent works tend to explore the two modalities integrated together. The other main common denominator is the exploration of interactions with the audience.

Only a small minority or works require external data as input (7%), but by contrast, the majority requires the audience to be active and perform actions directly impacting the CE (60%). Some works are entirely dependent on such actions: for instance, Cycles (Bisig & Unemi, 2010) requires the user to put their hand under the device containing the camera in order to let the virtual agents feed themselves. In other works however the user only interferes with the natural evolution of the CE, such as in A-Volve (Sommerer & Mignonneau, 1994), where the audience may insert a new fish in the pool, thus changing the *status quo* of the virtual tank. The following section analyses the interactive aspect in more detail.

3.2 Interactivity

Table #2 and Figure #5 capture and summarise the interactivity of the 40 works.

Table 2: The user (interactivity) functions of the 40 surveyed works

Work	Perspec.	User Function	Link.	Mode	Det.	Access	Class
CodeForm (1)	personal	configurative	implicit	3	no	random	2
Swarmic-art (2)	personal	configurative	explicit	2	no	random	2
Bornhof (3)	impersonal	interpretative	none	1	yes	controlled	1
WisLM (a) (4)	impersonal	explorative	explicit	3	no	random	2
WisLM (b) (4)	impersonal	explorative	explicit	3	no	random	2
Time of Dbl. (5)	personal	explorative	implicit	5	no	random	3
Pandemic (6)	personal	interpretative	implicit	4	no	random	2
Vishnu's (7)	impersonal	interpretative	none	2	no	random	2
EvoEco (8)	personal	explorative	explicit	3	no	controlled	1
Cycles (9)	personal	interpretative	explicit	3	no	random	3
Sra Graca (10)	impersonal	interpretative	explicit	4	no	random	2
Sonic Ecosystems (11)	impersonal	interpretative	none	2	no	random	2
Constellation (12)	impersonal	interpretative	none	3	no	random	2
Habitat (13)	impersonal	interpretative	none	3	no	random	2
Niches (14)	impersonal	interpretative	none	2	yes	controlled	1
Fluid Space (15)	personal	explorative	explicit	5	no	random	3
Quorum Sens. (16)	personal	explorative	implicit	4	no	random	3
Filterscape (17)	impersonal	interpretative	none	2	no	random	2
Infinite Game (18)	personal	explorative	explicit	5	no	random	3
Colour Cycling (19)	impersonal	interpretative	none	2	no	random	1
xTNZ (20)	personal	explorative	explicit	3	no	random	2
Funky Forest (21)	personal	explorative	implicit	5	no	random	3
E-volver (22)	personal	explorative	explicit	3	no	controlled	1
Plague (23)	personal	explorative	implicit	3	no	random	2
Ambient Light (24)	personal	interpretative	explicit	2	no	random	2
Lifedrop (25)	impersonal	configurative	none	2	no	random	2
Meniscus (26)	personal	configurative	explicit	5	no	random	2
Black Sq. (27)	impersonal	interpretative	none	4	no	random	2
Eden (28)	personal	explorative	implicit	4	no	random	2
Biotica (29)	personal	explorative	explicit	3	no	random	2
Living Melod. (30)	impersonal	interpretative	none	1	no	random	2
Listen. Skies (31)	personal	explorative	explicit	4	no	random	2
Iki Iki (32)	personal	configurative	explicit	3	no	random	3
Life Spacies (33)	personal	configurative	Implicit+ explicit	5	no	random	2
Garden of Ch. (34)	personal	interpretative	explicit	4	no	random	2
NerveGarden (35)	personal	explorative	explicit	2	no	random	2
Nagual Exp. (36)	impersonal	interpretative	none	1	yes	controlled	1
Relazioni Emer. (37)	personal	configurative	implicit	3	no	random	3

Work	Perspec.	User Function	Link.	Mode	Det.	Access	Class
Technos. (a) (38)	personal	configurative	explicit	2	no	controlled	2
Technos. (b) (38)	personal	configurative	explicit	2	no	controlled	2
EIDEA (39)	impersonal	interpretative	none	3	no	random	3
A-volve (40)	personal	explorative	explicit	4	no	random	2

With no exception all the works under scrutiny produce either a visual or audio outcome to be experienced and appreciated. This naturally results from the selection criteria used, which required works to be artistic or exhibited in public. The audience is an integral part of most works and the interactive devices are explicit and visible for the large part (45%). In 22% of the instances however, the body presence is captured without the help of any accessory haptic devices, usually by means of computer vision techniques. This percentage would have substantially risen if we had considered only interactive works. Also, note that in the near future, the new possibilities provided by interactive technologies such as Microsoft's Kinect and its descendants are likely to have a major impact on the field (*i.e.* raise the influence of body movement and gesture-based interactions).

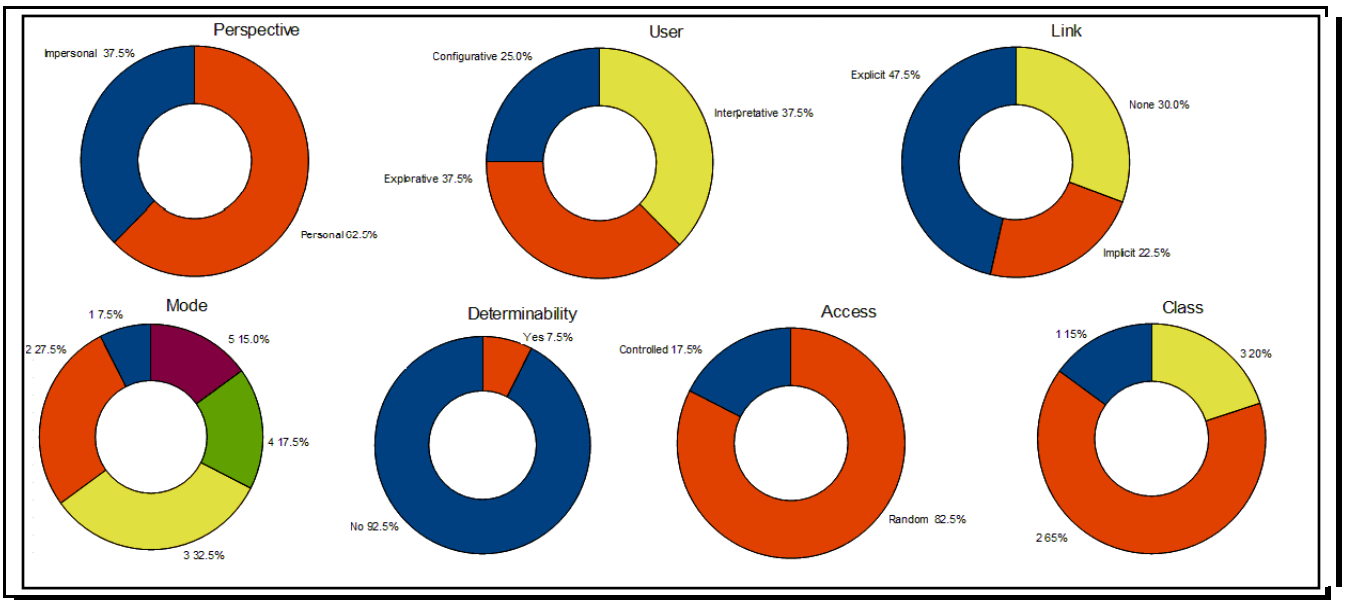

Figure 5: Diagrammatic summary of the Interactivity of the works.

The explorative component is present in 38% of the works, but only a rather small number of projects (25%) let the user configure the settings (or interfere with the evolution). Meniscus (Dorin, 2003) provides an example where the audience controls the level of virtual water in the simulation. This small percentage of works allowing configurative tasks is rather surprising, in particular since we have considered the actions of adding or removing members of the population (of the CE) as part of this category. As mentioned earlier one conclusion to derive from our study is the untapped potential for greater levels of interactivity, in particular for the exploration of the configurative roles played by the audience.

We further underline that although a CE is in essence a complex system often exhibiting non-determinable outcomes, it remains constrained by parameters restricted to operate only within set

ranges.[2] For instance, if the programmer designs the system as composed by individuals represented by triangles, these will never become circles or take other geometrical forms. Having full access to non-determinability remains a "holy grail" of ALife: *i.e.,* producing some open-ended systems which automatically generate and change their own rules of production.

In terms of the Linking variable, we notice that nearly half the works use explicit interaction devices such as a mouse in xTNZ, hands blocking a sensor's view in Cycles, or wearing special goggles as in Biotica. For nearly another quarter of the works the presence of the user is captured in a more discrete, implicit way (22%). In terms of the Class variable, the majority of works (65%) keep changing over time but not in a structural way (class #2), while a significant number exhibit more complex behaviors (class #3 at 22%). As for the Mode variable, about 2/3 of the works explore simultaneously four or more of the properties analysed: visual, haptic, aural, movement from the user and perception of procedural qualities. In terms of the Perspective variable, for 62% of the cases the user has a personal engagement with the story, either by creating a new creature (*e.g.* in AVolve (Sommerer & Mignonneau, 1994)), or adding food/energy (*e.g.* in Fluid Space (Ji & Wakefield, 2009; Ji, 2012)), or introducing a disease to the virtual world (*e.g.* in Pandemic (Dorin, 2012)).

Finally, the Access variable provides us with a clear pattern that distinguishes CEs from other interactive media instances such as games, as a large majority (83%) of the works represented here do not offer "levels" or hidden areas of the world that the user can activate by means of their actions.

3.3 Formal Parameters

Table 3 presents the classification of the 40 works with regards to their formal variables making explicit their mode of presentation or exhibition.

Table 3: The formal classification of the 40 surveyed works

Work	Format	Comp.	Visual	Depth	Color	SFX	Sonific.	Display	Scale
CodeForm (1)	video	repres	volumes	3D	multi	yes	granular	frontal−proj	human
Swarmic-Art (2)	website	repres	dots	2D	B/W	no	granular	comp−screen	micro
Bornhof (3)	still	abstract	lines	2D	multi	no	none	NA	micro
WisLM (a) (4)	video−inter	repres	volumes	3D	multi	no	preselect	frontal−proj	micro
WisLM (b) (4)	website	repres	volumes	3D	multi	no	preselect	comp−	micro
Time of Dbl (5)	installation	abstract	vol+ephe	3D	multi	yes	granular	multi−proj	human
Pandemic (6)	installation	abstract	surfaces	3D	multi	no	granular	frontal−proj	human
Vishnu's (7)	website	repres	volumes	3D	multi	no	preselect	comp−	micro
EvoEco (8)	website	abstract	dots	2D	multi	no	none	comp−screen	micro
Cycles (9)	sculpture	abstract	lines+surf	2D	multi	yes	none	vertical−proj	micro
Sra Graca (10)	sw−app	abstract	vol+ephe	3D	multi	yes	none	comp−screen	micro
Sonic Ecosystems	sw−app	abstract	NA	NA	NA	NA	granular	NA	NA
Constellation (12)	video	repres	surfaces	2D	multi	yes	No	retro−proj	macro
Habitat (13)	sw−app	repres	surfaces	2D	multi	no	preselect	comp−	micro
Niches (14)	still	abstract	lines	2D	mono	no	none	NA	micro
Fluid Space (15)	installation	abstract	vol+ephe	3D	multi	yes	granular	frontal−proj	human

[2] Note that most works (93%) are not determinable; the only exceptions being works presented to the public as static pictures.

Work	Format	Comp.	Visual	Depth	Color	SFX	Sonific.	Display	Scale
Quorum Sens. (16)	installation	abstract	vol+ephe	3D	multi	yes	NA	vertical−proj	human
Filterscape (17)	sw−app	abstract	NA	NA	NA	NA	granular	NA	human
Infinite Game (18)	installation	abstract	vol+ephe	3D	multi	yes	granular	frontal−proj	human
Colour Cycling (19)	video	abstract	dots	2D	multi	no	NA	comp−	micro
xTNZ (20)	video−inter	abstract	vol+ephe	3D	multi	yes	preselect	frontal−proj	micro
Funky Forest (21)	installation	repres	surfaces	2D	multi	no	preselect	frontal−proj/ vertical−proj	micro
E-volver (22)	video−inter	abstract	dots	2D	multi	no	NA	flat−panel	micro
Plague (23)	installation	abstract	surfaces	3D	multi	no	granular	frontal−proj	human
Ambient Light (24)	installation	abstract	surfaces	2D	multi	no	NA	flat−panel	micro
Lifedrop (25)	website	repres	lines	2D	multi	no	NA	comp−	micro
Meniscus (26)	video−inter	abstract	surfaces	2D	multi	no	NA	flat−panel	micro
BlkScholes (27)	installation	abstract	dots	2D	multi	no	NA	multi−proj	human
Eden (28)	installation	abstract	surfaces	2D	multi	no	granular	multi−proj	human
Biotica (29)	sculpture	abstract	volumes	3D	multi	no	granular	retro−proj	human
LivingMelodies (30)	sw−app	abstract	NA	NA	NA	NA	granular	NA	NA
ListeningSkies (31)	video−inter	represt	surfaces	3D	multi	no	granular	frontal−proj	human
Iki Iki (32)	mobile	abstract	surfaces	2D	multi	no	NA	mobile− phone	micro
Garden of Ch. (33)	video−inter	abstract	surfaces	2D	multi	no	NA	comp−	micro
Life Spacies (34)	video−inter	repres	volumes	3D	multi	no	NA	frontal−proj	human
NerveGarden (35)	website	repres	volumes	3D	multi	no	NA	comp−	micro
Nagual Exp. (36)	still	abstract	lines	2D	B/W	no	NA	NA	micro
Relazioni Emerg	video−inter	abstract	lines	2D	multi	no	granular	retro−proj	human
Technosph. (a) (38)	video−inter	repres	volumes	3D	multi	no	NA	frontal−proj	human
Technosph. (b) (38)	website	repres	volumes	3D	multi	no	NA	comp−	micro
EIDEA (39)	video	repres	volumes	3D	multi	yes	granular	frontal−proj	human
A-volve (40)	sculpture	repres	volumes	3D	multi	no	NA	flat−panel	human

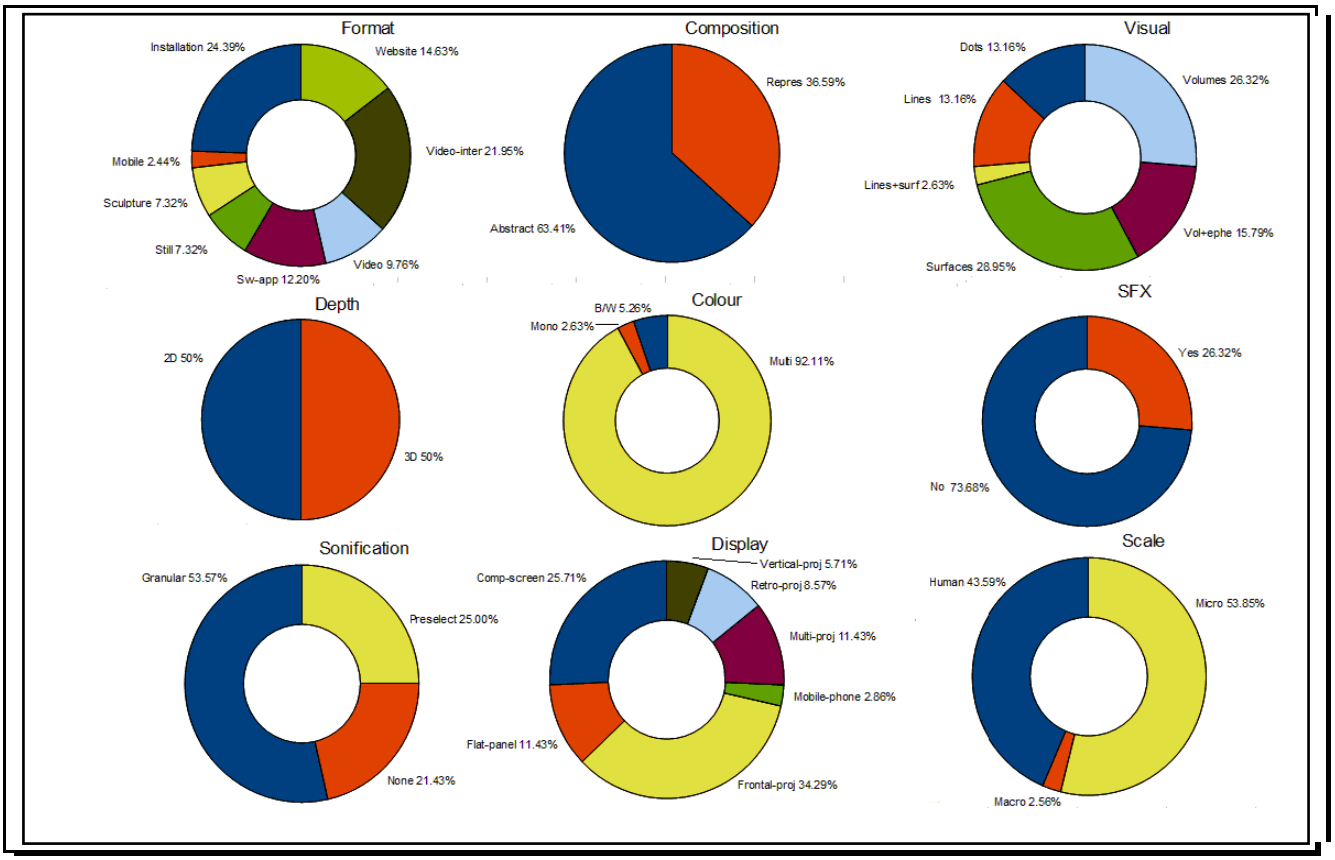

Figure 6: Diagrammatic summary of the formal presentation.

The openness and plasticity of CEs is demonstrated by this study. In the works analysed, while there is a similarity of methods used, this is combined with a great disparity of outcomes and heterogeneity in the Formats of production. The personal computer is not the privileged mode of operation, with only one third of the works taking the format of websites or software applications. Works exhibited in gallery spaces dominate the sample (nearly 70%). From this large group, video projections and interactive-video clearly dominate. As a consequence, works tend to operate at human body (44%) or smaller (micro) scales (54%), and we notice that only one project exploits macro scales (Constellation (Dorin, 2009b)).

When it comes to the Composition, we took in consideration the representational scheme of choice composed of the shape, colour, the trace used, and the scale of the artefacts. Results suggest that there is a clear dominance of the abstract over the representational. This is not too surprising taking into consideration the agenda from ALife of "life as it could be". In terms of Visual Forms, dots and lines are rarely used in comparison to surface shapes and volumes. Dots usually produce plasma-like looking works as a function of changing CE dynamics, whereas surface shapes and volumes are the carriers of more traditional modes of representation, including the use of perspective and foreshortening.

As could be expected, the Color variable is dominated by multi-chromatic works over black and white or monochrome works. Surprisingly however, there is not much sophistication involved in the resulting visualizations. Authors seem to prefer solid forms rather than SFX such as blending textures or using complex graphics. This result might be somewhat biased due to the temporal scale of the particular sample under analysis, which includes a fair number of works from the 1990's and early

2000's when rendering sophisticated visuals in real time was comparatively much harder than in recent years.

When it comes to the Depth variable, there is no clear dominance of the use of 3D versus 2D. This might change in the future, as 3D technologies (of production and display) become more accessible.

The freedom of expression of CEs is again suggested when we consider the Sonification variable. Granular and synthesized sounds are used in 54% of the works, while only 25% use pre-selected more "naturalistic" sounds. Examples of sonification include the literal translation of CE dynamics (*e.g.* Time of Doubles (Ji, 2012; Wakefield, 2012)), abstract formulations (*e.g.* Living Melodies (Dahlstedt & Nordahl, 2001)), or having visuals being entirely secondary while the focus of the work is on the sound generated (*e.g.* Filterscape (Eldridge & Dorin, 2009)). Surprising is the fact that there is no sonification at all in a large number of the works (22%), as reported in associated papers, blogs or websites. It is also worth mentioning that some works use sounds independently from the CE's dynamics (such as in WisLM (Antunes, 2012) and Vishnu's (Antunes & Leymarie, 2012)).

4. Discussion and Future Perspectives

For over 20 years artists have been experimenting with ways in which Computational Ecosystems (CEs), as a toolbox and aesthetical framework, could expand and enhance their praxis.[3] The collaboration between artists and scientists within the domain of ALife has produced new art forms, new visual languages, and new ways of relating life processes to aesthetics. And as new forms emerge, artists are finding even more creative, exciting applications. These are presented in a diversity of forms: from single-channel videos screened on a gallery monitor or video installations, to the intimacy of the personal-computer. Challenging traditional ideas of art and science, these artists use the technology as moving canvases and sculptures for often surreal, sometimes self-indulgent, usually powerful art works. They expand the visual vocabulary and force viewers to think about the relationship between art and science in a new way.

4.1 CEs as Art Forms

The use of CEs as an art producing medium establishes a dialogue with pictorial and representational traditions. It inherits methods and canons which have been in practice for centuries and now manifest themselves in structuring new works. For instance the canvas is slowly and patiently filled with "virtual ink" in Annunziato's works (Annunziato, 1998; Annunziato & Pierucci, 2000). Each agent on the canvas is a virtual drawing brush which traces virtual ink until it reaches another agent at which point it then stops its activity and "dies". Annunziato's methodology echoes the processes involved in classic drawing and painting: layers of ink are added to the canvas in a material composition of juxtapositions, accumulation and masking. A similar procedure is followed in Driessens and Verstappens's works where the canvas is akin a memory of spatial changes (Driessens & Verstappen, 2014). These works portrait the spatial dynamics of the community of agents working together on the canvas exhibited in a gallery space. Drawings result from changes in concentration and density in the community. However, in an interactive process visitors can destroy whole populations of agents whose drawings they do not like or care for. With the help of a touch screen, they can choose a new orientation

[3] We have to keep in mind that the sample scrutinized here illustrates about two decades of practice where we have witnessed an immense technological evolution. As a consequence, works from the first decade might exhibit features that are systematically distinct from those of the second. The ability to create (or make use of) certain formal properties or interactive features might not have existed earlier and we should keep this in mind. A more in depth analysis would be needed to clarify this point.

for the work from a set of possible and logical continuations which can be initiated from the present configuration. In a process of subtraction, similar to the one when material is carved out from a marble piece to let emerge a sculpture, Driessens and Verstappen's audience removes raw possibilities from a chunk of virtual potentials to let the work progress in a possibly more likeable direction. This operative arithmetic of addition and subtraction forms the essence of the dynamics of this "vivid painting in motion" as Lioret describes it (2012).

Other classic representational strategies include the omnipresent duality between interior and exterior spaces. This is emphasized in the tradition of visual arts by the frame surrounding the painting or photograph, or the pedestal supporting and elevating the vase or sculpture; it echoes the classical idea that the human stands outside, in the exterior space, to observe the artefact sitting in the interior space, the focus of our attention. Most works we analysed share this dichotomy by emphasising the computational nature of the artefacts produced and the window (or screen) paradigm which is still dominant. This dichotomy is used and integrated with contextual advantage in the narratives of works such as Senhora da Graça (Antunes & Leymarie, 2010) or EIDEA (Mitchell & Lovell, 1995) where the interior/exterior duality is emphasised by contrasting the "natural outlooks" of an exterior space from the mechanistic intricacies of the artefact production.

However, artists making "vivid painting in motion" do not constrain their practice to established processes and methods inherited from classical art despite being greatly influenced by these. The artefacts produced owe much as well to contemporary art forms such as video and installation art. Challenging the interior/exterior dichotomy, works such as Pandemic (Dorin, 2012), Eden (McCormack, 2001) and in general works in the format of installations try to blur the differences between the virtual and tangible spaces. These works combine a CE with sensing techniques, often adapted from computer vision, to capture the audience's location in a subtle way. For instance, the physical presence of the audience in Eden energizes a virtual world. The audience becomes the centre of attention of the virtual creatures who sing to call their attention and attract them in order to obtain more energy. A similar approach was followed in the Artificial Nature series where the body's shape and volumetric information is captured and transformed into energetic particles in a virtual space (Wakefield & Ji, 2009). The audience does not always play a positive role: in Pandemic (Dorin, 2012), for instance, the avatars of the members of the audience become a spreading disease.

We pointed out earlier that the generative powers of a CE rely on the gradual and cumulative effects of the changes produced by the dynamics of the autonomous elementary units of the system. Time is omnipresent. This is an essential component for any CE's operation. It is a structuring and definite variable, and works produced using CEs are naturally affiliated with the traditions of kinetic art.

As our study demonstrates, works tend to be abstract in their appearance. Members of the virtual population are represented by dots (Driessens & Verstappen, 2014), lines (Annunziato, 1998), surface shapes (Dorin, 2006), or 3D volumes (Antunes & Leymarie, 2010). The data illustrates the openness of the methodology and none of these forms dominates the others. In some instances we have outcomes with visuals rendered having plasma-like qualities (Driessens & Verstappen, 2014), whereas in others we have communities of 3D avatars walking in virtual worlds (Antunes & Leymarie, 2013). However only in a few cases does the work represent realistically the appearance of existing life-forms. Abstraction (of form) is dominant while the motto "life-as-it-could" inherited from ALife reigns over most of the spectrum of this praxis.

However, despite the dominant outcome with abstract visuals and sounds not constrained by realism, CEs remain highly representational. This has been pointed out before, in particular by Mitchell

Whitelaw (Whitelaw, 2004). ALife art owes much to the tradition of "organicism" in the arts, with its agenda and interest in representations of life. It is suggested that ALife art is not necessarily representational in the appearance of life forms, but rather in the way life *operates*. And this is indeed a fundamental aspect that is common to all the artefacts surveyed in our study.

Here it might be helpful to recall Rosalind Krauss when she questions the modernist medium-specificity in the arts. She argues the medium is not reducible as the "specific material support for a traditional aesthetic genre" (Krauss, 2011). This expanded notion of the medium that she is proposing, detached from the technical substratum, is rather grounded on a set of historically situated praxis, or what she calls the "technical support".[4] EvoArt provides examples of an artistic praxis where it is not mainly the technological medium that constitutes or defines the aesthetics: it is the ideas implemented that are important rather than the means of implementing them. The technical support of EvoArt is the set of ideas and methods informing this particular artistic praxis, including artificial life, cyberculture, systems theory, cybernetics, and the CE as a generative technique. The generative technology remains open and may be used for the purpose of varied artistic agendas as confirmed by our survey.

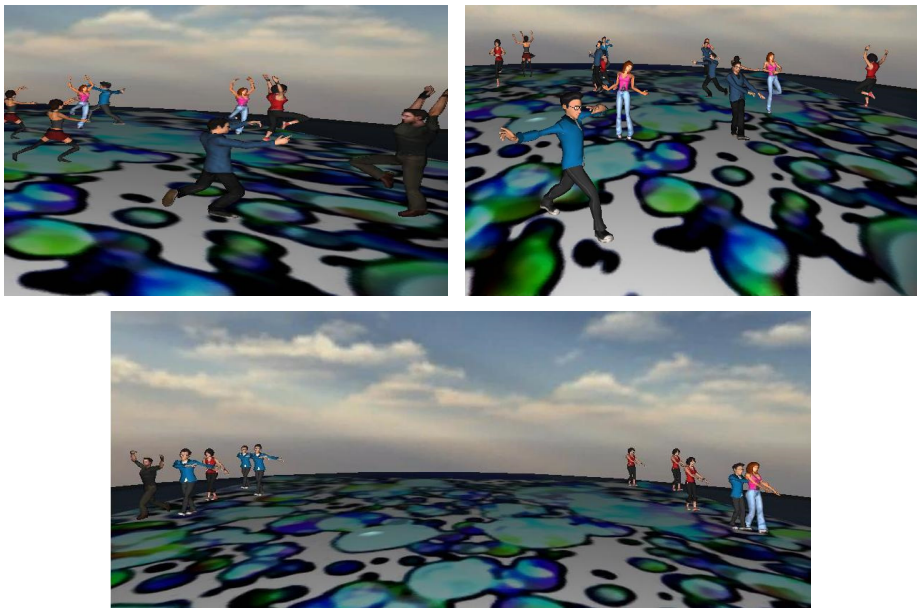

Figure 7: Three stills from *Vishnu's Dance of Life and Death*, a generative choreography in a virtual environment (Antunes & Leymarie, 2012). The sequences of gestures and movements are created in unexpected ways by reflecting the interior dynamics and workings of a CE in operation. © Antunes & Fol Leymarie, 2012.

4.2 CEs and Virtual Worlds

How do CEs inform virtual worlds? Based on the survey we conducted we can shortlist a number of characteristics and directions to exploit and explore further: (i) first and foremost is the *autonomy* of the system, which is formed by communities of agents, self-motivated and with various and varying

[4] The purist modernism tradition dwells much around the medium, of playing with the properties of the medium. Consider painting; a modernist will ask what can be done with painting, how far can we take it, use its material constraints? and then follows the questioning of what are the "materials of painting". Krauss contests that idea and argues that it is the "technical support" one should consider, which is not strictly rooted in the properties of the medium, but rather on the set of ideas that inform the practice. *E.g.* the painter might still be working with canvas and ink, but the work is subordinated to an idea, a subject and this is what becomes central. So for instance Ed Rusha is working with the subculture of LA, the automobile, its slang, the movie-stars (Krauss, 2011).

behaviors (*e.g.* Eden (McCormack, 2001)); (ii) moreover, such agents forming communities can have *multiple representations* and change over time (in the audible and/or visual domains) – such as being a youth in the early stages of a performance and become later an adult (*e.g.* xTNZ (Antunes & Leymarie, 2008)); (iii) additionally, as the first genre of EvoArt implies, agents can *evolve* over generations, by means of Mendelian genetics and Darwinian evolution and natural selection (*e.g.* Senhora da Graca (Antunes & Leymarie, 2010)); (iv) CEs can be *modulated* by *user inputs*, such as when agents are added and removed by the user's actions, who can further interact with them and their resources or even modify their genetic properties (*e.g.* A-Volve (Sommerer & Mignonneau, 1994)); (v) CEs can be controlled by *external sources*, such as weather conditions (*e.g.* (Mitchell & Lovell, 1995)) or stock market exchange data (*e.g.* BlackScholes (Demos, 2012)).

Figure 8: Two stills from *Where is Lourenço Marques?,* a virtual world where a population of gregarious humanoids is animated by a CE [5]. © Antunes & Fol Leymarie, 2012.

As discussed previously, a critical aspect of a CE lies in its plasticity. As our study shows, CEs form a solid framework which is current in the production of a diverse and wide range of artistic outcomes. Virtual world developers can rely on this basis to incorporate CEs in their methodology and toolbox of proven technologies and art praxis. Examples of CEs combined with virtual worlds also illustrate the potentials of bringing together these two realms. Examples range from the abstract "vivid painting in motion" (Lioret, 2012) (*e.g.* in Cycles (Bisig & Unemi, 2010)), to food-chains composed of autonomous Non-Player-Characters acting as herbivores or carnivores and roaming in a virtual space (*e.g.* in Technosphere (Prophet, 1996)), to the animation of performing and improvising dancing avatars (*e.g.* in Vishnu's Dance of Life and Death (Antunes & Leymarie, 2012), Figure 7), to the talkative gregarious humanoid avatars inhabiting a lost city (*e.g.* in Where is Lourenço Marques? (Antunes & Leymarie, 2013), Figure 8).

4.3 To Conclude

We have looked at the context and features of artworks produced with CEs, as these have been presented to public audiences over the last two decades. The core of our study is a survey on the structure and attributes of artworks produced using a CE as framework, covering 40 published works through 20 years of praxis which we reported here for the first time. We discussed and compared these works in terms of three categories of variables (contextual, interactivity and format). In terms of Contextual variables (section 3.1), our analysis shows that a large majority of works operate autonomously, with some inputs provided by the audience and are focused around the visualisation of

life processes. In terms of Interactivity (section 3.2), almost all works involve visualisation, sonification or a combination, and nearly half the projects involve the audience in influencing CEs' outcomes. Finally, in terms of Formal variables (section 3.3), a majority of works are exhibited in gallery spaces, and are set at the human scale (rather than say, the architectural scale). Forms and geometries used tend to be abstract rather than photo-realistic or purely representational.

Future projects could demarcate themselves from the works we surveyed by in particular: (i) further explore the use of external inputs (rather than mostly having an audience influence a CE's outcomes), (ii) allow users to reconfigure a CE's settings and evolution, (iii) give more control to users in accessing hidden levels or yet undiscovered areas of a virtual world (and maintain interest), alike in the design of commercial games, (iv) use advances in real time graphics, integrate more special effects, and perhaps explore further the use of 3D visualisations (*e.g.* with autostereoscopy and new wearable AR and VR systems such as Google glasses), (v) produce multimedia works which integrate more intimately the different modalities, in particular the visual and aural (which tend to be left independent in their production), and also integrate haptics and gestures thanks to recent and foreseeable developments in hardware and software, (vi) favour and explore further the dimensions of the environment, society, the political or the economy, rather than the prevalent life process referential, (vii) promote works to the macro scales, such as the architectural (*e.g.* projecting on the facades of buildings and monuments) or urban (*e.g.* using mobile platforms).

In summary, CEs provide a rich framework in support of EvoArt which has been explored in multiple formats and as part of diverse artistic agendas. By studying these artefacts we can identify a number of techniques and approaches which might inform the development of future virtual worlds, either to instil these with Darwinian mechanisms of natural selection and Mendelian genetics, or use these CEs to create generative soundscapes or as an abstract generative engine and explore its dynamics as a way to animate characters with unique behaviors (Antunes & Leymarie, 2013).

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