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Complexity, Coordination Dynamics and the Urban Landscape

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Abstract: Similar to living complex systems, cities are composed of a huge number of interacting parts, each with its specific properties, rhythm, etc., that, by means of self-organization, give rise to a functioning complex system. A major challenge is thus to follow the self-organized adaptation process by which the huge number of diverse parts coordinate their action and behavior into a coherent whole. *Coordination dynamics*, the science of coordination, elaborates on this issue, showing how patterns of coordination form, adapt, persist and change in living things. Recent studies on cities and complexity exposed that human agents differ from other living things in that they adapt not only through behavior but also through the construction of artifacts, thus giving rise to *hybrid complex systems* (HCSs) and to cities as such. This entails a new challenge regarding the various aspects and roles of artifacts in coordination dynamics. This study introduces the notions of hybrid complex systems and coordination dynamics and then focuses on one aspect that concerns coordination in cities: the ways the artificial urban landscape participates in coordinating the dynamics between the human urban agents.

Keywords: complexity; artifacts; self-organization; complex adaptive systems; hybrid complex systems; metastability

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Citation: Portugali, J. Complexity, Coordination Dynamics and the Urban Landscape. *Buildings* **2024**, *14*, 1327. https://doi.org/10.3390/buildings14051327

Academic Editors: Derek Clements-Croome and Haifeng Liao

Received: 1 March 2024
Revised: 11 April 2024
Accepted: 27 April 2024
Published: 8 May 2024

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1. Introduction

From the very inception of complexity theory, the city was used as a metaphor and example to convey the notion of a complex system—e.g., in Prigogine's 1977 Nobel lecture [1], that is, as an open, far-from-equilibrium system typified by the phenomena of self-organization, phase transition, and more. Soon after, the domain of *complexity theories of cities* (CTCs) emerged by applying all theories of complexity to the study of cities [2]. Since then, the development of CTCs followed closely the development of ideas in the core theories of complexity. Thus, from the 1970s to the 1990s, cities were studied as complex systems, while, following the studies of Gell-Mann [3] and Holland [4,5], they were studied as complex adaptive systems (CASs).

More recently, it was shown that cities still qualitatively differ from CASs, thus exhibiting a new kind complex system termed hybrid complex systems (HCSs), that is, systems composed of artifacts which are simple systems and human agents which are complex systems [6,7]. So far, studies on HCSs focused mainly on the various ways they differ from complex systems and CASs; here, the aim is to direct attention to, and develop a theorization about, the relations between the artificial and natural components of HCSs, with special reference to the ways they take place in the dynamics of cities, that is, the way urban agents, by means of their action and behavior, produce urban artifacts, interact with them, and how the resultant artificial urban landscape feeds back and affects the behavior, action of, and interaction between, the urban agents.

Similar to CASs, HCSs are composed of a huge number of parts, each with its specific properties, rhythm, etc., in relations of negation and/or complementarity with other parts that, by means of self-organization, give rise to a coherent whole through their interaction—a functioning complex system. A major challenge is thus to follow the self-organized adaptation process by which the huge number of diverse parts of such systems eventually coordinate their action and behavior. Haken's theory of synergetics [8] and its extension by the research domain of coordination dynamics [9] elaborate on this issue by reference to CASs and to adaptation by means of behavior. As we show below, HCSs add a new dimension to this process: coordination and adaptation by means of the production of artifacts which in the case of cities as HCSs entails an urban artificial landscape whose pattern and evolution is characterized by various forms of coordination.

The discussion below opens with two introductory sections: Section 1 follows the transition from cities as complex systems, through CASs, to HCSs. It then briefly introduces the notion of SIRNIA as the theoretical model of cities as HCSs. Section 2 introduces the research domain of CD, its notions of *metastability* and *complementary pairs*, and three preliminary applications to cities. Sections 3 and 4 that follow form the core of the paper: Section 3 suggests an integration of CD in the context of HCSs by examining the role of the environment in CD and by suggesting ways by which artifacts and the artificial environment of cities participate in coordinating the relations between the urban agents. Section 4 complements the above by suggesting to see the city as a real potential landscape, similar to the abstract/mathematical potential landscape commonly used in CD studies. This is then illustrated by means of links to urban theory and to two case studies. The paper concludes by noting, firstly, that while cities exhibit a fascinating case study of coordination dynamics, urban studies refer to the various aspects of coordination in a top-down manner and thus only implicitly. Secondly, this this paper shows how the conceptual and theoretical perspectives of CD can inform the domain of CTCs.

2. Hybrid Complex Systems (HCS)

2.1. From CSs through CASs to HCSs

As just mentioned, the evolution of CTCs followed the two steps of the evolution of complex systems in general: from cities as complex systems to cities as CASs. In both steps, the application to cities was made by analogy: analogously to a material complex system (e.g., the laser process or the Bénard cells) in which the interaction between the parts give rise to the global system, in cities too, the parts—the urban agents—by means of their interaction among themselves and with their environment, give rise to the city as a whole system. This transition from complex system to CAS was made, on the one hand, by searching for, and finding, similarities and analogies, while on the other, by searching and identifying differences: the first search has led to the conclusion that material and living systems are both complex, while the second search has led to the conclusion that the transition from material to living complex systems involves a qualitative change—a phase transition in the parlance of complexity. More specifically, the question 'in what way a living complex system differs from a material complex system?' has led to the response: by the process of *adaptation*, which does not exist in material complex systems but is central to organic living complex systems. The notion of CASs thus implies that the transition from a material complex system to a living complex system involves a qualitative change, that is, a phase transition.

The notion of HCSs originated from the same kind of search for similarities and differences [7]: On the similarity side, since the 1970s, studies indicate that cities are complex systems and were thus often employed as a typical case study of such systems—e.g., in Prigogine's Nobel lecture and more [1]. On the difference side, however, it was realized that while cities are indeed complex systems and more specifically CASs, there is still a qualitative change—a phase transition—between CASs as they exist in nature and cities as such—a qualitative change that typifies the two basic scales of urban dynamics: as noted above, at the scale of cities, artifacts form an integral component of an urban system, while at the scale of individual urban agents, artifacts are also an integral component of urban agents' behavior; namely, urban agents' adaptive behavior is typified by the production of artifacts, thus making cities HCSs.

2.2. Artifacts

> "The world we live in today is much more a man-made, or artificial, world than it is a natural world. Almost every element in our environment shows evidence of human artifice." (Herbert Simon ([10], p. 2) in his *The Sciences of the Artificial*).

While the notion of an artifact commonly refers to material entities such as tools, buildings, or machines, Simon [10] emphasizes that it also includes artificial entities such as administration, planning, and design. To the latter, it has been added that while small-scale artifacts are produced and used by individuals, other large-scale collective artifacts emerge out of the interaction between the individual parts, thus giving rise to the artificial urban landscape—to its material components (e.g., buildings or roads) as well as to the planning regulations and rules that accompany them [6,7]. From this follows two kinds of artifacts: conceptual (cultural, political, religious, and also city plans of all kinds, etc.) vs. material (ranging from personal tools to collective ones such as neighborhoods, cities, and whole metropolises). An HCS is thus hybrid also in the sense that it is composed of material and conceptual artifacts. For example, a typical urban street is composed of road and pavement plus, first, the planning rule that the pavement is for pedestrian movement, while the road is for vehicle movement. Second, despite the planning rule/law, in some situations, the pavement is also used for riding bikes and scooters (see further below). (There is a third kind of artifact that will not be delt with here—the products of what Schwab [11] has termed *The 4th Industrial Revolution* (or in short 'Industry 4.0'): AI or AL machines/artifacts that imitate/simulate human cognitive capabilities, such as, e.g., Chat GPS or autonomous self-driving cars. The notion of HCSs does not (yet) refer to such objects as their relation to HCSs requires a separate study. For a good starting point to such a discussion, see Dumas et al. [12] and further bibliography there).

The notion of SIRNIA is a theory and model that was specifically designed to capture the complexity of HCSs. As this notion has been described in some detail in the past [13,14], the next section is a concise reminder—a preparatory step toward subsequent discussions.

2.3. SIRNIA, a Concise Reminder

The notion of SIRNIA is composed of SIRN (synergetic inter-representation networks) and IA (information adaptation). Figure 1 presents the basic SIRNIA model as it applies to a single urban agent, which, from the perspective of complexity theory, is a CAS. As illustrated graphically in Figure 1, our urban agent is subject to a flow of data that come from the environment (the city) and a flow of information originating from the agent's mind/brain. The term *information* refers, on the one hand, to the quantity of information conveyed by a message, as defined by Shannon's information theory [15], while on the other, to the meaning conveyed by a message, which can take two forms: semantic information (SI), referring to the meaning per se and pragmatic information (PI)—referring to the action conveyed by the message [16].

From Figure 1, it can be seen that the process of information adaptation forms the core of the SIRNIA model. Its essence is an interaction between the two flows of information to which the urban agent is subject: It first transforms the data conveyed by the environment (e.g., city) into quantitative Shannon information (SHI), which in its turn triggers an information flow from the mind/brain that adapts the local information flow from the environment to the global information flow previously constructed ("stored") in the mind/brain. In this process, if the data from the environment is insufficient, the mind/brain adds data, resulting in *information inflation* (I-inflation); when it is superfluous, it extracts data, resulting in *information deflation* (I-deflation). The outcome is the meaningful entity/image that we see (SI) and the entailed behavior and action (PI).

In order to apply the basic SIRNIA model to real case studies, three sub-models were derived from it [13,17]: the intrapersonal, referring to activities of a single urban agent; the *interpersonal sequential* sub-model, referring to an interaction between a sequence of agents; and finally, the *interpersonal collective* sub-model, referring to the simultaneous interaction among many agents, that is, to the urban dynamics as a whole.

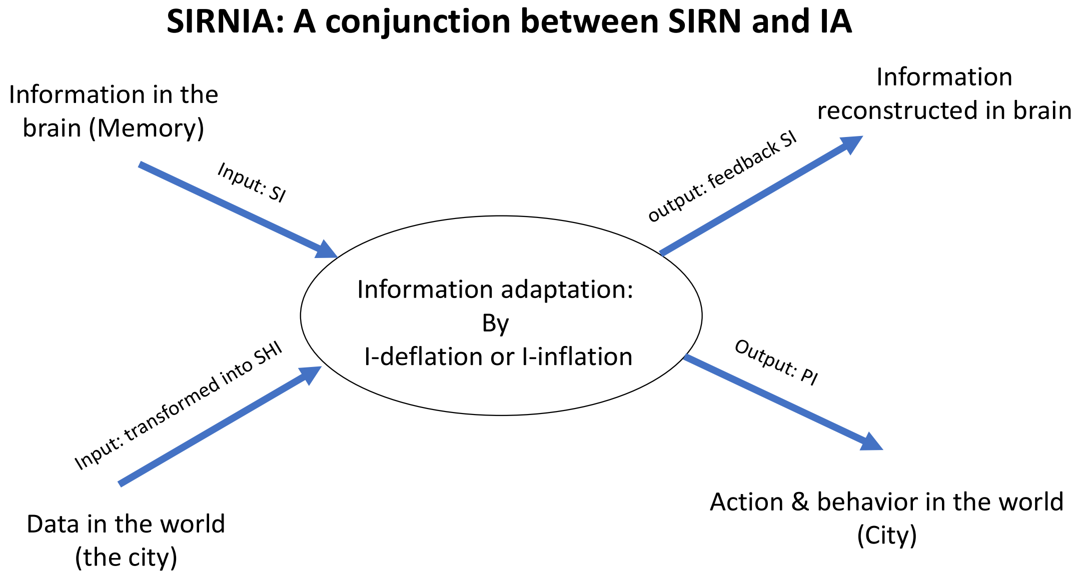

Figure 1. The basic SIRNIA model. For details, see text. SHI—Shannon information. SI—semantic information. PI—pragmatic information.

2.4. Aspects of Information Adaptation

As can be seen from Figure 1, the process of IA at the core of SIRNIA gives rise to two interrelated qualitative outputs: SI and PI. SI, associated as it is with processes of perception and pattern recognition, provides an interpretation of the information conveyed by the world (environ, city, etc.) and thus functions as a preparatory stage to PI—the second output. For example, SI interprets the situation as possible 'danger' and thus indicates for the PI the required action and/or the possible adaptive action and behavior in the face of such a danger, e.g., FFF (freeze, fight, flight).

The two qualitative outputs are 'interrelated' in the sense of the *embodied cognition*'s [18] approach and Gibson's notion of *affordances*, according to which perception and action are two aspects of the same cognitive/behavioral process [19], namely, that the SI stage of perception enfolds the action possibilities afforded to the perceiving body by the environment and thus the PI stage of their execution. (These relations between the process of IA, SI, and PI stood at the center of a heated debate in cognitive science between classical cognitivism and its information processing approach and embodied cognition, which challenged the classical view. For details and relations to spatial cognition and the dynamics of cities, see [20]).

Subsequent studies [14,16] have identified several forms of PI as adaptive behavior, ranging from *reflexive behavior*, through *multiple choice behavior*, to niche construction (see further discussion below) and to PI as adaptation by means of the construction/production of artifacts. As can be seen, the first two refer to behavior and action *within* the environment without changing it, whereas the second two to action *on* the environment that does affect it. Action on the environment can further take two forms: niche construction, which is typical of many animals, and the production of artifacts, which is unique to humans.

The transition to HCSs thus follows the observation/property that unlike the rest of animals, humans alone adapt not only through behavior but also through the construction of artifacts; that is, their PI is sometimes behavior and sometimes the artifacts of two basic forms: singular artifacts, such as working tools of all kinds, and collective artifacts, such as the artificial components of cities as HCSs (e.g., buildings, roads, etc., but also planning rules and other factors). Such artifacts come into being by the dynamics of cities and the various CTCs theorize about this process. The general consensus in the domain of CTCs is that cities emerge bottom-up out of the interaction between their parts—the urban agents. To the latter view, the theory of *synergetic cities* [14] adds that once a city comes into being, its top-down nature affects the interaction between the parts (by a process termed the "slaving principle") and so on in circular causality.

3. Coordination Dynamics

CASs are composed of a huge number of parts, each with its specific properties, rhythm, etc., in relations of negation and/or complementarity with other parts that, by means of self-organization, give rise to a coherent whole through their interaction—a functioning complex system. The theory of synergetics and its extension by the research domain of coordination dynamics elaborates on this issue. In this section, we briefly introduce this domain starting from the synergetics finger movement paradigm, through the notions of bistability and multistability, to metastability and complementarity.

In an entry to *The Encyclopedia of Complexity*, Kelso [9] defines the notion of coordination dynamics as follows:

> Coordination Dynamics, . . . the science of coordination, describes, explains and predicts how patterns of coordination form, adapt, persist and change in living things. In coordination dynamics the parts communicate via mutual information exchange and information is meaningful and specific to the forms coordination takes. Coordination dynamics embraces both spontaneous self-organizing tendencies and the need to guide or direct them in specific ways in a single conceptual framework. Life, brain, mind and behavior are hypothesized to be linked by virtue of sharing a common underlying coordination dynamics.

3.1. The Finger Movement Experiment and the HKB Model

Coordination dynamics' point of departure was the finger movement experiment originally conducted by Kelso [21] and further elaborated and modeled by Haken, Kelso, and Bunz [22] in the context of Haken's [8] theory of synergetics; hence, it is also called the HKB model. In a typical finger movement experiment, a test person is asked to move his/her index fingers in parallel at the tempo of a metronome when the tempo is controlled by the experimenter. A typical result is that at the beginning when the tempo of the metronome is slow, the test person performs the behavioral task quite well. However, as the experimenter increases the speed of the metronome beyond a certain threshold, quite involuntarily, a switch to another kind of finger movement occurs—a phase transition to a symmetric movement (Figure 2 left). In terms of synergetics, the control parameter here is only the speed of the finger movement. This behavioral pattern exhibits all the ingredients of synergetics, including the phase transition and the so-called critical fluctuations and critical slowing-down.

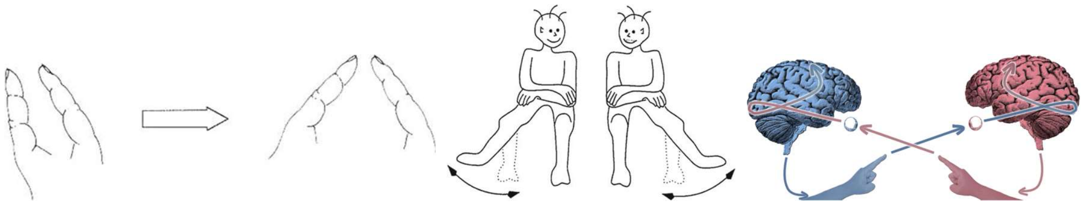

Figure 2. (**Left**): Kelso's finger movement experiment. While initially people can move their index fingers in parallel, beyond a critical speed of the finger movements, the relative position of the fingers switches involuntarily to the antiparallel, i.e., symmetric, position. (**Center**): The Schmidt et al. leg movement experiment with results identical to Kelso's finger movement experiment [23]. (**Right**): The experimental paradigm of social coordination dynamics. Two participants simultaneously perceive and produce behavior in view of each other. The subjects move their fingers in continuous fashion while at the same time observing their partner doing the same. The paradigm's simultaneity of dyadic perception and action—bidirectional coupling—is geared toward observing self-organizing processes.

Schmidt et al. [23] conducted a similar experiment but with two people instead of one (Figure 2, center). The two people were asked to move their lower legs in an antiparallel fashion and to watch each other closely while doing so. Once again, as the speed of the metronome and the leg movement increased beyond a certain speed, an involuntary transition to the in-phase motion suddenly occurred, identical to the HKB [22] phase transition in the single person's experimental model ([24], pp. 87–90). The important property of this experiment is that, in this case, we are dealing with a collective behavior—a process that is central to social and urban dynamics and to cities as HCSs. Figure 2, right, is another experiment that exhibits the same results, this time in the context of an explicit study on coordination dynamics as a foundation for understanding social behavior [25].

3.2. Metastability and the Complementary Pair

In terms of coordination dynamics, at the beginning (when the tempo is slow), the above two experiments are typified by a *bistability* regime in which, depending on initial conditions, the system can be in one of two positions (attractors): in-phase or out-phase, as in the cases of the rabbit–duck, old–young woman, vase-faces illusions (Figure 3). Bistability is a special case of the more general *multistability* regime, the essence of which, according to Engstrøm and Kelso [26], is as follows:

Figure 3. The rabbit–duck, old–young woman, vase-faces illusions.

> In the case of multistability, which attractor is reached in the multistable regime primarily depends on initial conditions. Once the system has settled into an attractor, a certain amount of noise or a perturbation is required to achieve a switching to another attractor. If control parameters such as attention or frequency are modified, a bifurcation or phase transition from multistable to monostable states and vice versa may occur.

The above quotation is taken from Engstrøm and Kelso's [26] discussion on "coordination dynamics of the complementary nature", in which they direct attention to the ubiquitous human tendency to dichotomize things, events, or processes and perceive them as contraries, i.e., good–bad, among others. In the face of this tendency, they bring the coordinative regime of *metastability*, meaning 'beyond stability'; the reason for metastability is twofold: weak coupling and heterogeneity of the components [27]. According to Tognoli et al. [25], this is "one of the chief discoveries of Coordination Dynamics" identified in brain studies and "offers new insight into how the human brain works" [28,29]. More specifically [25]:

> In the metastable brain, classical dualities like segregation and integration, competition and cooperation, individual and collective, parts and wholes, etc. exist in a kind of coordinated communion, a complementary code. They are not polarized opposites, diametrically opposing either/or. In *The Complementary Nature* [30] we introduced the tilde (~) or squiggle symbol to express this basic truth: both members of a complementary pair and the dynamic relation between them are required for a full understanding of ourselves and the complex world we live in. It's not one *versus* the other. Dissent between religions or cultures results from an overemphasis on one complementary aspect over another.

According to this view, the apparently/seemingly polarized entities of a given complementary pair (such as, e.g., body~mind, town~country) are interpreted as complementary *aspects* (ca1 and ca2 in Figure 4). The general idea is that contraries are complementary, not contradictory, with the implication that "not only the polar complementary aspects of complementary pairs that matter, but also all the stuff and all the action falling in between them" [31].

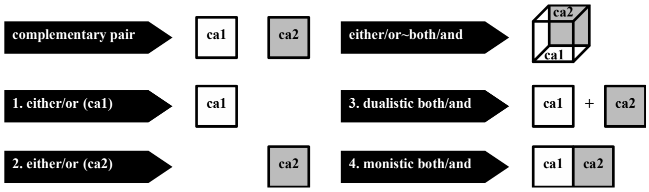

Figure 4. Kelso and Engstrøm's ([30], Figure 1) illustration of four basic interpretations of the complementary pair ca1~ca2 and their reconciliation. The Necker cube represents the inextricable relation between the complementary aspects.

3.3. Preliminary Applications to Cities

Coordination dynamics, with its notions of metastability and complementarity, was already applied to cities in three preliminary studies. In the first, Kelso et al. [31] applied the complementary pair theory to a pair of notion that at first blush appears as an apparent contradiction: self-organization versus urban design. They first suggest that from the perspective of the complementary pair, the two (seemingly) contrary pairs consist, in fact, of two complementary aspects of the single complementary pair self-organization~design. Then, following Portugali and Stolk [32], they consider the three SIRN sub-models noted above (intrapersonal, interpersonal, and the sequential simultaneous) as three scales of the urban design process. Finally, they demonstrate that the three form two complementary pairs which link the three sub-models, as shown in Figure 5.

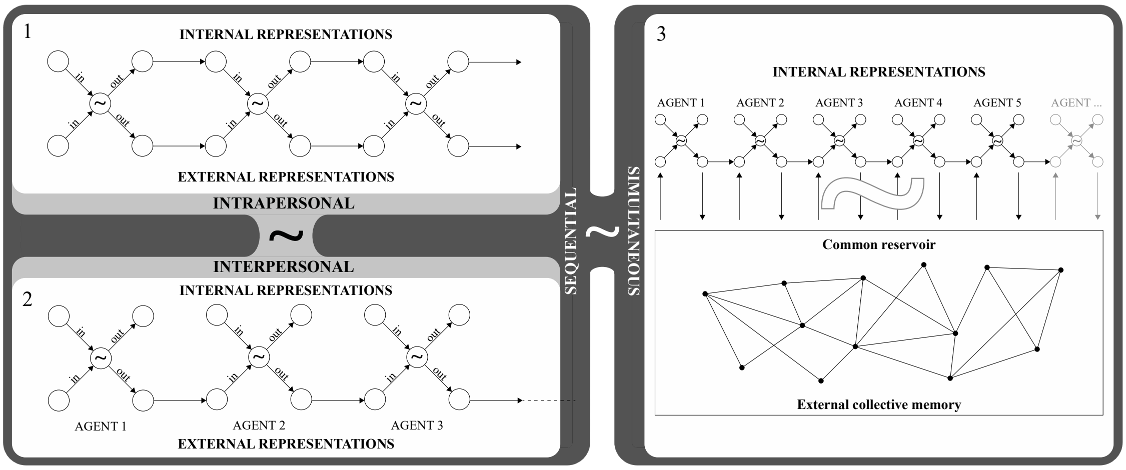

Figure 5. The three SIRN sub-models as a related metastable~multistable system (see text for discussion). Here 1 refers to an intrapersonal dynamics; 2 to an interpersonal dynamics while 3 to a sequential simultaneous dynamics.

This very preliminary application of coordination dynamics and complementary pairs to the domain of cities has far reaching implications that will have to be elaborated in the future. For example, the contradiction of top-down and bottom-up, so common in CTC studies, vanishes in light of the above discussion and is perceived as a complementary pair bottom-up~top-down. Or more generally, "the duality of cities as hybrid complex systems implies a tension between the contraries 'natural' and 'artificial'" [6]. From the above study follows a different perspective on this duality: a complementary pair 'natural~artificial', whose two components are natural and artificial aspects of the city as complex system.

A second application commences with Kelso's study on the emergence of agency [33]. At the core of Kelso's paper is a seminal experiment conducted by the late Carolyn Rovee-

Collier (1942–2014) and her associates regarding the phenomenon called *mobile conjugate reinforcement* (MCR), as illustrated in Figure 6. A typical MCR experiment starts with a ribbon attached from a 3-month-old infant's foot to a mobile suspended overhead. As illustrated in Figure 6 left, at the beginning, the mobile is still while the baby exhibits spontaneous kicking—the baby and mobile are uncoupled. After some time (t = 5, Figure 6 middle), as the baby realizes that by kicking it can make the mobile move, the baby and the mobile are coupled and the baby's kick rate and the amplitude of the mobile movement rapidly increase up to a steady state. Moreover, the phase relation between the baby's leg movement and the motion of the mobile increases, characteristic of a resonant coupled state. At t = 20, the baby and the mobile are again uncoupled; the kick rate decays back to a baseline level. Based on a theoretical/mathematical study by Kelso and Fuchs [33] that uses the concepts, methods, and tools of coordination dynamics, Kelso [33] concluded:

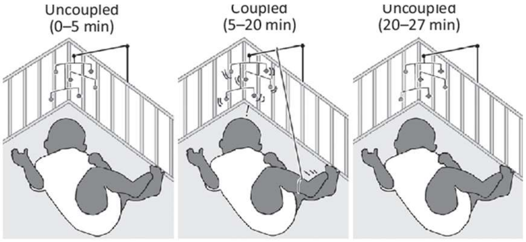

Figure 6. The baby–mobile experiment: the three phases of the MCR paradigm.

> "... the birth of agency is due to a eureka-like, pattern-forming phase transition in which the infant suddenly realizes it can make things happen in the world. The main mechanism involves positive feedback: when the baby's initially spontaneous movements cause the world to change, their perceived consequences have a sudden and sustained amplifying effect on the baby's further actions. The baby discovers itself as a causal agent.
>
> And, that:
>
> "[s]uch metastable coordination dynamics is characteristic of systems like brains and bodies composed, as they are, of parts that are heterogeneous. In all likelihood, once formed, the interaction between baby and mobile is metastable, indicative of relative not pure absolute coordination or synchrony"

In a subsequent study, Portugali [34] suggested four implications of the above to the study of cities as HCSs: (1) that "agency arises out interaction with objects in the environment" (there is another potential interpretation due to Karen Barad's [35] *Meeting the universe half way*, namely *intra-action*—meaning the organism is never really separate from its environment. This breaks down the subject–object distinction and speaks to the so-called measurement problem in quantum mechanics ... [27]). (2) "The toy indicates that ... an agent ... planned and designed this artifact using his/her agency capacity ... (3) a ... free, spontaneous, purposeless and self-organized ... [play], creates one of the most important properties of human life, action and behavior." (4) "artifacts, the products of humans planning, design and production are integral part of cognition"—a point that forms the essence of the notion of HCSs and of cities as such.

A third application is Kelso's paper "Democracy demands wisdom" [36]. It refers to the view that modern liberal democracy as it has evolved since the 18th century is composed of a conjunction between individualistic (liberal) and collectivist (popular) values and tendencies and, that until the end of the 20th century, there was a harmony between these two tendencies. The crisis is that since the early 21st century, these relations of harmony and complementarity have turned into a negation. Examining this crisis from the perspective of his notions of coordination dynamics and *The Complementary Nature* [30], Kelso suggests that the reason for the crisis of democracy "goes much deeper than democracy itself. What's wrong, fundamentally, is that people see their relations with themselves, others and the world as either-or. The result is that they are unable to tolerate dissent and acceptance of opposing views. This is what has to be fixed." (See further below in Section 4).

4. Coordination Dynamics (CD) in the Context of Cities as HCSs

4.1. The Role of the Environment in CD

In his above noted study on the emergence of human agency in a human infant (Figure 6), Kelso [5,33] observed that while the baby's action and behavior were intensively studied, not a single study has recorded the dynamics and reaction of the external environment, "thereby obviating the possibility of obtaining any information about its relation to the baby's movements". (See further discussion in [34]). While this is so with respect to the MCR experiment, the impact of the environment within which the coordination takes place is not missing in CD, nor are the ways it affects the coordination between the parts of a given system. For example, in studies on learning, it was shown (both empirically and theoretically) that the learning process is determined by whether the environment cooperates or competes with the individual learner's *intrinsic dynamics* [37]. More specifically, intrinsic dynamics refers to "the pre-existing capabilities that a learner or learning system . . . brings into the learning environment", when the latter conveys "functional information", that is, "new information that modifies the (intrinsic) dynamics" [7,38]. As can be seen, this process is similar to the process of information adaptation in the SIRNIA model described above (Section 2.3).

In the latter CD studies on learning, the environment is treated as a source of information. However, in order to link CD to cities as HCSs, I herewith suggest to direct attention to CD in the context of *constructed environments*, namely, the structure of niches constructed by animals. For example, the coordination between a couple of birds and their constructed nest, between the bees and their constructed honeycomb, or the termites and their constructed mound. Does the structure of the nest the couple has constructed play a role in coordinating their activities, and how? Does the structure of the honeycomb the bees have constructed play a role in coordinating their activities, and how? Does the structure of the mound constructed by the termites play a role in coordinating their activities, and how?

The nest, honeycomb, and mound are examples of the niches constructed by these animals—a process typical of many other animals. In recent years, it was suggested that the process of niche construction is an integral component in the basic evolutionary processes such as natural selection. Termed *niche construction theory* (NCT), this view is currently subject to debate among biologists [39,40]. Now, if, as suggested by NCT, the nest, the honeycomb, and the mound play an active role in their evolution, *do* they play a role in CD too? Tentatively speaking, in all the above examples, the answer is positive—it makes sense that the properties of the constructed environment have an effect on the CD. The question is *how*? One possible answer comes, as just noted, from Zanone and Kelso's [37] approach to learning. The aim of the present study, however, is to examine the dynamics of coordination by means of artifacts with special reference to the artificial component of cities as HCS. As a first step toward this aim we develop below a conjunction between Gibson's [19] ecological approach to cognition and his notion of *affordances*, Norman's [41] study regarding "everyday things", and the role of artifacts in urban theory.

4.2. The Role of Artifacts and the Artificial Environment in Coordination Dynamics

Semantic and pragmatic information (SI and PI), the two qualitative outputs of the SIRNIA model described above, are 'interrelated' in the sense of Gibson's [19] notion of *affordances*, according to which animals' and humans' perception of and behavior in the environment is determined by the action possibilities afforded to a given body by a given environment. Such affordances form the boundary conditions and constrain the CD that takes place in the migratory processes of, e.g., birds, fish, or gnu. Note that the environmental affordances afford specific forms of coordination between the animals while at the same time "dis-afford" other forms of coordination.

Gibson's theory provided the source of inspiration to Don Norman's [41] book *The Design of Everyday Things* (originally published as *The Psychology of Everyday Things*). In it, Norman shows that the artifacts ("everyday things") produced by humans are designed in line with humans' body capabilities so that a chair is seatable (or not) in that it affords seating, a baseball is grabable, and so on.

Norman's main focus is, firstly, on the so-called 'table-top artifacts', that is, small-scale artifacts designed to be used by single individuals. The suggestion here is to go one step beyond Norman's to larger-scale artifacts, namely, to HCSs, specifically to settlements, neighborhoods, and cities. Secondly, his focus is on the design and use of table-top artifacts; such artifacts are commonly produced by designers and craftsmen. Here, by turning our attention to larger-scale artifacts, we are dealing with artifacts that emerge out of the interaction between many agents with no designers, that is, with complex, adaptive, self-organized systems composed of artifacts that are simple systems and human agents that are complex systems. Thirdly, Norman's focus is on the design process, while here we want to focus on the role of artifacts in the dynamics of coordination, that is, on how certain artifacts, be they social networks, or the new AI chatGPT or settlements of all kinds and cities participate in coordinating the interaction between humans. The issue has recently been studied in the domain of CD with respect to the role of AI but by considering each AI instrument as an artificial agent that interacts with human agents. Here, our aim is to explore how the artifacts affect the CD between the human agents and thus social dynamics—a question still overlooked in the domain of CD, where a machine is considered as one of the interacting agents (Tognoli et al. 2020 [25]). Here too, a full-scale study is beyond the scope of the present study. However, here, as a preliminary step, we will explore this issue in the context of cities as HCSs.

4.3. The Role of Artifacts in Urban Studies

The question of how the artifacts of cities affect the CD between human agents and thus social dynamics has always been, though implicitly, at the background of urban studies. Three main traditions are relevant to the present study: The first is the social theory oriented in urban studies. A partial and not inclusive example includes the structuralist–Marxist view that the urban artifacts are essentially external representations of the deep structure of society (e.g., Harvey [42], Lefebvre [43], Castells [44]). For instance, the 'deep' rich–poor dichotomies in society are externally represented by rich vs. poor urban neighborhoods. Also, in this domain is the view of the phenomenological–humanistic approaches to cities that describe different artificial parts of the city in terms of a negation between *place* and space or rather between place and *placelessness* (e.g., Tuan [45]; Relph [46]): The first refers to buildings or urban structures that emerged out of intimate relations between people and artifacts, while the second refers to buildings or urban structure that emerged out of alienated relations between people and their relations to the urban fabric of cities.

The second tradition centers around the 'language–city' dyad [7,47]. Three main figures are prominent here: One is Lynch's [48] *The Image of the City*, with his notion of urban *legibility*: Similar to linguistic legibility, which refers to the ease with which readers can decode the written symbols, urban legibility refers to "the apparent clarity [an urban agent can decode the morphology] of the cityscape". The second is Christopher Alexander, who explicitly compares "his" *A Pattern Language* [49] to a natural spoken language, while in *The Timeless Way of Building* [50], he elaborated on the ways patterns of space are associated with patterns of events—a view similar to Gibson's [19] notion of affordances, as illustrated in Figure 7 left, and to the SIRNIA notion of PI (see further below). The third is Bill Hillier's [51] *Space syntax*, suggesting, e.g., the spatial morphology of the cities' road networks function as a syntactic network that determines/affects the cities' semantic structure, e.g., their land uses and patterns of movement (Figure 7 right). All three suggested "that there is literally a language of cities with its specific syntax, semantics, pragmatics and the rest" [47].

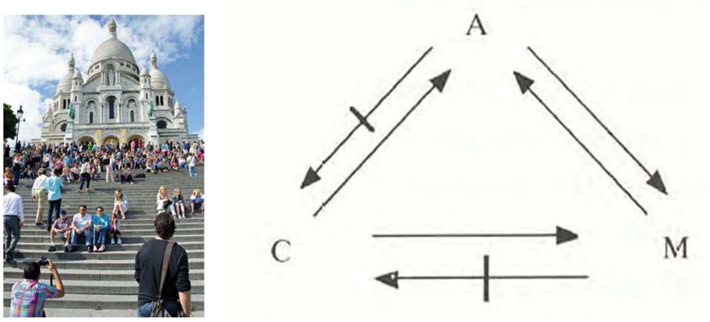

Figure 7. (**Left**)*:* A pattern of space (e.g., the steps to the Sacré-Coeur in Paris) affords/conveys also the pattern of event = the PI action of seating. (**Right**)*:* According to space syntax, the relations between the city's global morphological configuration (C), the city points of attractive land uses (A), and movement (M) are asymmetric: C determines both A and M but not vice versa; on the other hand, A and M might influence each other ([52], Figure 3).

Finally, the third tradition is 'complexity theories of cities' (CTCs). It is interesting to note that the above three—Alexander, Hillier, Lynch—are also connected to CTCs: Alexander is considered a forerunner of CTCs [7], Hillier [53] has made links between his space syntax and CTCs, and the Lynch theory was connected by the links between *Complexity, Cognition and the City* [13]. This is hardly surprising in light of the fact that language is used by Haken [8] as an example to convey the dynamics of his theory of synergetics: languages arise bottom-up out of the interaction between their parts (the people), but once a language comes into being, it "enslaves" the parts by describing and prescribing the interaction between the parts, and all this by means of self-organization. As we have seen above, all CTCs hold the view that the urban artificial landscape emerges bottom-up by means of self-organization out of the interaction between the parts (the urban agents). To the latter, synergetics adds that, once emerged, the top-down urban landscape enslaves the behavior of the parts and so on in circular causality. Further studies show that the process involves cognitive and official planning and design in line with the SIRNIA theory and model.

As can be seen, in all the above, CD is usually an implicit consequence of larger scale processes. What the research domain of CD adds to the story is a view on the dynamic and structure of cities that commences from the process of CD itself: First, as it takes place within the mind/body of single individual urban agents; next, between two urban agents; and then all the way to society, to which we here attempt to add to cities as HCSs.

5. The City as a Potential Landscape

5.1. Abstract Landscapes

A common way to describe and analyze the dynamics of a system is by means of the so-called *potential landscape*. For example, in his synergetic approach to *Brain Dynamics*, Haken [54] describes the dynamics by means of the *potential landscape* (V) in a space of two order parameters symbolized by the two balls in Figure 8. Given an order parameter (OP), V specifies its potential landscape, that is, spectrum of possibilities and potentialities as attractors (Figure 8). This allows quantification of both OP and V. Thus, the ball on the top of the hill is in a *multistable* state as depending on initial conditions (in fact, every small fluctuation of the landscape), and it can be attracted to one of the valleys below, while the ball at the bottom of the valley is at a *stable* state as small fluctuations will not affect its position.

The finger movement experiment and thus the HKB model discussed above (see Figure 2) were also modeled by means of such a potential landscape in which, as the control parameter changes, the corresponding potential "landscape" was deformed (Figure 9). According to Haken [54], this model can represent (or "explain") or has even predicted a number of experimental findings which apply to complex systems at large, such as *hysteresis* (the finger movement coordination is quite different depending on the history), *critical slowing down* (when the movement is disturbed, e.g., by small kicks, it takes a comparatively long time until the original, coordinated movement is restored), and *critical fluctuations* (according to synergetics, close to the critical control parameter values, in the present case ωc, the variables of a system may undergo pronounced fluctuations).

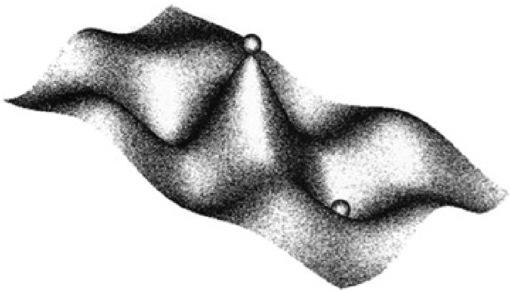

Figure 8. Example of potential landscape in a space of two order parameters (*Source*: [54], Figure 4.7).

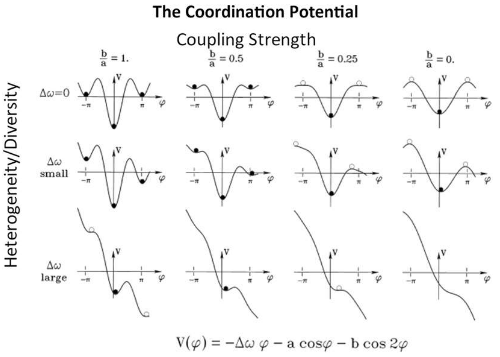

Figure 9. Kelso's ([55], Box 1) illustration of changes of potential landscape due to changes of the control parameter. *Top row*, the original HKB model; *second and third rows*—its extended symmetry-breaking version. Notice that in the bottom right, "even though all the fixed points have disappeared, some curvature in the potential remains: the system still exhibits coordination tendencies to where the fixed-point states used to be. This is the *metastable* regime of the coordination dynamics which is characteristic of coordination on many levels . . ." (Kelso [55]).

Metastability can also be described by a potential landscape, as in Figure 10. In this figure, ball 1 illustrates a metastable state, ball 2, a transitional 'saddle' configuration, while ball 3 represents a stable state.

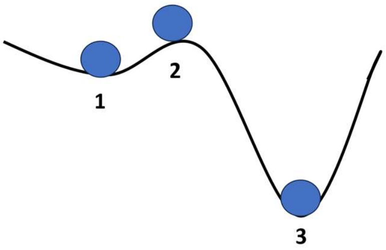

Figure 10. A simple illustration of metastability by means of a potential landscape. (See text for the meaning of 1–3). This illustration and the one that follows are consistent with statistical physics; they are useful to convey the notion of metastability but not how metastability emerges and evolves, which is the focus of coordination dynamics studies. As illustrated in Figure 9 above, by Kelso ([55], Box 1), once symmetry is broken and heterogeneity among the components is present (the potential tilts), all states (stable and unstable) disappear and only (coexisting) tendencies remain.

As discussed above, in developing the notion of a 'complementary pair' (CP), Engstrøm and Kelso [26] suggest that the ubiquitous human tendency to dichotomize and perceive things, events, or processes as contraries overlooks the coordinative regime of *metastability* in which the above seeming negations are in fact complementary. Figure 11 is a suggestion to build a potential landscape that describes both the ubiquitous human tendency to dichotomize and the coordinative regime of metastability. Here, following Kelso's 'complementary pair', metastability refers to a system that exists beyond stability, as if in between (i.e., beyond) two stable states that negate each other, symbolized by balls A and B in Figure 11. According to this conceptualization, the metastable regime can be seen as a ball moving between the two hollows *a* and *b* on the left and right of the ball, which symbolize the two aspects of the complementary pair A~B. As long as the ball moves back and forth between the two *a* and *b* hollows, the system is metastable and forms a complementary pair. However, once it moves beyond the saddles on the left and right of *a* and *b*, the system collapses from the complementary pair A~B to a negation, that is, to a bistable regime with either A or B. Metastability is thus a delicate regime that is constantly being threatened by the two extreme states A vs. B. For example, in the above case of the crisis of democracy studied by Kelso [36], after half a century of metastable regime between the two tendencies of democracy (liberalism and the rule of the demos), the democratic system collapsed into a bistable regime.

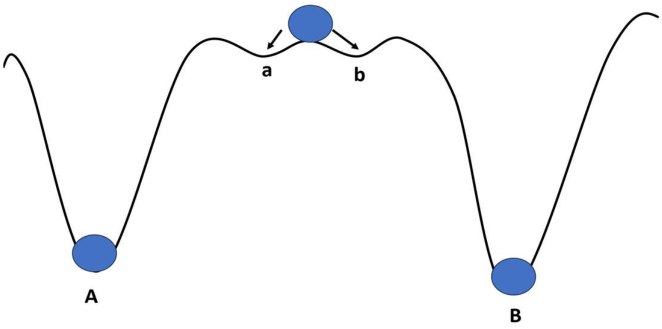

Figure 11. A potential landscape describing both the ubiquitous human tendency to dichotomize (A or B) and the coordinative regime of metastability A~B (the ball on top), where a and b are aspects of A and B. Compare to captions of Figures 9 and 10.

5.2. The Urban Potential Landscape

The suggestion here is that similar to the abstract mathematical potential landscape that participates in affecting the behavior of the system (ball), so does the real urban landscape: Firstly, it functions as a real potential landscape that affects the behavior of urban agents and the coordination dynamics among them. Secondly, like its mathematical counterpart, the real urban landscape is characterized by the co-existence of negations and contradictions that affect the quality of life and wellbeing of the urban residents. Thirdly, the mathematical potential landscape can be a conceptual/methodological device that can describe real urban landscape situations. We illustrate this first by reference to movement, next in terms of Alexander's [56] notion of the city as a *semi-lattice* network, and finally by reconsidering the case study of Tel Aviv's balconies.

5.2.1. Movement

Take, for example, *movement*, which is among the most dominant activities people execute in the city. For simplicity, assume that we have two forms of movement: walking and driving. Apparently, the two negate and conflict with each other. In order to coordinate these two forms, the common urban design solution to a typical urban street is built with pavement for walkers and road for drivers. In terms of potential landscape, this street structure is bistable as it allows either walking or driving. Now, introduce to this street an urban agent with a scooter (or a bike). Examining the street from the perspective of Gibson's affordances, our agent realizes that both the pavement and the road afford riding the scooter. By deciding to use the pavement (or the road), our agent transforms the pavement (or the road) from a stable to a metastable landscape. By choosing to use both, the street as a whole is being transformed from a bistable into a metastable structure. Note that if all movers behave carefully, harmony prevails as walking and driving co-exist as the complementary pair walking~driving. However, when some movers are not careful in their behavior, conflicts arise, as is now the case in Tel Aviv, for instance.

5.2.2. A City Is Not a Tree

An urban *plat map* of lots, blocks, and plots, is the basic planning tool in every city. One of its major functions is to define the private vs. the public domains in the city (Figure 12). On the face of it, Figure 12 represents a clear-cut bistable structure: private lots with their buildings versus public streets with their pavements and roads, and nothing in between.

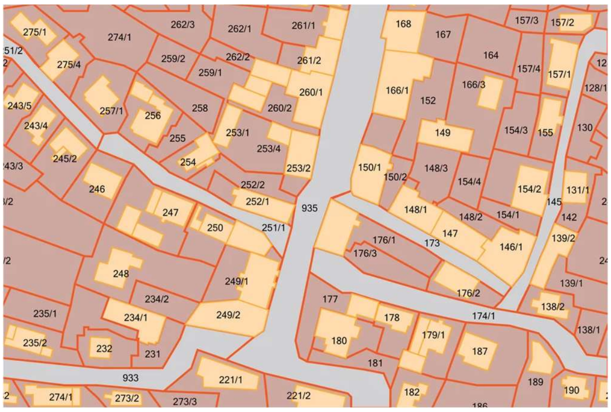

Figure 12. Typical urban plat map.

This is indeed so if you look at such a map from the formal technical perspective, that is, from the perspective of what Alexander [56] has described as a tree structure or network. In his seminal "*A City Is Not a Tree*", he suggests that a city is rather a semi-lattice structure, network, and system. To illustrate the nature and complexity of a semi-lattice network, he gives the following example:

> For example, in Berkeley at the corner of Hearst and Euclid, there is a drugstore, and outside the drugstore a traffic light. In the entrance to the drugstore there is a newsrack where the day's papers are displayed. When the light is red, people who are waiting to cross the street stand idly by the light; and since they have nothing to do, they look at the papers displayed on the newsrack which they can see from where they stand. Some of them just read the headlines, others actually buy a paper while they wait.
>
> This effect makes the newsrack and the traffic light interactive; the newsrack, the newspapers on it, the money going from people's pockets to the dime slot, the people who stop at the light and read papers, the traffic light, the electric impulses which make the lights change, and the sidewalk which the people stand on form a system—they all work together.

The main aim of Alexander in this paper was to criticize the prevalent planning and design approaches of the 1960s to solve urban conflicts and negations by means of the *divide et impera* principle (Latin for "divide and rule"). When encountering a conflict between, e.g., different urban land uses and activities, the solution is division or zoning. Zoning, according to Jacobs [57], is one of the planning policies that is responsible for what she has termed *the death of great American cities*. To this, Alexander adds that real quality of life in cities stems from co-existance, i.e., from a semi-lattice urban structure. At the outset of his paper, he writes: "from a human point of view" the modern planning and design approaches are "entirelly unsuccessful". (Alexander [56], p. 1)

A city is an HCS, composed of artifacts as simple systems and people, each of which is a complex system. If you look at the city from the perspective of the urban artifacts, you see a tree structure, as in Figure 12. However, when you look at it from the perspective of the city as a whole, artifacts and people (that is, as an HCS), you see the complex urban scenario just described. And if you apply it to a regular city street, the real urban network includes, in addition to the private buildings and the public roads, the people who sit on the balconies, who see and/or talk to each other, the people walking in the street who see the people on the balconies and are seen by them, etc., as in the corner of Hearst and Euclid in Berkeley. From this perspective, the distinction of the public and private is not anymore clear-cut—the street is part of the private network of the houses, balconies, and the people and now private apartments with their balconies and the public street turned into a semi-lattice network, that is, a metastable urban pattern.

5.2.3. Tel Aviv's Balconies

The history of Tel Aviv's balconies nicely illustrates the tree vs. semi-lattice urban patterns in the city. This case study, termed 'the butterfly effect of Tel Aviv's balconies', was studied several times in the past in order to illustrate self-organization processes in the city [13,17], the play between cognitive and professional forms of planning [58], and more. Here, I present a new version of it that refers to one of the major divisions in the structure of cities—between the public and private domains, that is, to spatial urban parameters/elements that reflect urban planning and design decisions and affect the perceptions, emotions, behaviors, quality of life, and wellbeing of Tel Aviv's residents and users.

Tel Aviv was founded at the beginning of the 20th century (1909). In its first decades, the residential areas of its urban landscape were typified by one-story buildings, each with a balcony facing the street, often surrounded by a small garden and a fence (Figure 13, 1). As can be seen, while formally the streets of Tel Aviv had a tree structure, that is, a clear-cut distinction between private and public domains, this potential urban landscape affords interaction as described above so that, practically, the street was part of the private network of the houses, balconies, and the people, now private apartments with their balconies and the public street turned into a semi-lattice network, that is, a metastable urban pattern/landscape.

Figure 13. *From left to right*: 1—Tel Aviv 1911. 2—A typical Bauhaus building. 3—An intruded pillared floor. 4—A typical open balcony in the 1950s. 5—A closed balcony. 6—*No balconies*.

Starting in the 1930s, a major change took place in the urban landscape of Tel-Aviv following the introduction of the Bauhaus architectural style: typically three-story residential buildings with balconies facing the street (Figure 13, 2). The intimate relations between the private apartment and the public street gave way to a less intimate relations, where the intensity of the links between the balconies and the street decreased from floor to floor. The links between balconies and street were further weakened after the year 1939, since when all buildings were constructed with an intruded, pillared floor (Figure 13, 3) so that the lowest balcony was not at the ground floor level anymore.

This pattern continued during the 1940s and 1950s until the end of the 1950s or early 1960s (Figure 13, 4), when an anonymous resident in Tel Aviv "decided to enlarge his/her apartment by closing the balcony and making it a half-room. . . . One of the neighbors liked the idea and did the same. . .. and before long the vast majority of balconies in [Tel Aviv and] the country as a whole was closed (Figure 13, 5). At this stage, the municipalities decided to intervene and started to tax all balconies, open and closed, as if they are a regular room. In response, developers started to build buildings with closed balconies" (Figure 13, 6) ([13], p. 287).

As noted, at the outset of this section, in past studies this story of balconies was used to illustrate various properties of cities as complex systems such as self-organization, nonlinearity, and cognitive planning. Here, the aim is to illustrate how changes in the artificial urban landscape affect the relations between the private and public domains of the urban landscape and thus the coordination dynamics between the urban agents and the quality of life and wellbeing of the residents. As just described, Tel Aviv was originally founded as a semi-lattice metastable urban potential landscape; as the city evolved, gradually its urban landscape was transformed (is still transforming) into a tree structure with a bistable structure.

6. Conclusions

Cities exhibit a fascinating case study of coordination dynamics between a huge number of people, firms, artifacts, and more. Just consider this: every morning, millions of people wake up more or less at the same time, travel to work more or less at the same time, return home, and so on. This rhythm by which people coordinate their activities has not escaped the eyes of urban researchers. Thus, Jane Jacobs ([59], p. 50) "liken it to the dance… an intricate ballet in which the individual dancers and ensembles all have distinctive parts which miraculously reinforce each other and compose an orderly whole". In his *time geography*, Hägerstrand [60] showed how the daily routine of individuals is determined by three sets of constraints: embodied *capability* constraints, socio-economic *coupling* constraints, and regulatory *authority* constraints. From the perspective of synergetics, Weidlich [59] has shown how the rhythms of different urban elements affect the dynamics of cities so that the slow rhythm variables function as order parameters for fast ones, while Portugali [13] has demonstrated how the synergetics "slaving principle" describes, prescribes, and thus coordinates the interaction between the urban agents. Still, in the context of CTC, Bettencourt et al. [61] developed the notion of *urban allometry*, demonstrating statistical correlations between city size and the pace of life in cities (and thus implicitly of coordinative patterns). (For further details on this issue, see [14,62]).

The above examples are typical of many other studies in that in all of them the process of coordination is implicit and is being theorized or described in a top-down manner, and when experiments are involved, they are usually big data oriented. Coordination dynamics, per contra, presents a bottom-up view based as it is on detailed "small-data" experiments that commence from the behavior of a single person (finger movement) to two people and to the collective dynamics of social behavior. (There actually was an intermediate, quite important step which studied coordination (syncopation~synchronization) with environmental stimuli (body~world). This introduced heterogeneity between the interacting elements, which along with coupling, dictates the nature of the coordination dynamics. Then, there is the previously referred to learning work as well [27].) The aim of this paper is to lay the foundation for a study of coordination in the context of urban dynamics and of cities as hybrid complex systems. This context suggests two new potentials: The major one is to add to the domain of CTCs the conceptual and theoretical perspectives of coordination dynamics. A byproduct of the latter is to add to the domain of coordination dynamics an explicit consideration of the role of the environment in the process. Materializing these two potentials will have to await further studies.

Funding: This research received no external funding.

Data Availability Statement: The data presented in this study are openly available.

Acknowledgments: I would like to thank Scott Kelso—a leading researcher in the domain of coordination dynamics—for valuable comments on a preliminary draft of this paper.

Conflicts of Interest: The author declares no conflict of interest.

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