A Glimpse at Emergence in Agent-Based Simulations

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Abstract

Emergence, the formation of complex patterns generated by interaction of comparatively simple individual units, appears in many systems including transport system. Often, emergent effects are highly significant, consequently, the ability to reproduce them is crucial for modeling these systems. Multi-Agent-based simulations are due to their structural similarity to the modeled multi-part systems, expected to be particularly suitable for capturing these effects.

The multi-agent transport simulation is focused here. The functional form of MATSim components, and, consequently, also its potential for emergence is not yet researched intensely. In this paper, the functional form of the network load simulation is studied with simulation experiments using a very simple scenario. To extend the discussion, additionally *ApplauSim*, a simulation of synchronized applause developed by the authors, is presented.

Keywords

MATSim, emergence, ApplauSim, microsimulation

1 Introduction and Problem

"Agent-based modeling is the canonical approach to modeling emergent phenomena [...]" Bonabeau (2002, p.7280). Emergent phenomena often are highly significant, such as phantom traffic jams (Manley and Cheng, 2010, Helbing, 2001, Li, 2005, Gray and Griffeath, 2001, Bonabeau *et al.,* 1995) and additionally they are interesting in their own right for any researcher's urge of understanding. Defining emergence is difficult and numerous definitions exist (Odell, 1998, Kubik, 2001, Manley and Cheng, 2010, Bonabeau and Dessalles, 1997, Bonabeau *et al.,* 1995, Vollmer, 2005), but commonly emergence is defined as a phenomenon where the outcome on one level is more than the sum of its constituting parts at a lower level. The superposition principle—characterizing linear systems—is thus invalid. Hence, a relationship between emergence and non-linearity is established (Goldstein, 1999, p.49/55), (MacKay, 2008, p.T274), (Langton, 1986), (Halley and Winkler, 2008, Richter and Rost, 2004). Some authors even say that "it is true, however, that linear systems—so rare in the world—cannot give rise to any emergent behavior" (Bonabeau *et al.,* 1995, p.340).

As a very first emergence analysis step, we analyze functional form of the network loading simulation of the multi-agent transport simulation MATSim (MATSim, 2013). This investigation of course does not conclude the emergence discussion, but gives very first insights; independent of the functional form of the network load simulation, the many interactions between agents and feedback loops present in MATSim, are a prolific ground for non-linearity and emergence (see e.g., Goldstein (1999, p.55)). However, the investigation here is also interesting for comparison with the very prominent Bureau of Public Roads (BPR) Function, specifying travel time as a usually non-linear function of flow and capacity (U.S. Bureau of Public Roads, 1964).

In this paper, a dummy MATSim simulation example scenario is studied to get some first indications about functional form of travel times for varying demand and supply. In MATSim context, two of the few examples looking basic properties of the queue-based network loading simulation or global emergent phenomena are Charypar *et al.* (2009) (fundamental diagram) and Rieser and Nagel (2008) (network traffic flow breakdowns) respectively. Another loosely related work, the agent-based rhythmic applause simulation *ApplauSim* (Horni and Montini, 2013), developed by the authors, is presented, to extent the emergence discussion and for providing a playground for future investigations on that topic.

2 Method

2.1 Assessing Functional Form of System

Assessing functional form of system components is not straight-forward. Here, in the first instance, the relationship between travel time t, demand or flow V, and capacity C is analyzed. Clearly (although not obvious at first sight) even for this precisely operationalized variable, assessing functional form is not straightforward. Having the BPR function, as detailed below, in mind it is clear, that varying demand and supply is *not* isomorphic, in other words, marginal distributions are not identical and thus, both demand and supply need to be systematically varied.

The BPR function is defined as follows.

$t = t_0[1 + \alpha(V/C)^\beta]$

where t_0 is the free-flow travel time. α and β are calibration parameters, where β usually lies between 5 and 11. In other words, a non-linear relation is usually assumed [1]. Examples for $\alpha(V/C)^\beta$ for $\beta = 1.0$ (linear case) and $\beta = 5.0$ (non-linear case) and varying demand and supply are shown in Figure 1.

Computed travel times dependent on demand and capacity are here compared to this natural specification of travel time.

2.2 MATSim Simulation Experiments

The very basic scenario depicted in Figure 2 is simulated with varying demand and supply. The network is initially empty. From 8 to 9 o'clock a varied number of agents travel from their home to the work locations with uniformly distributed start times. Trip travel times and link passing times for the center link (marked in the figure) are evaluated. No signal lights and back-traveling gaps are modeled. Simulation is run from 0 to 24 o'clock. One single iteration is performed including network load simulation and excluding replanning.

[1] Remember the definition of linearity: $y = m \cdot x$, i.e., two variables x, y are proportional with constant factor m.

2.3 ApplauSim

To extent the emergence discussion toward other microsimulations another example is presented. ApplauSim developed by Horni and Montini (2013) models synchronous applause, an interesting convergence phenomenon of interacting persons (see e.g., Matthews (2000), Sumpter (2010)). In a descriptive sense, period doubling has shown to be essential for synchronous applause (Néda *et al.*, 2000, Morsch, 2005). This was confirmed by ApplauSim simulation experiments. Horni and Montini (2013) additionally, in an explicative sense, tried to understand why period doubling is so important for synchronous applause. Hypothesis was that *constant* (i.e., frequency-independent) perception and motor activity errors render impossible synchronization for high clapping frequencies as the relative influence of these errors is larger for higher frequencies.

Earlier models of synchronous applause are often mainly based on coupled oscillators (see the seminal paper of Kuramoto and Nishikawa (1987) lying the base for this technical approach). Different to these models, here, the individual frequency and phase adaption was not based on an weighted average of neighbors' frequencies and phases, but on the perception of aggregate loudness. Persons adapt to the strongest rhythm perceived in a certain time window, where as an assumption in the model, both perception and adaptation are affected by constant errors. Details of this process are given in Horni and Montini (2013, p.4ff).

Results are presented in Section 3. In the first instance, two basic configurations (configuration 1 and 2) derived from Néda *et al.* (2000, S.6991) were simulated, one with high average frequency and large standard deviation (μ = 4.0, σ = 1.0) and another with low average frequency and small standard deviation (μ = 2.0, σ = 0.5). The dynamics from one to the other configuration are simulated in a future instance.

Results (see e.g., configuration 3) revealed that for synchronous applause additionally a few synchronizers are necessary. These are people knowing the game and unperturbedly and synchronously clapping with the average frequency. For the base configurations 1 and 2 different spatial distribution and numbers of the synchronizers were tested. Another configuration, number 4, contains no perception errors at high frequencies.

Summarizing, following configurations for a concert hall with 36 listeners in a quadratic concert hall were simulated.

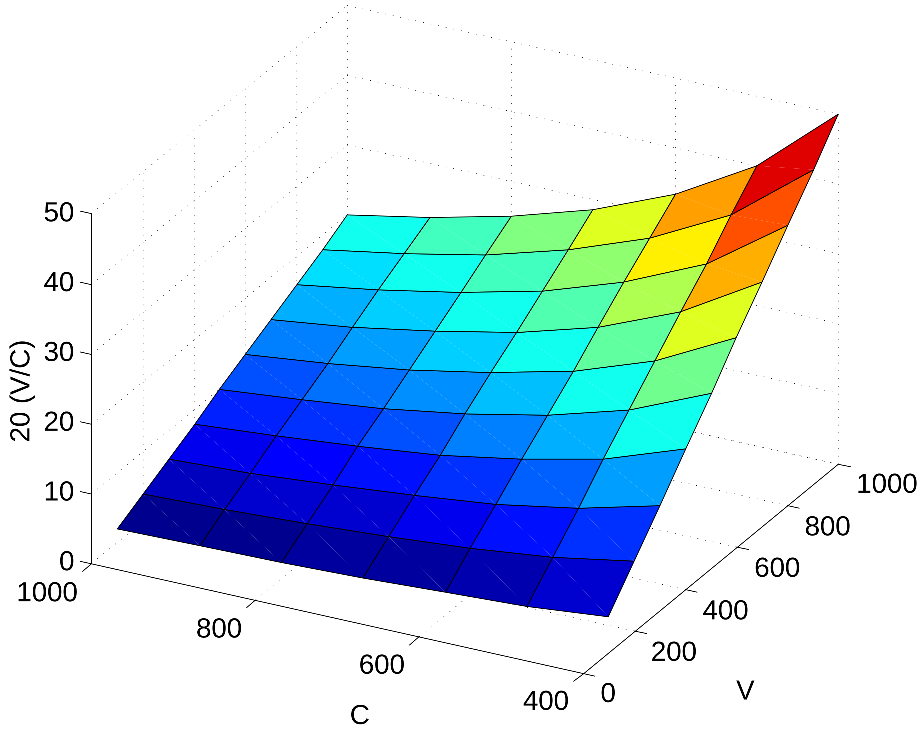
1. high frequencies
   (a) 6 synchronizers in the center (Figure 3(a))
   (b) 6 synchronizers at the fringe (Figure 3(b))
   (c) variable number and distribution of synchronizers

2. low frequencies
   (a) 6 synchronizers in the center
   (b) 6 synchronizers at the fringe
   (c) variable number and distribution of synchronizers
3. no synchronizers, low frequencies
4. no errors, high frequencies

30 runs are performed per configuration. Results are shown visually.

Figure 1: BPR-like specification of travel time

(a) $20.0 \cdot (V/C)^{\beta}$ with $\beta = 1.0$ (linear)



(b) $0.5 \cdot (V/C)^{\beta}$ with $\beta = 5.0$ (non-linear)

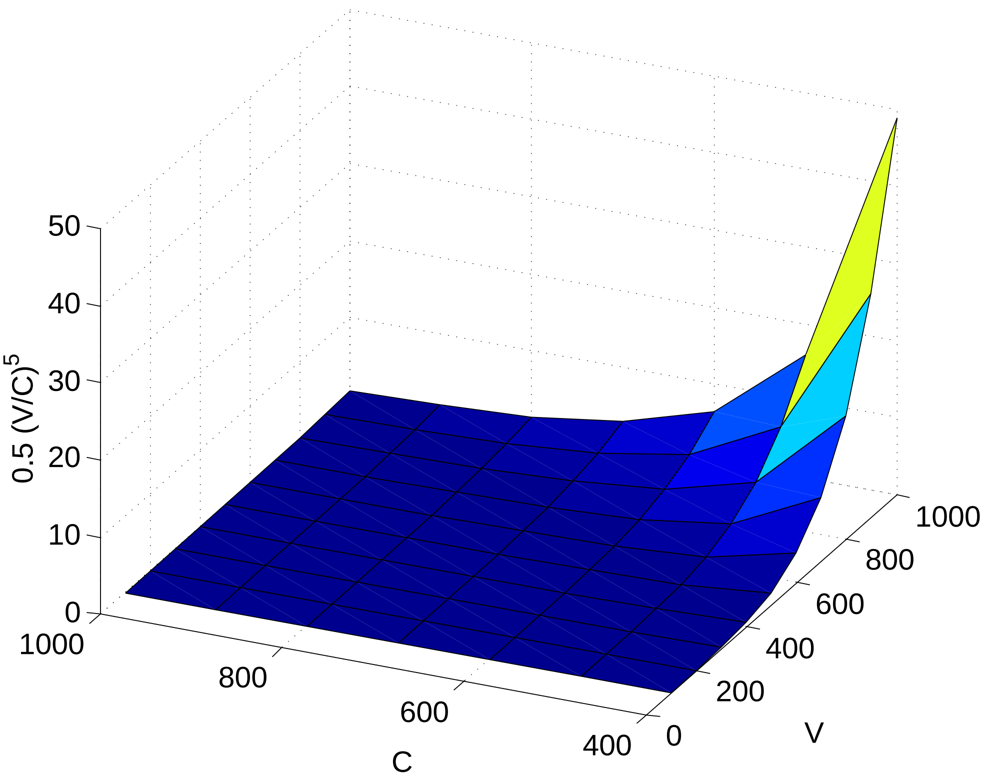


Figure 2: MATSim Barbell Scenario

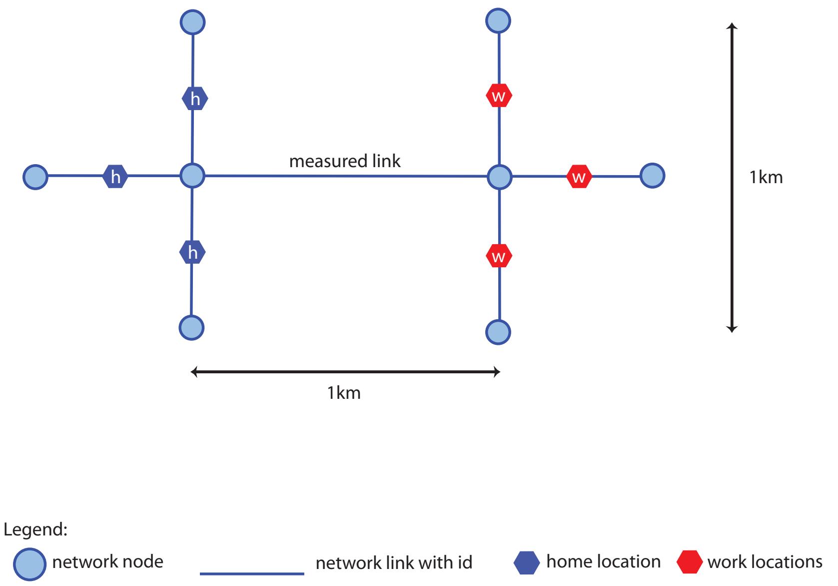
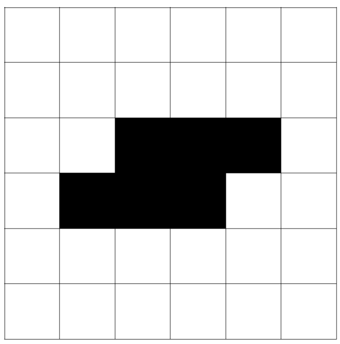
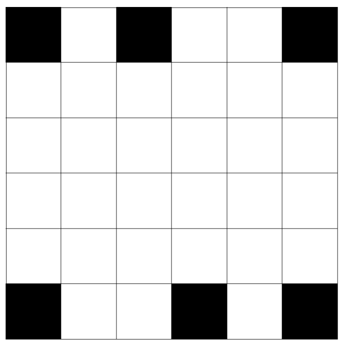


Figure 3: **Distribution of Synchronizers (black)**

(a) Configuration (a)



(b) Configuration (b)



3 Results and Discussion

3.1 Barbell Scenario

The simulation results are shown in Figure 4(a) and 4(b) for the link travel times and the trip travel times respectively. A comparison with Figure 1 reveals that this translates to a *linear* function. For a clearer picture, capacity is hold constant at $C = 600$ vehicles per hour (as an example) as shown in Figure 5, where also a linear relationship is observed. Functional form is very similar for both link and trip travel times. In other words, also the two intersections (i.e., network nodes) do not add substantial non-linearity here.

The MATSim simulation results are preliminary; plausibility checking and reproduction is crucially required. A comparison with Charypar *et al.* (2009) is not directly applicable. They investigate the characteristics of the queue simulation and found a trapezoidal flow-density-relationship, which is commonly observed in empirical data. That study is performed on a ring network and the simulation includes back-moving gaps.

In addition to the tentativeness of our results, the scenario is very simple with only two possibilities for node interactions. A next step could be to investigate the Sioux Falls network, readily available for MATSim, and finally the comprehensive evaluation of the Zurich scenario. If for all these future analyses, the results found here were confirmed, adaptation of the waiting queue approach (such as inclusion of back-moving gaps (Charypar *et al.,* 2009), or interactions between different modes) and modeling of intersection dynamics (such as traffic signals (Charypar *et al.,* 2009)) probably needs to be intensified also for the *standard* configuration. Inclusion of research on waiting queues, in particular, functional form of relationship between waiting time and load, might be productive dos Santos and Porta Nova (e.g., 1999).

3.2 ApplauSim

As mentioned earlier, simulation experiments, investigating period doubling as a main precondition for synchronous applause, were conducted, where influence of frequency-independent perception and motor activity errors were investigated.

Comparing configurations 1 and 2, in fact, for low frequencies much better convergence is apparent in the results. Looking at configuration 1.a. and 4, the important role of perception and adaptation errors is revealed. It can be seen, that, in-line with the hypothesis of ApplauSim, the errors reduce convergence; without errors even high frequency settings converge fast as shown in configuration 4, which is in contradiction to empirics.

Comparison of configurations 1 and 2 with configuration 3 shows that—at least for ApplauSim but maybe also in reality—additionally synchronizers are required to establish synchronous applause.

Xenides *et al.* (2008) find that *clusters* of synchronizers catalyze convergence. This finding was not reproduced with ApplauSim. No significant differences between configurations (a) and (b) and for the different spatial distributions of configuration (c) exist.

Clearly, future investigations are required. The smaller frequencies dispersion of the base configurations 2 promote faster convergence per se. Thus, the dynamics from one to the other configuration should be included in a next instance. Furthermore, looking closer at the time horizon would be interesting to reveal if the difference in convergence is a general or only a temporal phenomenon, where higher frequencies just simply require more time for convergence. Naturally, different concert hall sizes and size of audience has to be studied. Furthermore, agent heterogeneity should be extended, for example, by individual clapping volumes.

3.3 Conclusions

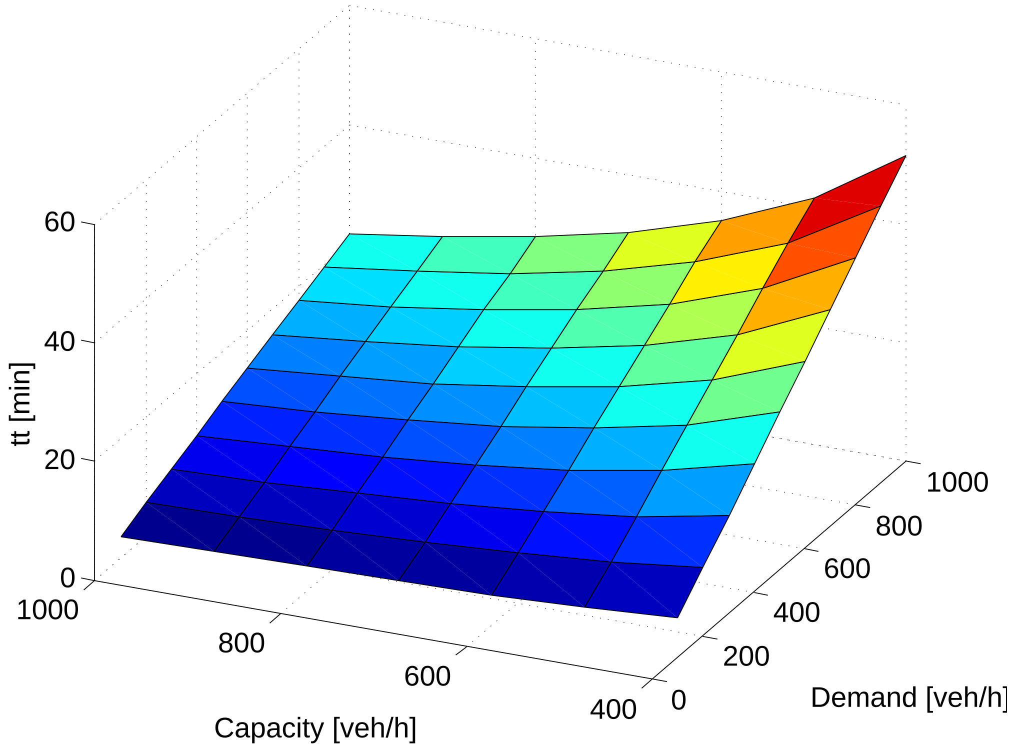
MacKay (2008, p.T274) calls emergence “one of the most seductive buzzwords of complexity science”, but Odell (1998) advises that “when constructing agent systems, you should regard emergence as an important concept” and later that “you can try to “design in” the emergence that you want”. Hence, the emergence discussion should be done even when entering highly experimental ground paved with fuzzy buzzwords.

For the occurrence of emergence, non-linear parts might be neither sufficient nor strictly necessary. However, the potential for emergence might be higher if they were non-linear. Thus, the MATSim volume-delay function is analyzed. For the toy scenario it seems to be linear. Nevertheless, the many agent interactions and the extensive feedback, which are non-linear in nature Goldstein (1999, p.55), might generate emergent phenomena. The importance of having a non-linear volume-delay function is still given by the non-linearity of the BPR function.

The two simulations are productive for a microsimulation emergence discussion. ApplauSim, in our opinion, can also be used to discuss *delineation* between emergent or only collective phenomena. Synchronous applause is a collective phenomenon, however, the synchronous clapping as such is probably *not* more than the sum of the clapping individuals and thus not strictly emergent; the process of establishing synchronous applause on the other hand probably is.

Figure 4: MATSim Travel Times for Barbell Scenario

(a) Link Times



(b) Trip Times

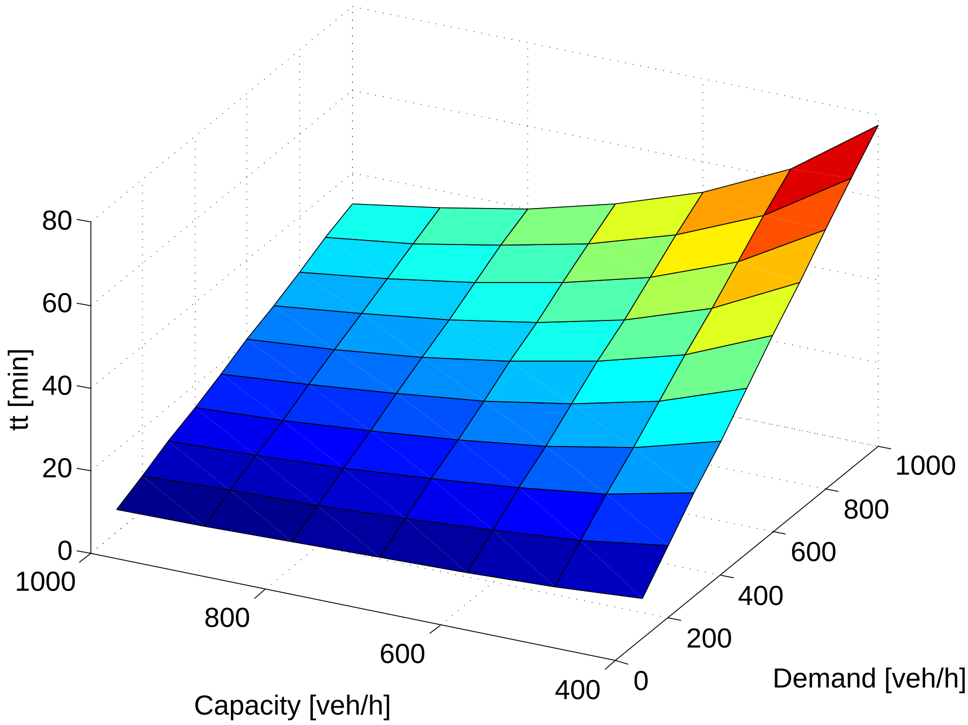
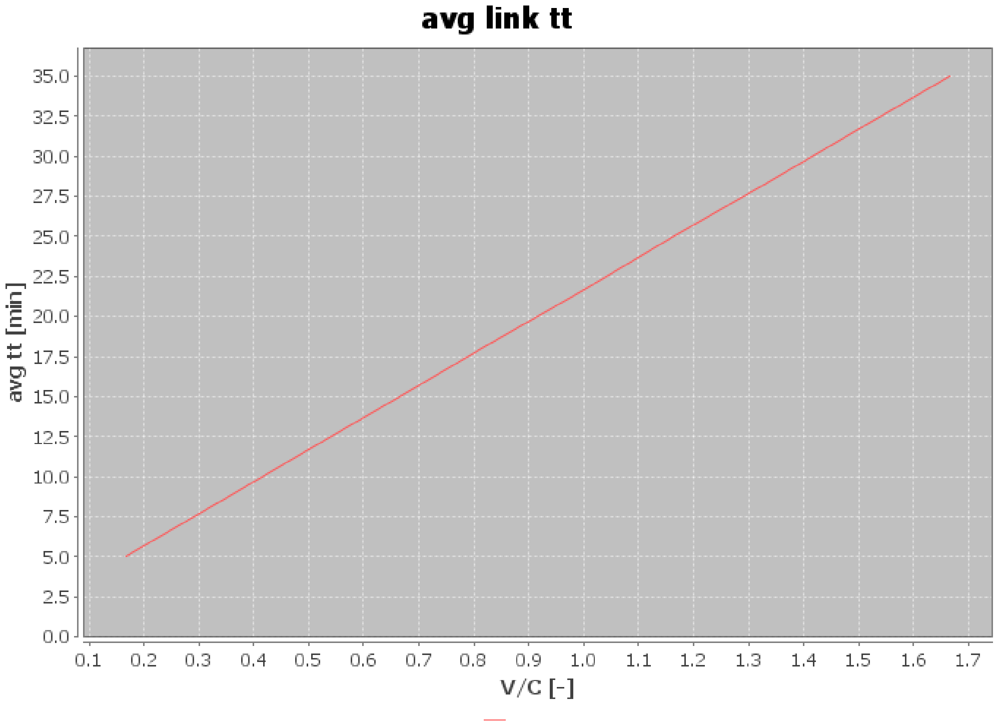


Figure 5: MATSim Travel Times for Barbell Scenario, Fixed Capacity

(a) Link Times



(b) Trip Times

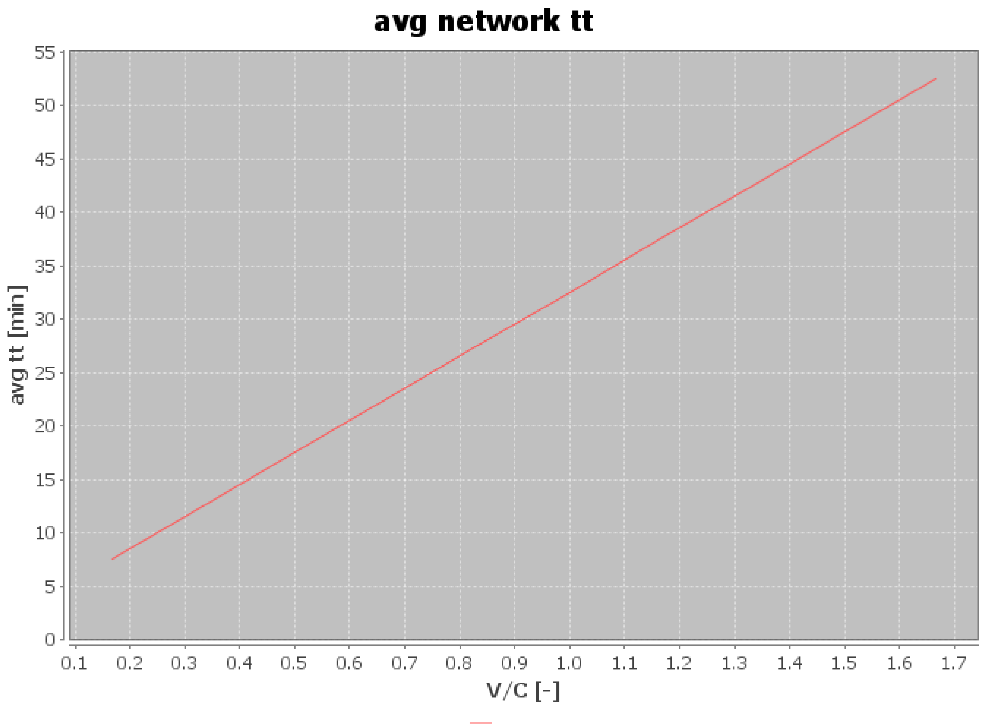
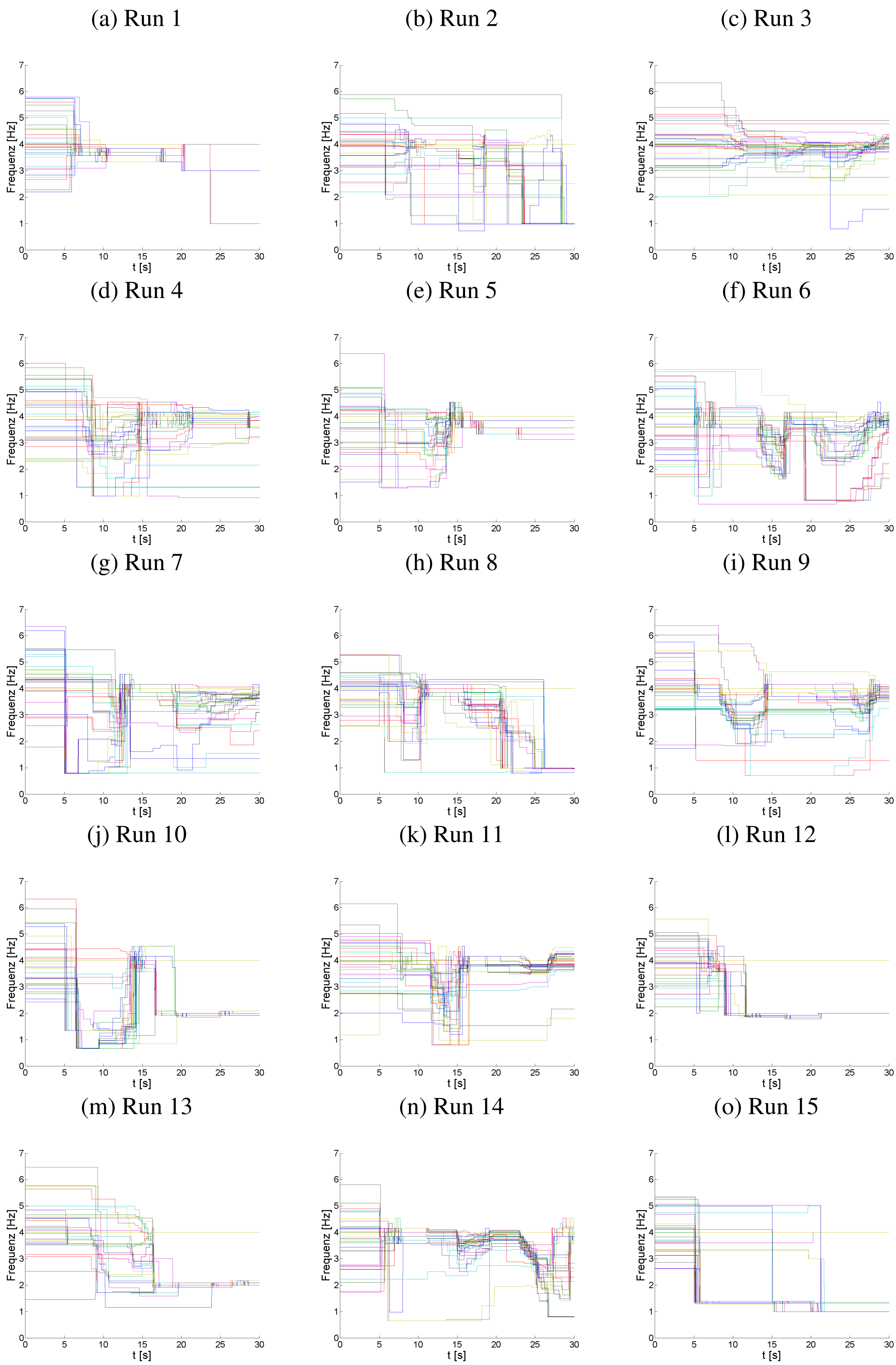


Figure 6: Frequencies configuration 1.a (high frequencies, 6 synchronizers in the center)



(a) Run 1 (b) Run 2 (c) Run 3

(d) Run 4 (e) Run 5 (f) Run 6

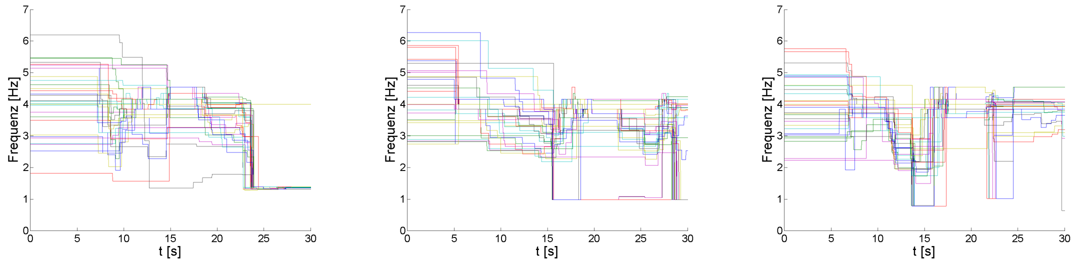
(g) Run 7 (h) Run 8 (i) Run 9

(j) Run 10 (k) Run 11 (l) Run 12

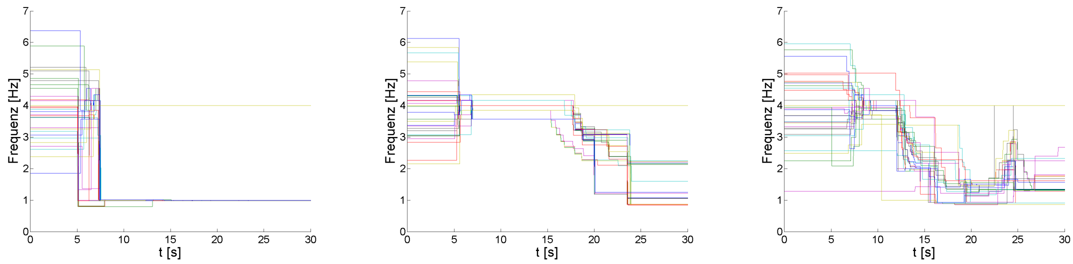
(m) Run 13 (n) Run 14 (o) Run 15

Figure 7: Frequencies configuration 1.a (high frequencies, 6 synchronizers in the center)

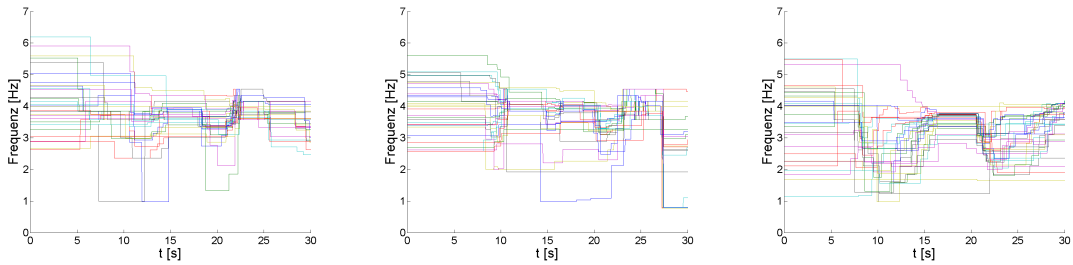
(a) Run 16 (b) Run 17 (c) Run 18



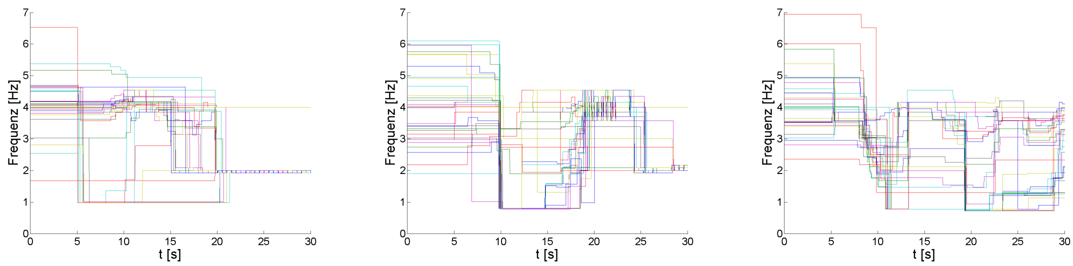
(d) Run 19 (e) Run 20 (f) Run 21



(g) Run 22 (h) Run 23 (i) Run 24



(j) Run 25 (k) Run 26 (l) Run 27



(m) Run 28 (n) Run 29 (o) Run 30

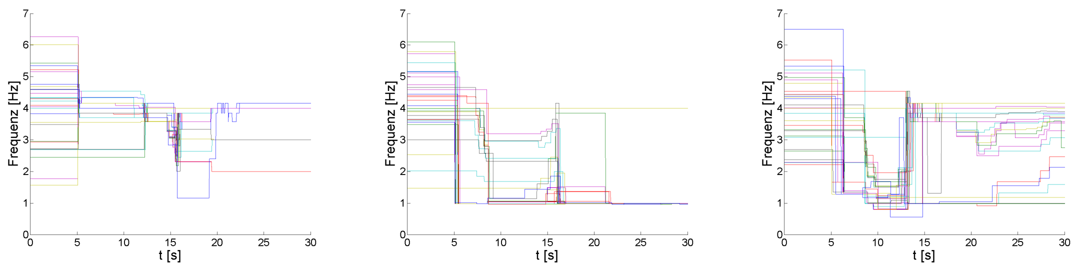
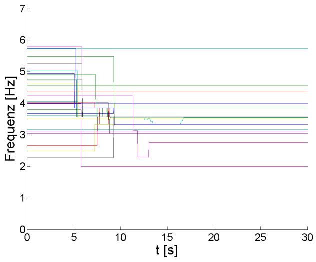
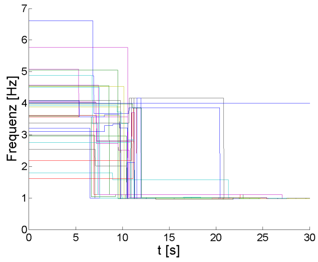


Figure 8: Frequencies configuration 1.b (high frequencies, 6 synchronizers at the fringe)

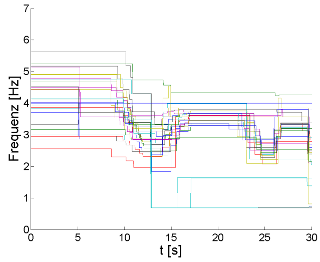
(a) Run 1



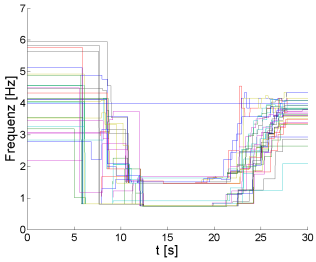
(b) Run 2



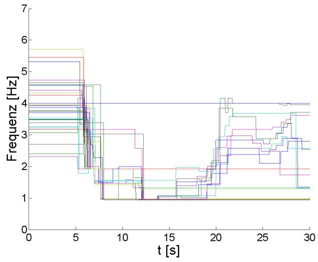
(c) Run 3



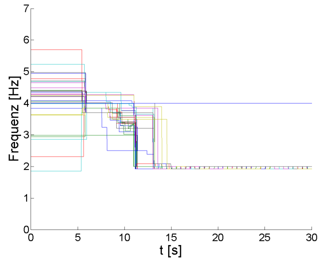
(d) Run 4



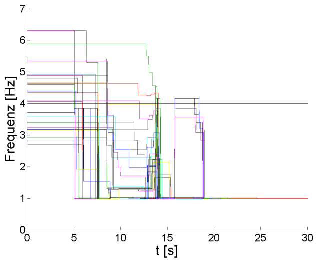
(e) Run 5



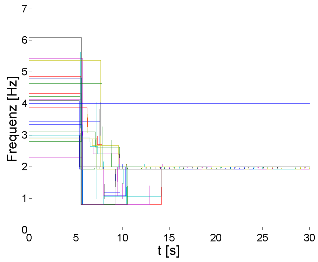
(f) Run 6



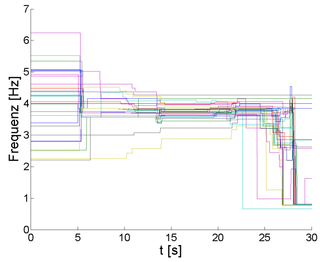
(g) Run 7



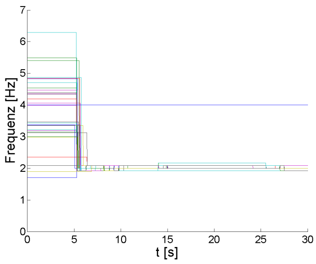
(h) Run 8



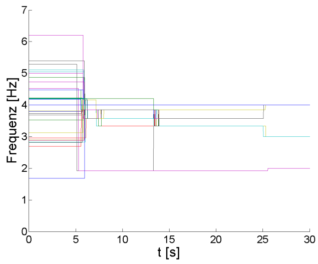
(i) Run 9



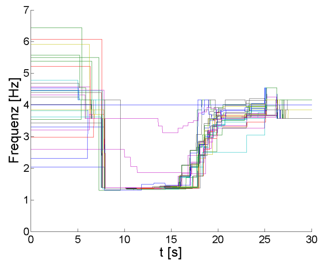
(j) Run 10



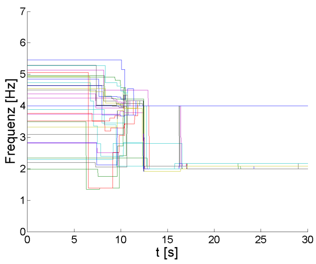
(k) Run 11



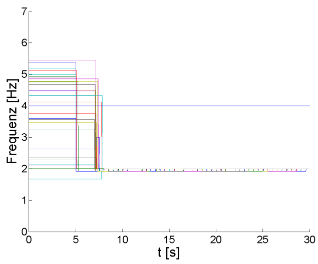
(l) Run 12



(m) Run 13



(n) Run 14



(o) Run 15

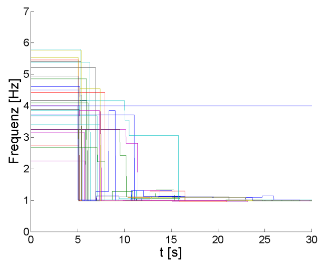
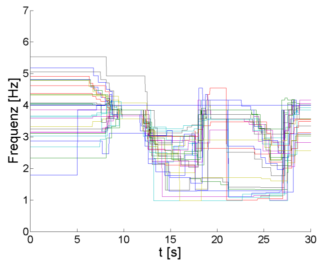
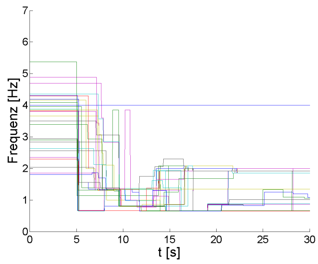


Figure 9: Frequencies configuration 1.b (high frequencies, 6 synchronizers at the fringe)

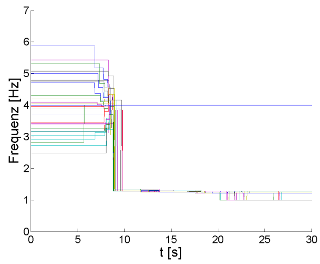
(a) Run 16



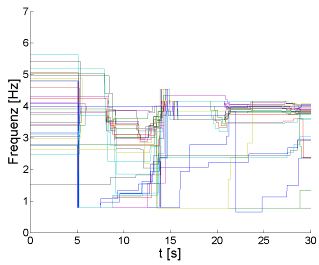
(b) Run 17



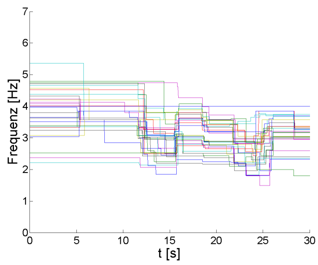
(c) Run 18



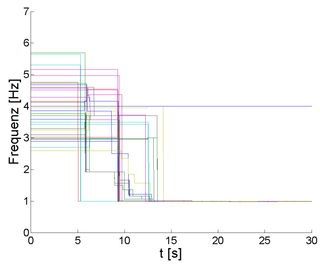
(d) Run 19



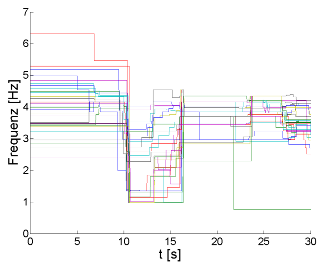
(e) Run 20



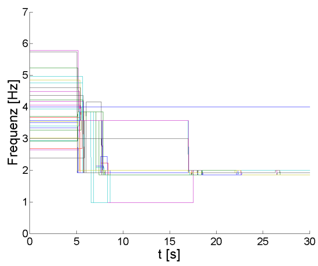
(f) Run 21



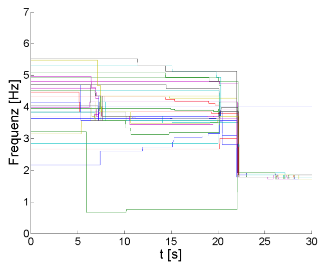
(g) Run 22



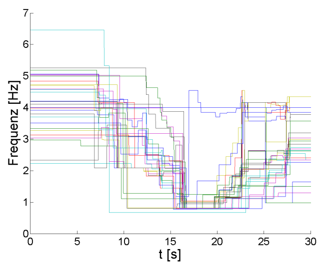
(h) Run 23



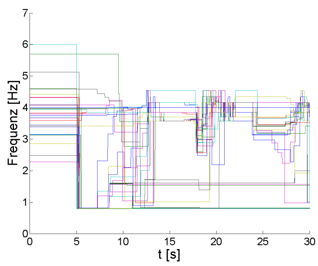
(i) Run 24



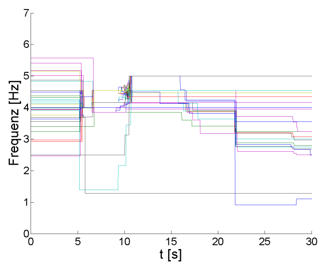
(j) Run 25



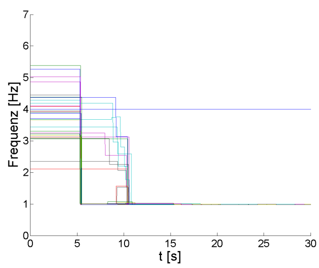
(k) Run 26



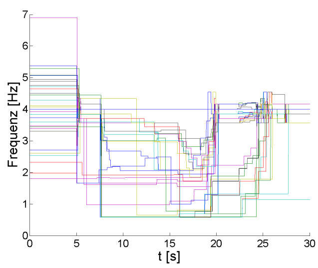
(l) Run 27



(m) Run 28



(n) Run 29



(o) Run 30

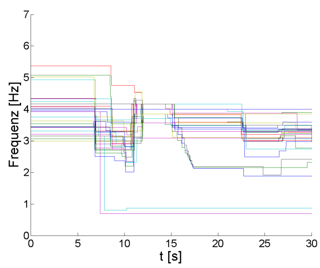
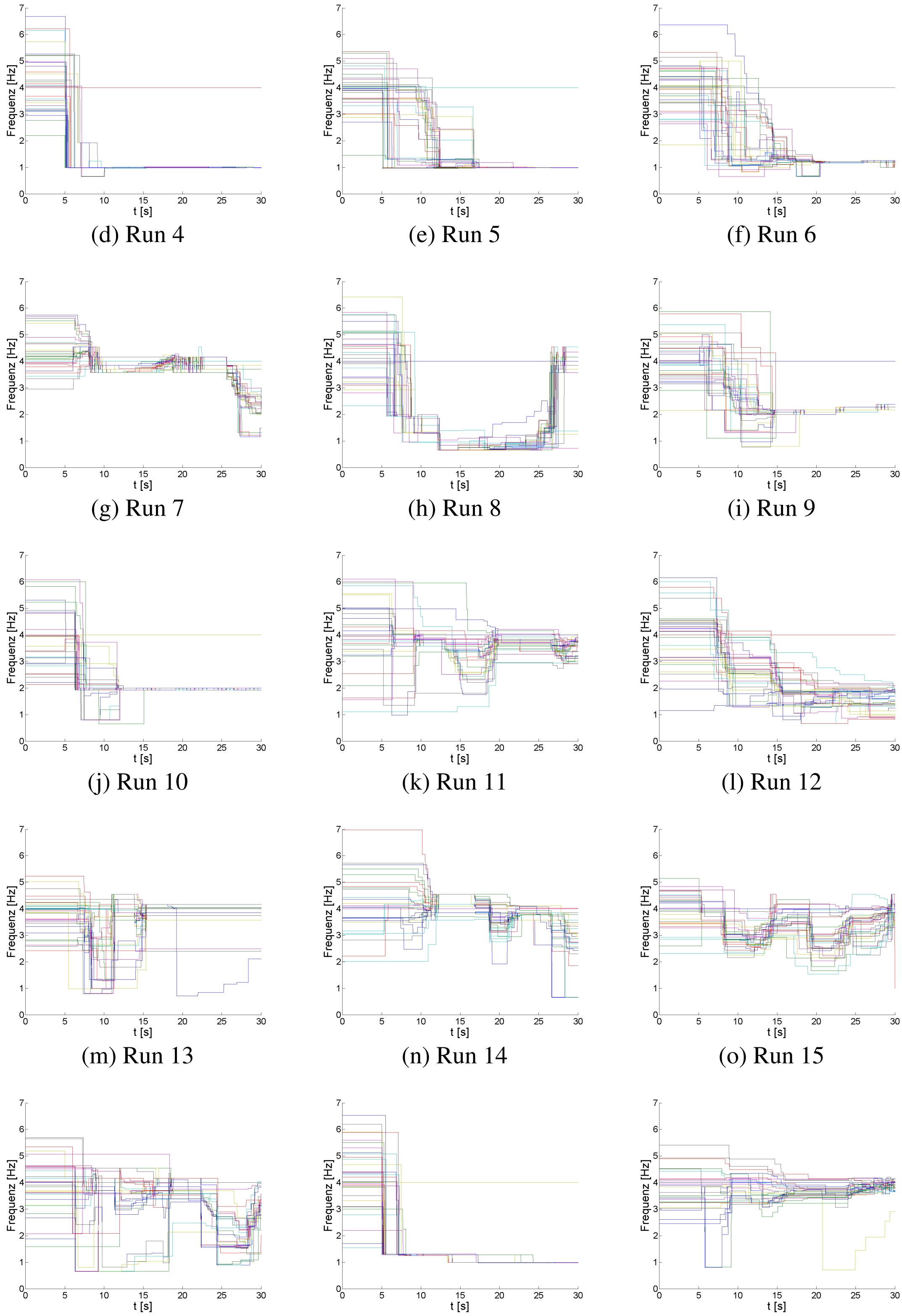
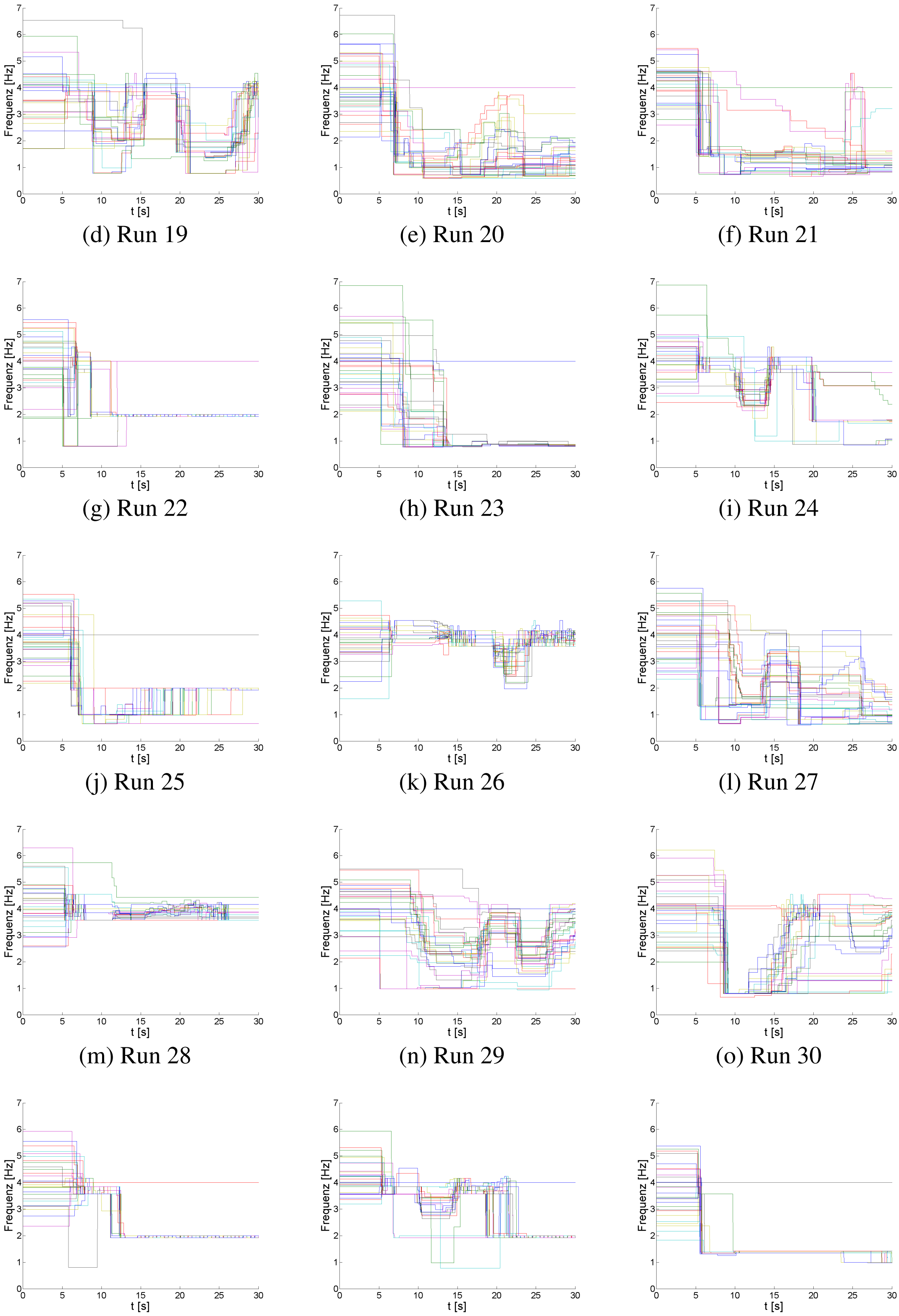


Figure 10: Frequencies configuration 1.c (high frequencies, variable number and distribution of synchronizers)



(a) Run 1 (b) Run 2 (c) Run 3
(d) Run 4 (e) Run 5 (f) Run 6
(g) Run 7 (h) Run 8 (i) Run 9
(j) Run 10 (k) Run 11 (l) Run 12
(m) Run 13 (n) Run 14 (o) Run 15

Figure 11: Frequencies configuration 1.c (high frequencies, variable number and distribution of synchronizers)



(a) Run 16 (b) Run 17 (c) Run 18

(d) Run 19 (e) Run 20 (f) Run 21

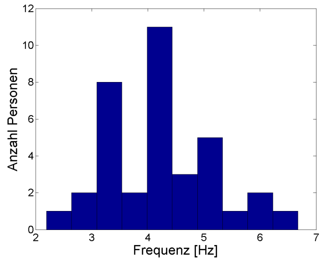
(g) Run 22 (h) Run 23 (i) Run 24

(j) Run 25 (k) Run 26 (l) Run 27

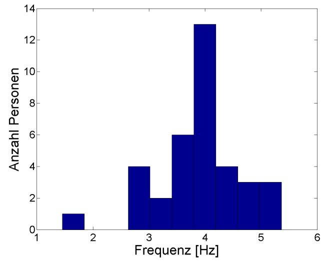
(m) Run 28 (n) Run 29 (o) Run 30

Figure 12: Start frequencies, configuration 1.c

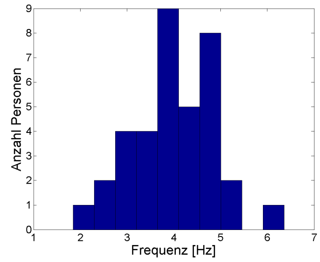
(a) Run 1



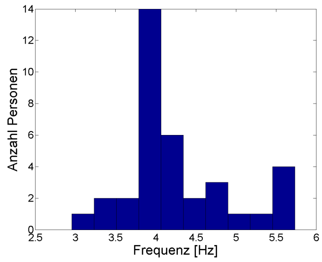
(b) Run 2



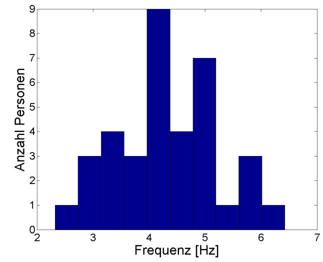
(c) Run 3



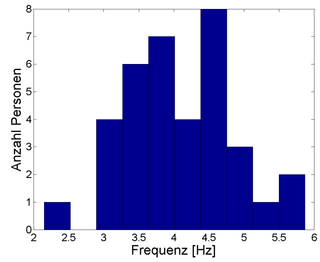
(d) Run 4



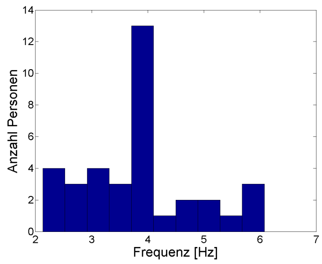
(e) Run 5



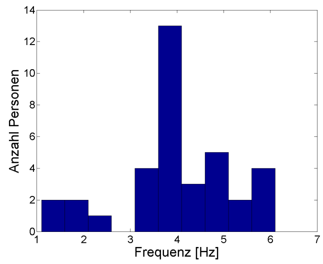
(f) Run 6



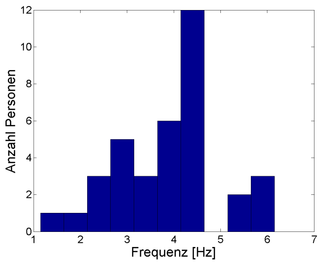
(g) Run 7



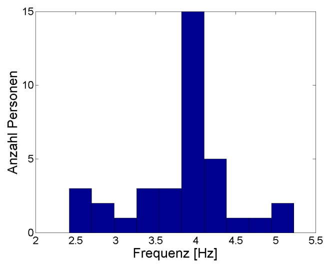
(h) Run 8



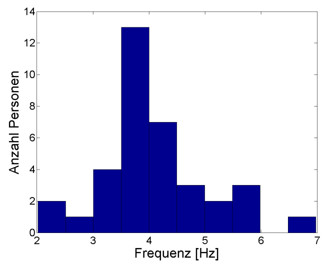
(i) Run 9



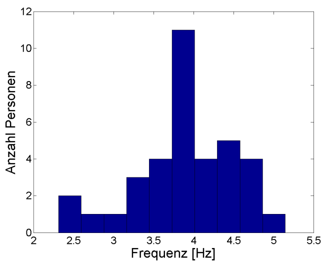
(j) Run 10



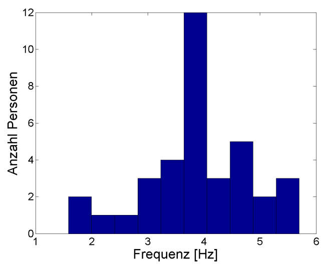
(k) Run 11



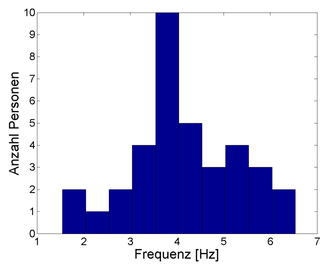
(l) Run 12



(m) Run 13



(n) Run 14



(o) Run 15

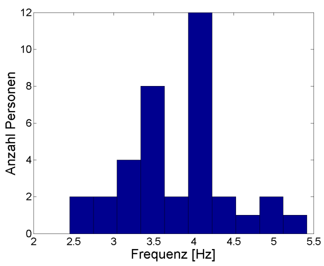
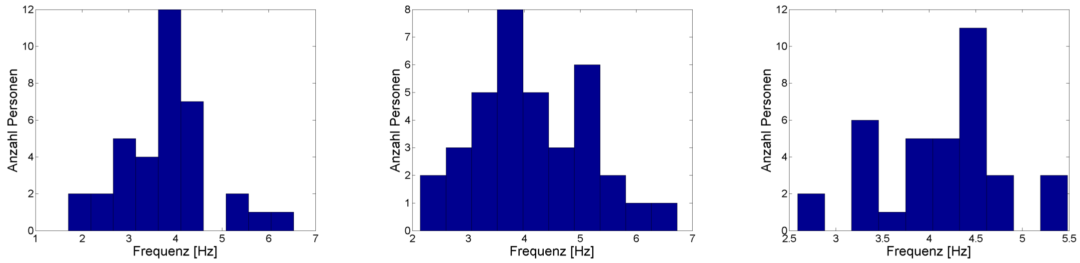
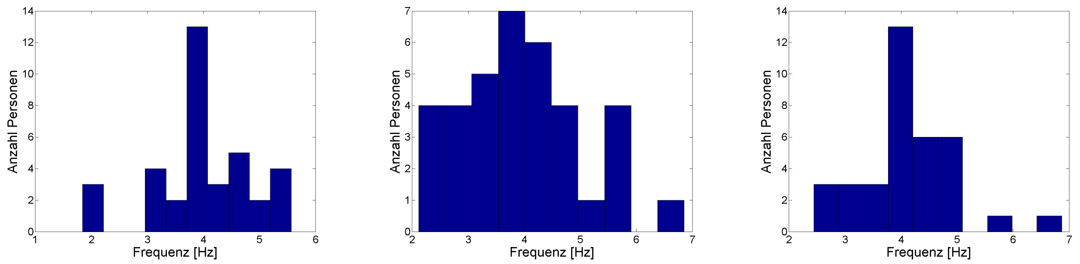


Figure 13: Start frequencies, configuration 1.c

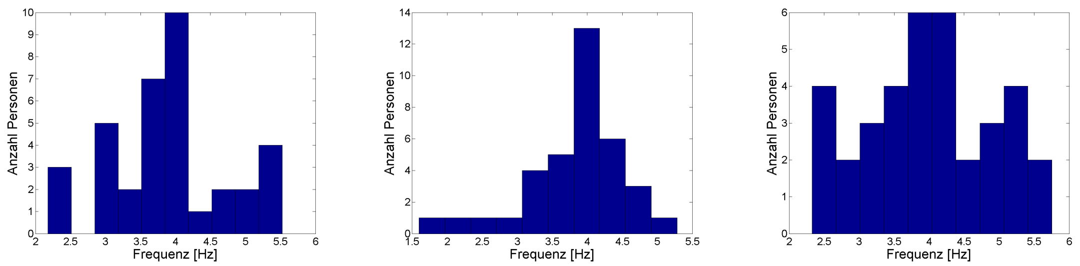
(a) Run 16 (b) Run 17 (c) Run 18



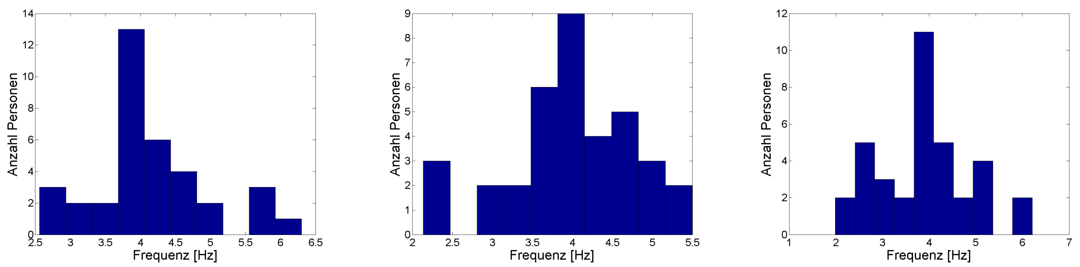
(d) Run 19 (e) Run 20 (f) Run 21



(g) Run 22 (h) Run 23 (i) Run 24



(j) Run 25 (k) Run 26 (l) Run 27



(m) Run 28 (n) Run 29 (o) Run 30

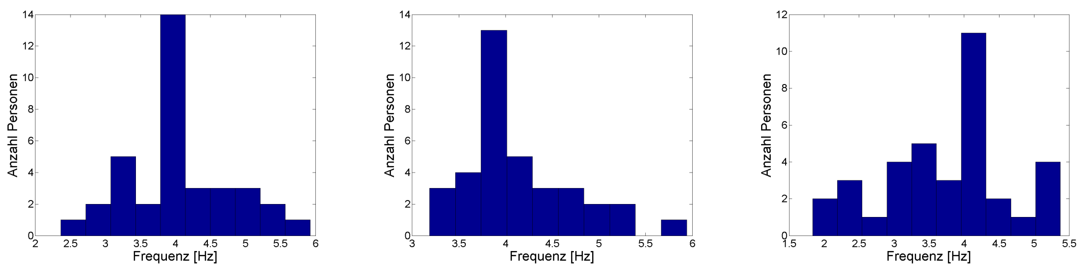
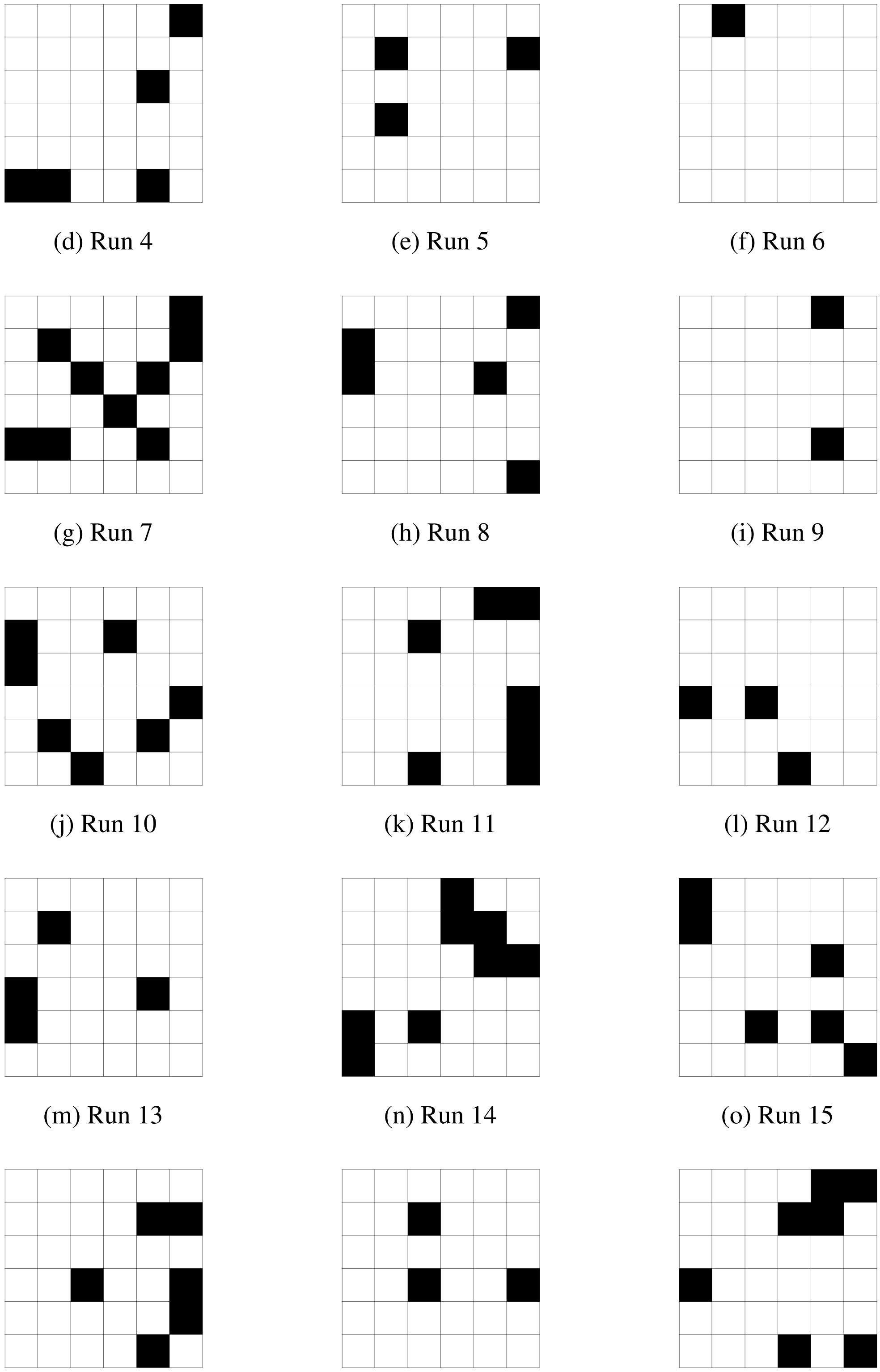


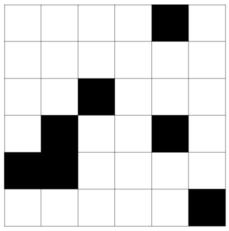
Figure 14: Distribution of synchronizers, configuration 1.c



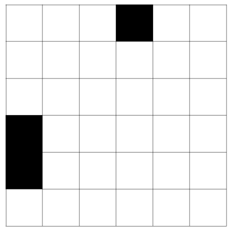
(a) Run 1 (b) Run 2 (c) Run 3
(d) Run 4 (e) Run 5 (f) Run 6
(g) Run 7 (h) Run 8 (i) Run 9
(j) Run 10 (k) Run 11 (l) Run 12
(m) Run 13 (n) Run 14 (o) Run 15

Figure 15: Distribution of synchronizers, configuration 1.c

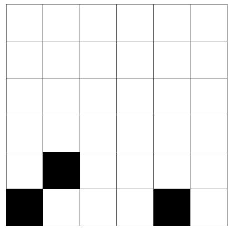
(a) Run 16



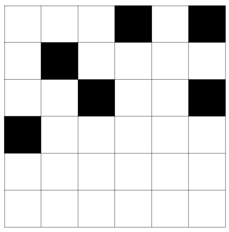
(b) Run 17



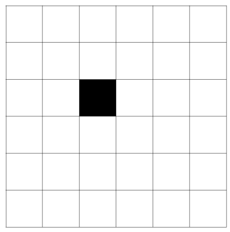
(c) Run 18



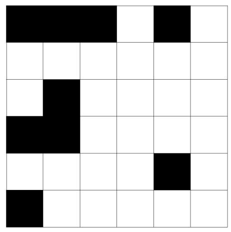
(d) Run 19



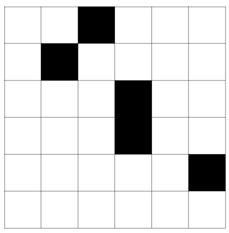
(e) Run 20



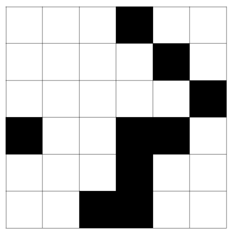
(f) Run 21



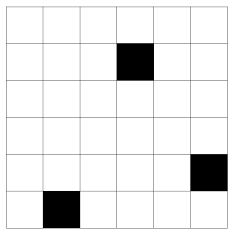
(g) Run 22



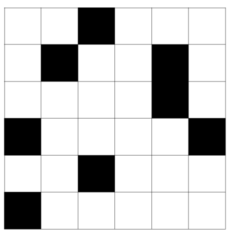
(h) Run 23



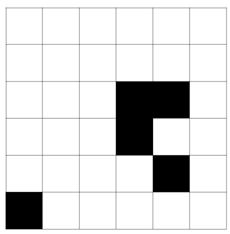
(i) Run 24



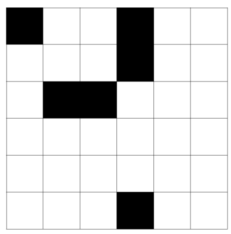
(j) Run 25



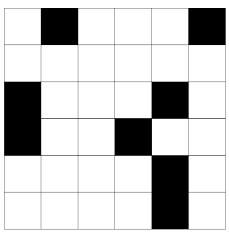
(k) Run 26



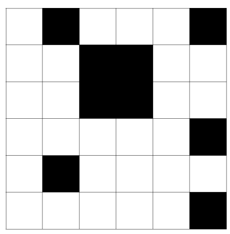
(l) Run 27



(m) Run 28



(n) Run 29



(o) Run 30

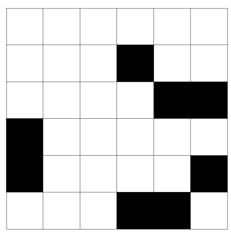
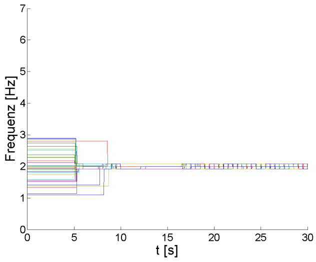
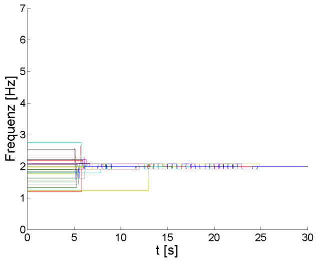


Figure 16: Frequencies configuration 2.a (low frequencies, 6 synchronizers in the center)

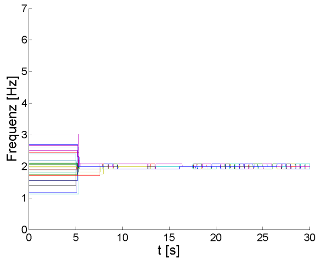
(a) Lauf 1



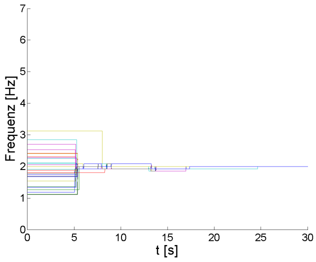
(b) Lauf 2



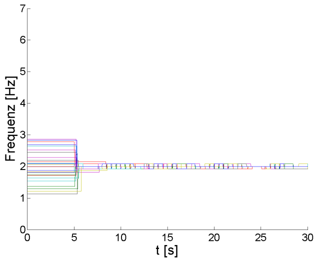
(c) Lauf 3



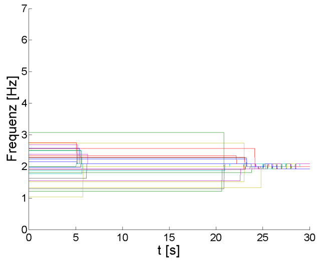
(d) Lauf 4



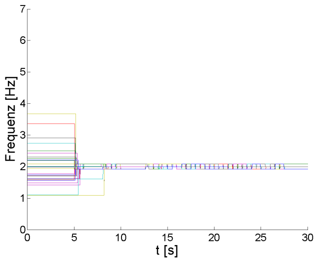
(e) Lauf 5



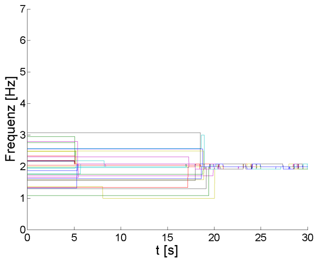
(f) Lauf 6



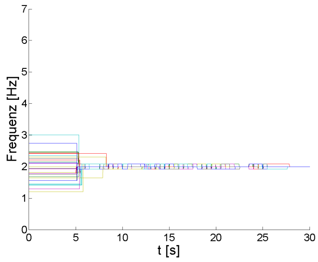
(g) Lauf 7



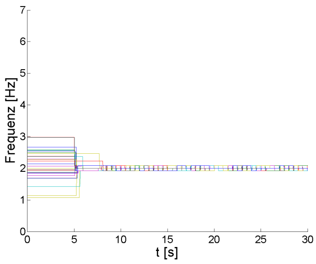
(h) Lauf 8



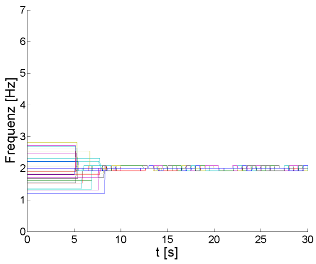
(i) Lauf 9



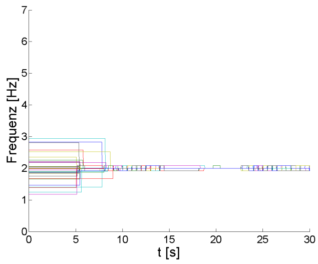
(j) Lauf 10



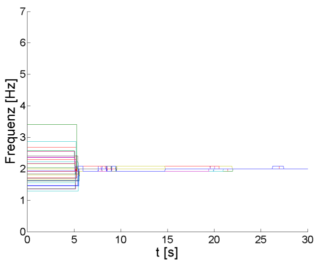
(k) Lauf 11



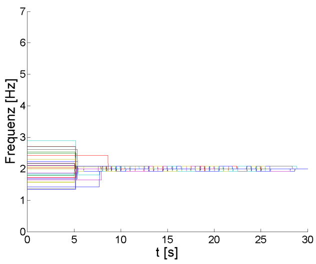
(l) Lauf 12



(m) Lauf 13



(n) Lauf 14



(o) Lauf 15

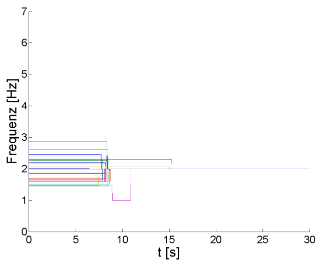
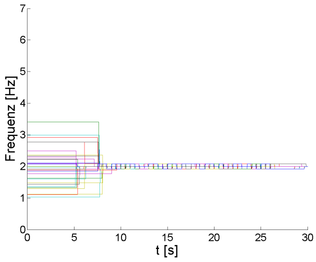
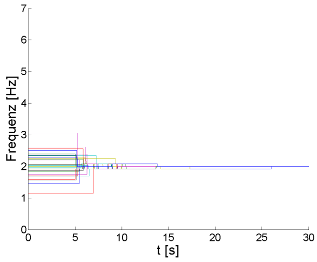


Figure 17: Frequencies configuration 2.a (low frequencies, 6 synchronizers in the center)

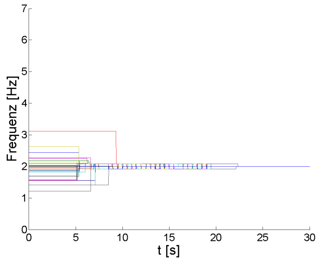
(a) Run 16



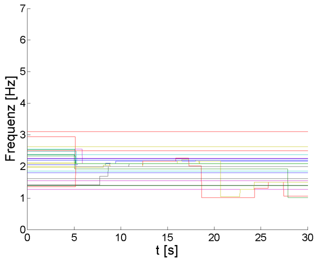
(b) Run 17



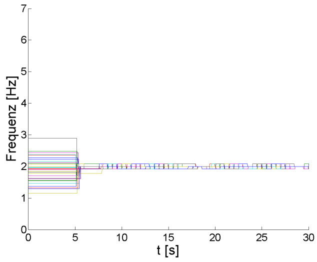
(c) Run 18



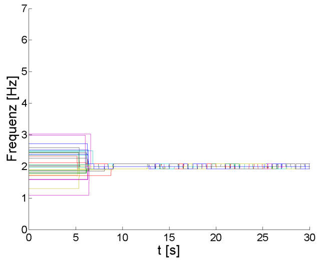
(d) Run 19



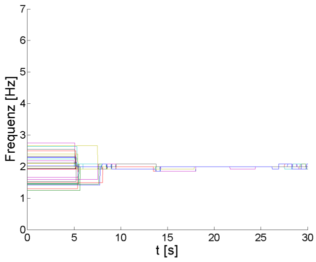
(e) Run 20



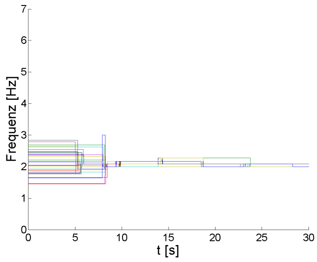
(f) Run 21



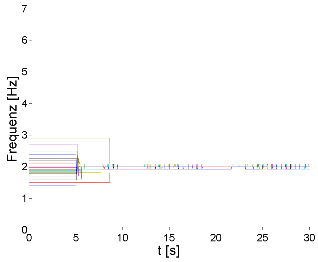
(g) Run 22



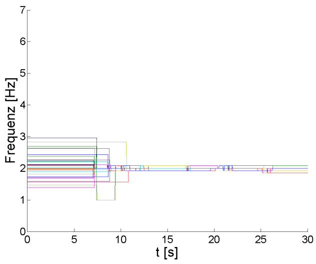
(h) Run 23



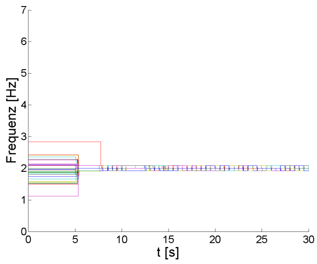
(i) Run 24



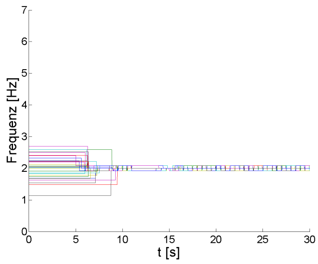
(j) Run 25



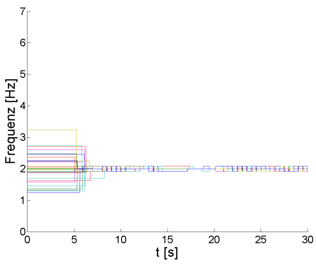
(k) Run 26



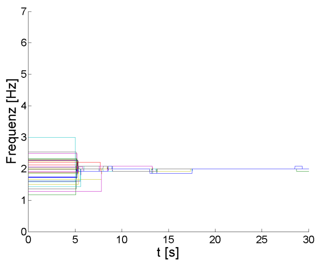
(l) Run 27



(m) Run 28



(n) Run 29



(o) Run 30

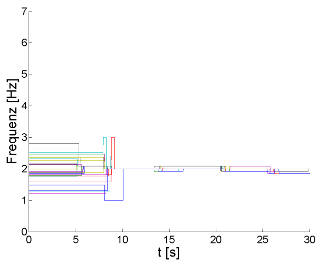
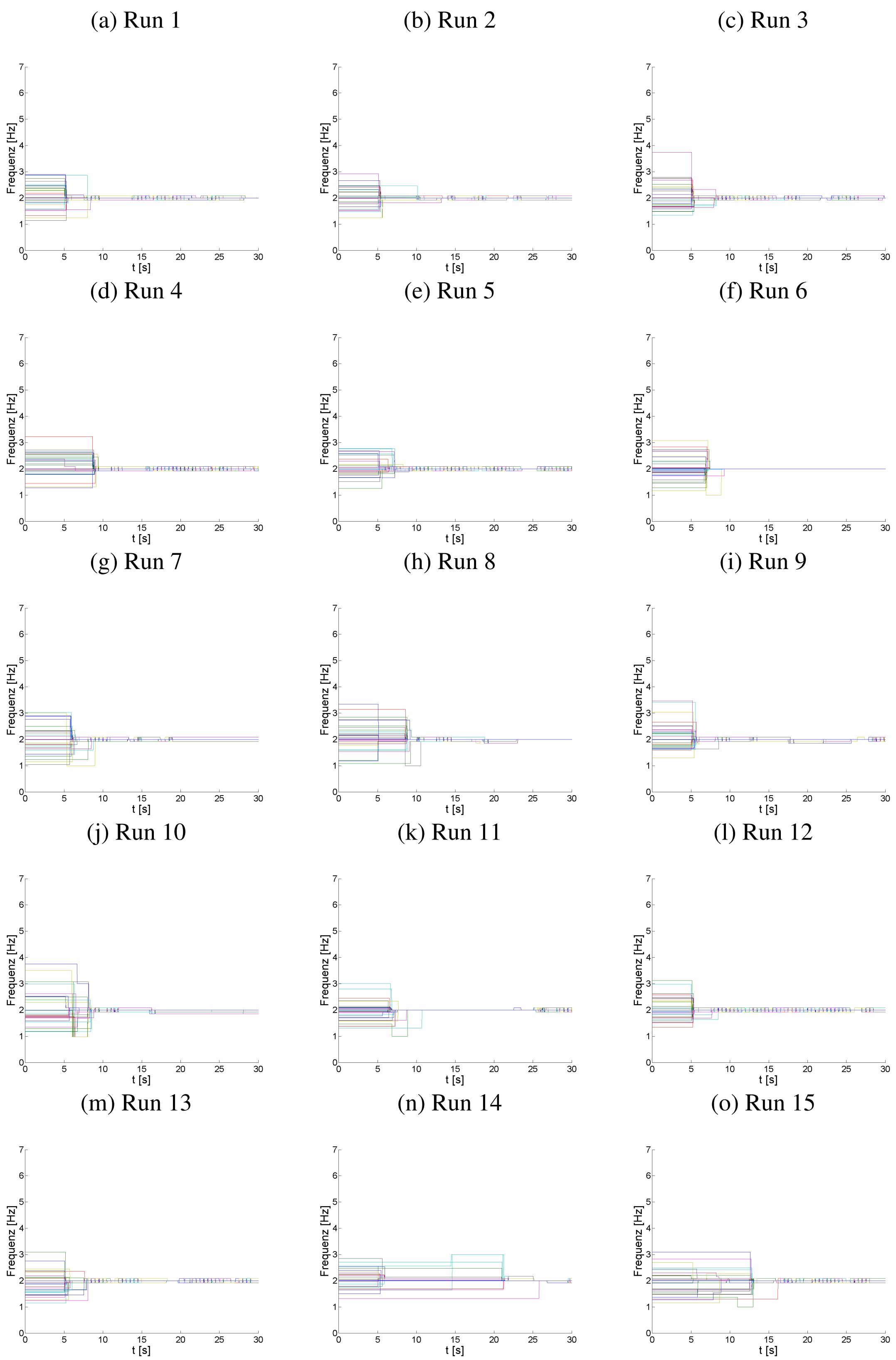


Figure 18: Frequencies configuration 2.b (low frequencies, 6 synchronizers at the fringe)



(a) Run 1 (b) Run 2 (c) Run 3

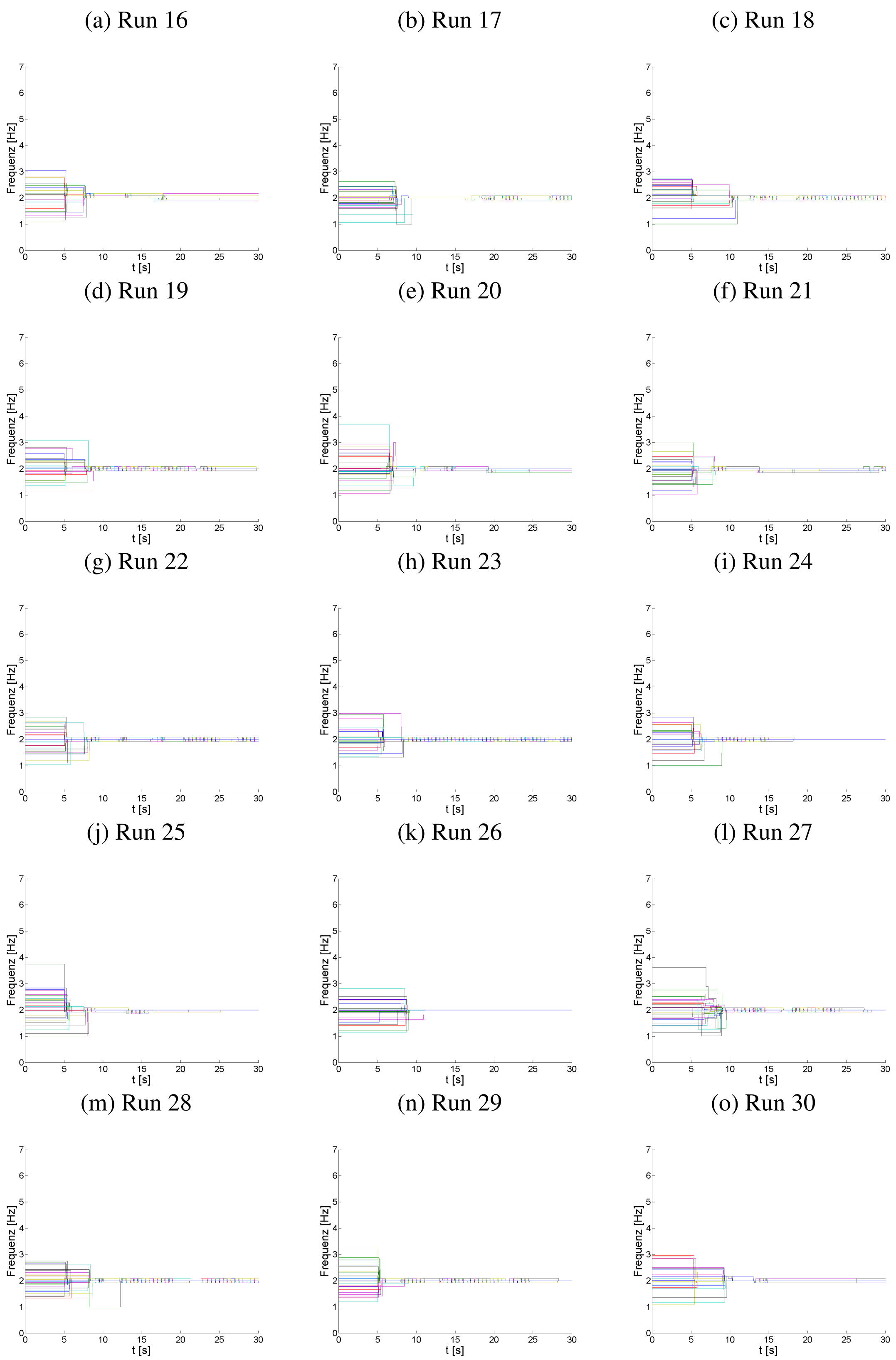
(d) Run 4 (e) Run 5 (f) Run 6

(g) Run 7 (h) Run 8 (i) Run 9

(j) Run 10 (k) Run 11 (l) Run 12

(m) Run 13 (n) Run 14 (o) Run 15

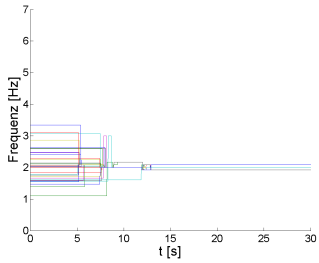
Figure 19: Frequencies configuration 2.b (low frequencies, 6 synchronizers at the fringe)



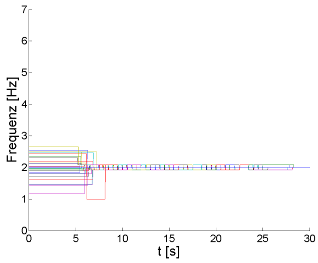
(a) Run 16 (b) Run 17 (c) Run 18
(d) Run 19 (e) Run 20 (f) Run 21
(g) Run 22 (h) Run 23 (i) Run 24
(j) Run 25 (k) Run 26 (l) Run 27
(m) Run 28 (n) Run 29 (o) Run 30

Figure 20: Frequencies configuration 2.c (low frequencies, variable number and distribution of synchronizers)

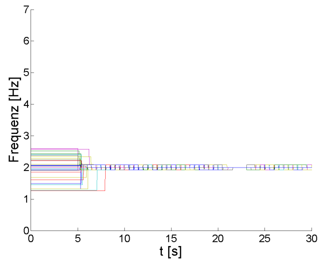
(a) Lauf 1



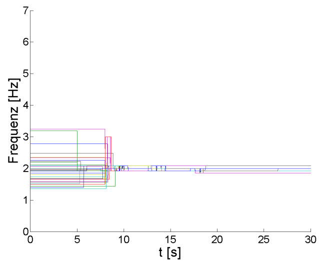
(b) Lauf 2



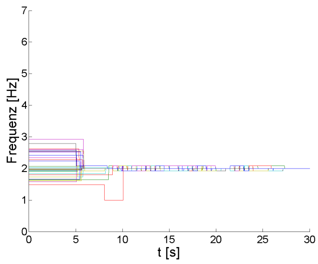
(c) Lauf 3



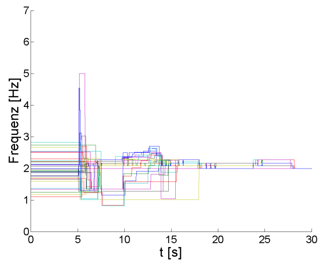
(d) Lauf 4



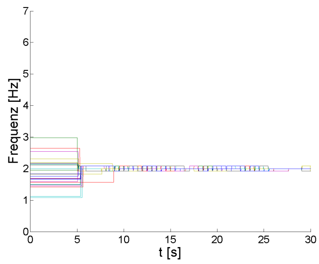
(e) Lauf 5



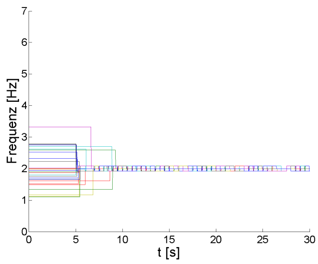
(f) Lauf 6



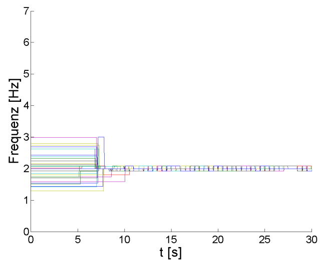
(g) Lauf 7



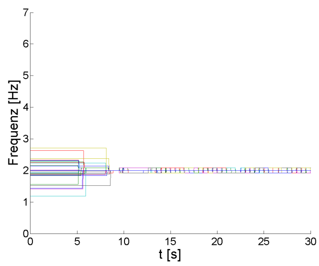
(h) Lauf 8



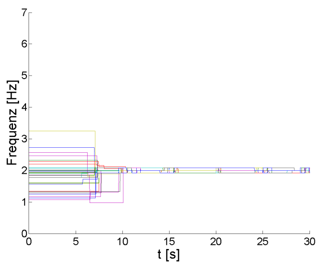
(i) Lauf 9



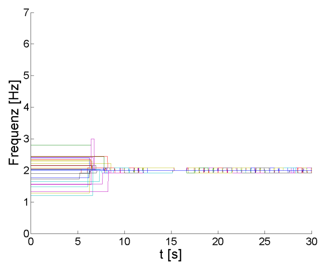
(j) Lauf 10



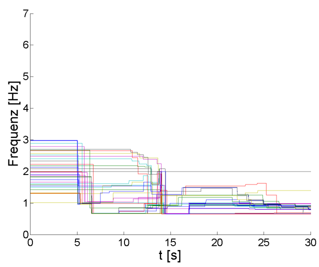
(k) Lauf 11



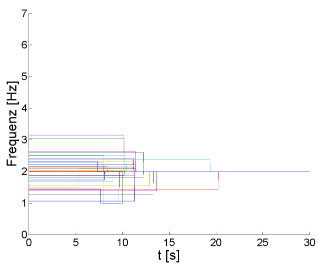
(l) Lauf 12



(m) Lauf 13



(n) Lauf 14



(o) Lauf 15

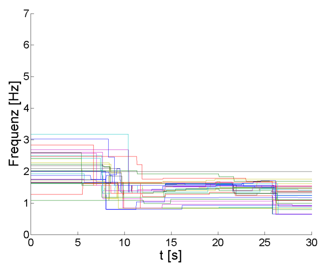
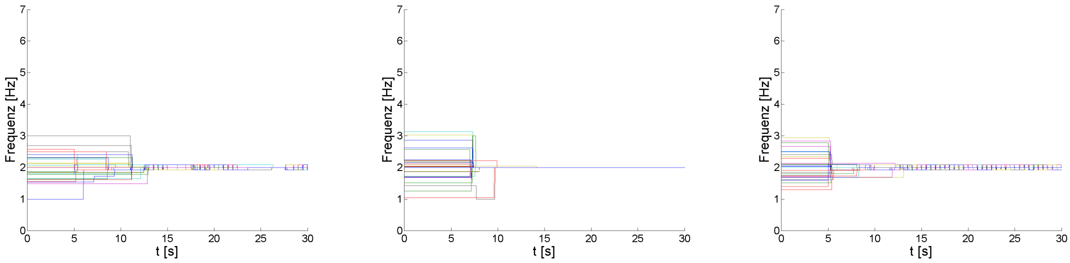
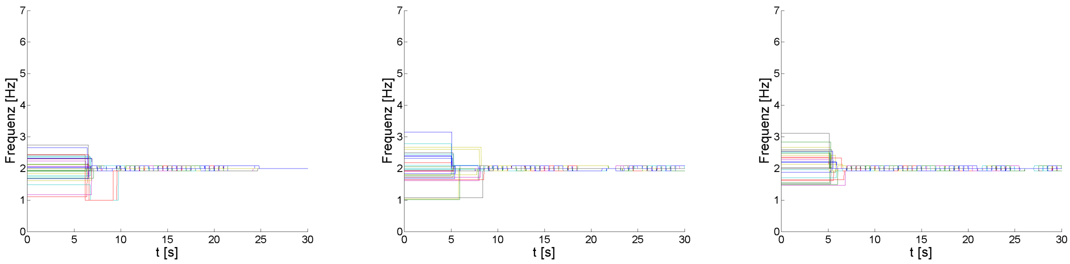


Figure 21: Frequencies configuration 2.c (low frequencies, variable number and distribution of synchronizers)

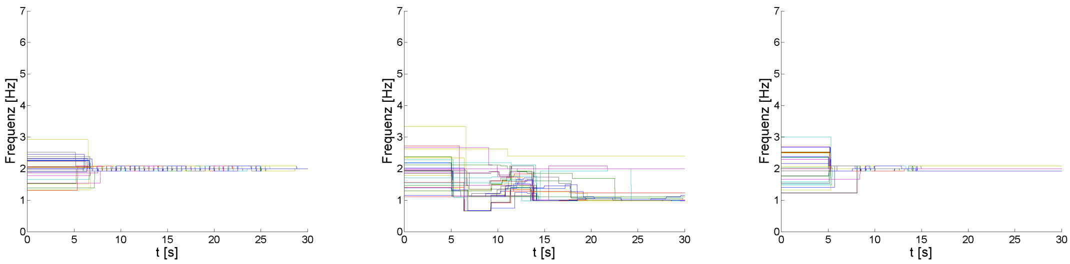
(a) Lauf 16 (b) Lauf 17 (c) Lauf 18



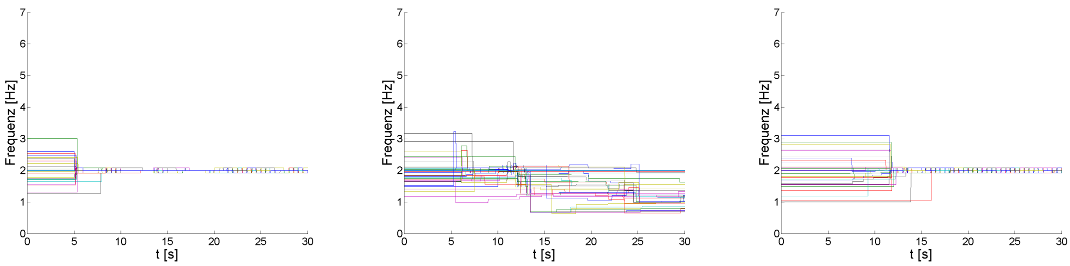
(d) Lauf 19 (e) Lauf 20 (f) Lauf 21



(g) Lauf 22 (h) Lauf 23 (i) Lauf 24



(j) Lauf 25 (k) Lauf 26 (l) Lauf 27



(m) Lauf 28 (n) Lauf 29 (o) Lauf 30

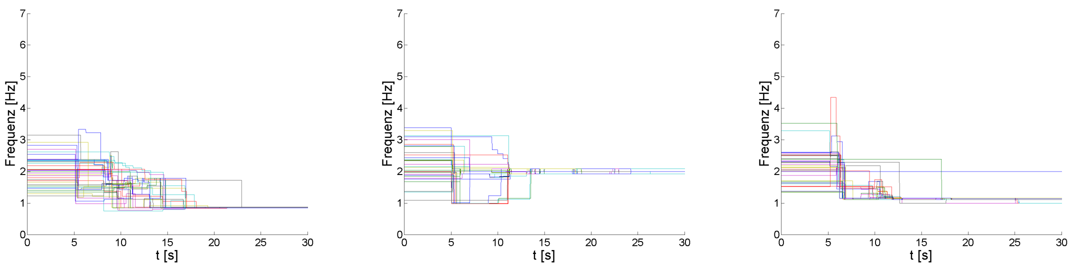
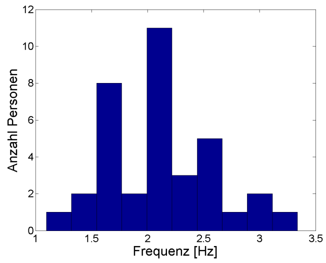
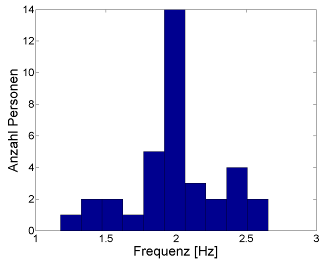


Figure 22: Start frequencies, configuration 2.c

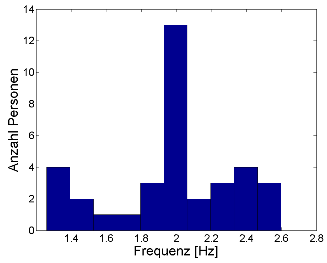
(a) Lauf 1



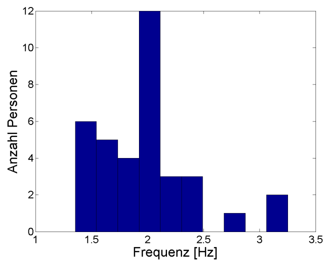
(b) Lauf 2



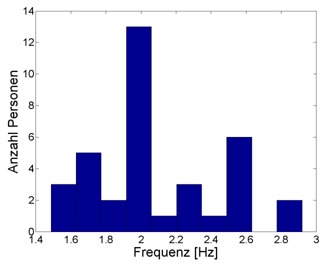
(c) Lauf 3



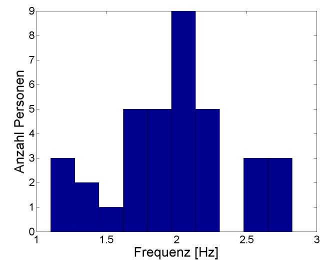
(d) Lauf 4



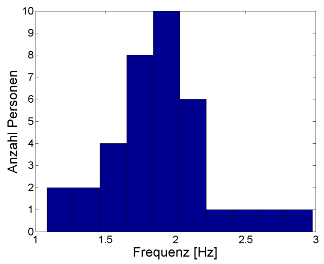
(e) Lauf 5



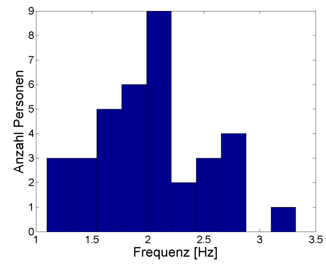
(f) Lauf 6



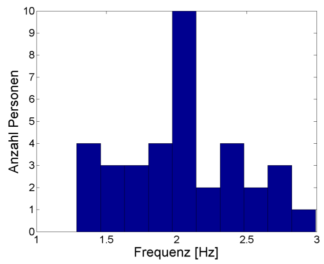
(g) Lauf 7



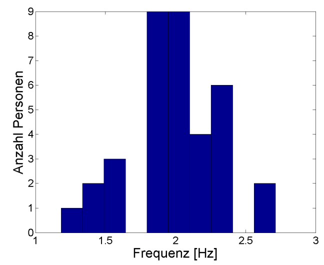
(h) Lauf 8



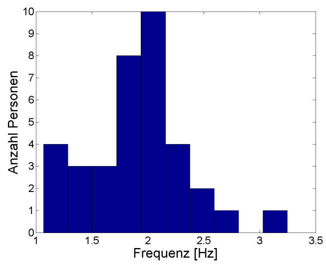
(i) Lauf 9



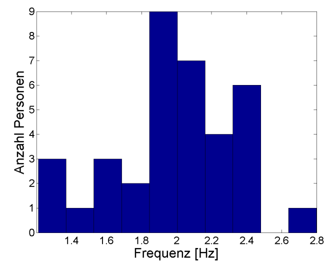
(j) Lauf 10



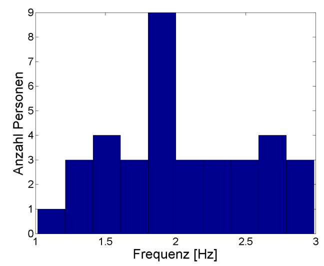
(k) Lauf 11



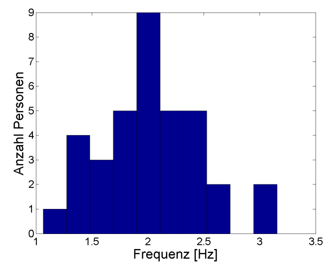
(l) Lauf 12



(m) Lauf 13



(n) Lauf 14



(o) Lauf 15

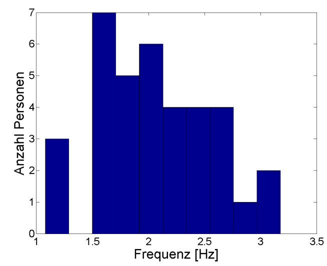
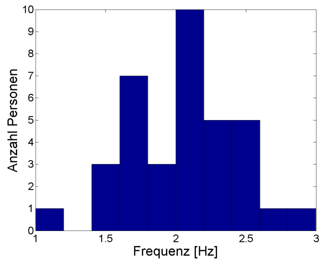
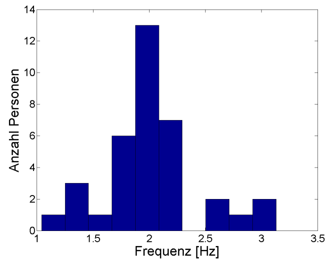


Figure 23: Start frequencies, configuration 2.c

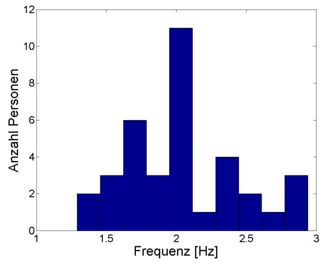
(a) Lauf 16



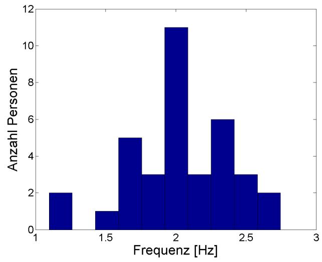
(b) Lauf 17



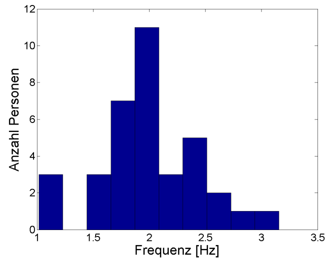
(c) Lauf 18



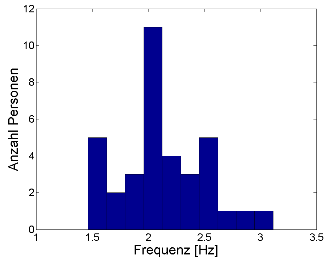
(d) Lauf 19



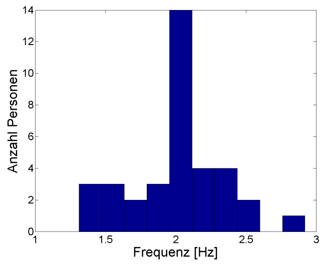
(e) Lauf 20



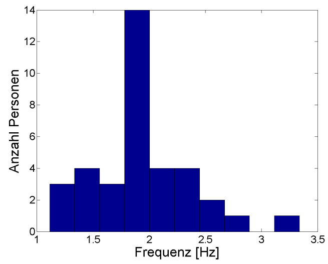
(f) Lauf 21



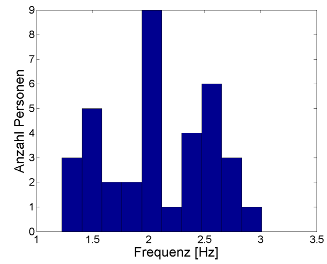
(g) Lauf 22



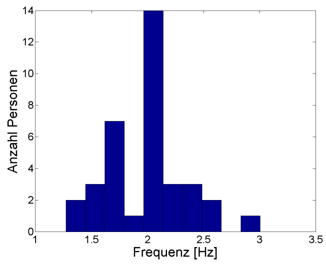
(h) Lauf 23



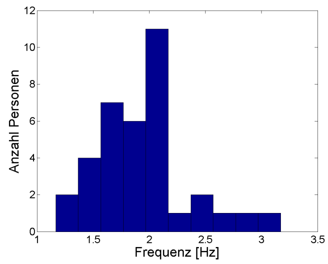
(i) Lauf 24



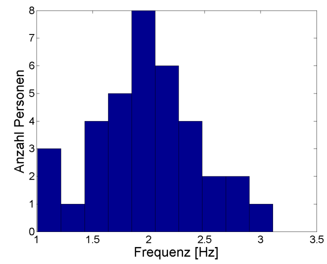
(j) Lauf 25



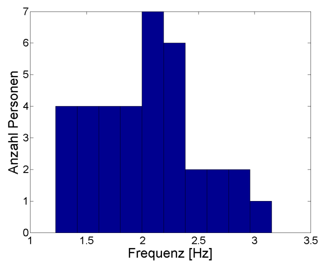
(k) Lauf 26



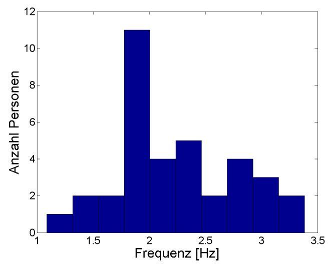
(l) Lauf 27



(m) Lauf 28



(n) Lauf 29



(o) Lauf 30

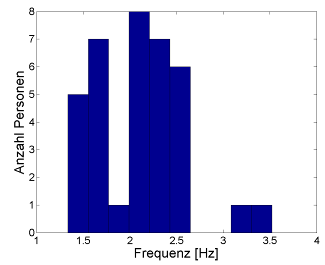
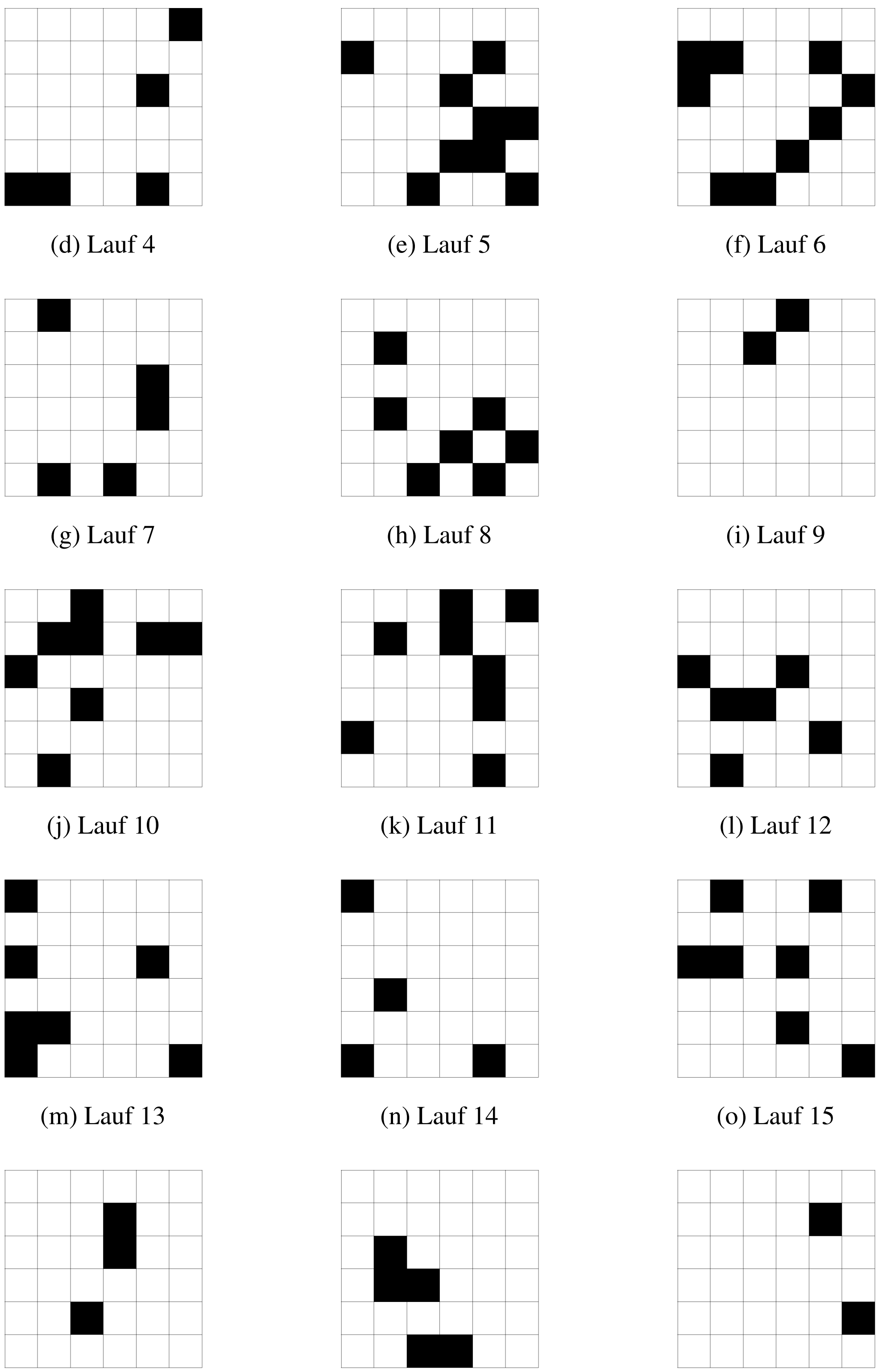


Figure 24: Distribution of synchronizers, configuration 2.c



(a) Lauf 1 (b) Lauf 2 (c) Lauf 3
(d) Lauf 4 (e) Lauf 5 (f) Lauf 6
(g) Lauf 7 (h) Lauf 8 (i) Lauf 9
(j) Lauf 10 (k) Lauf 11 (l) Lauf 12
(m) Lauf 13 (n) Lauf 14 (o) Lauf 15

Figure 25: Distribution of synchronizers, configuration 2.c

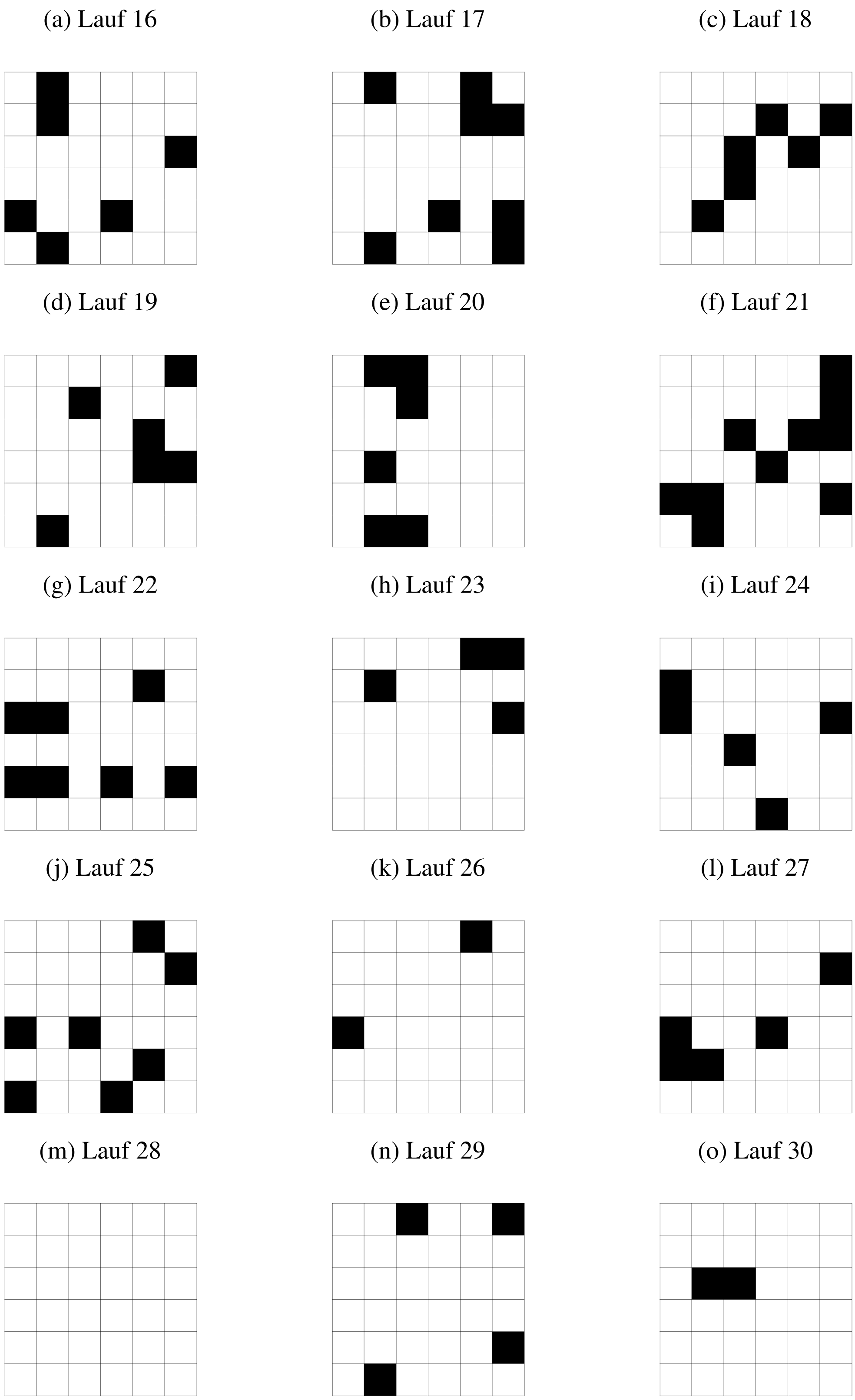
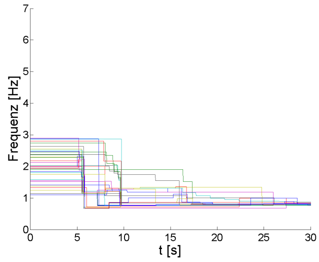
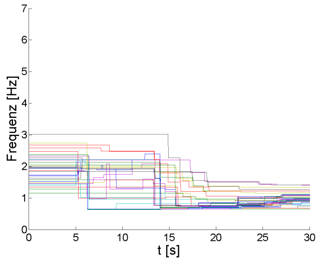


Figure 26: Frequencies configuration 3 (no synchronizers, low frequencies)

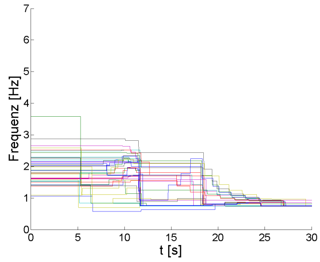
(a) Run 1



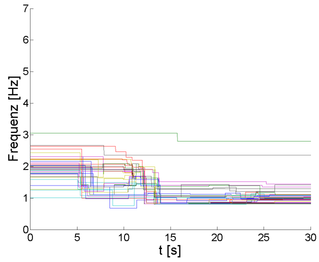
(b) Run 2



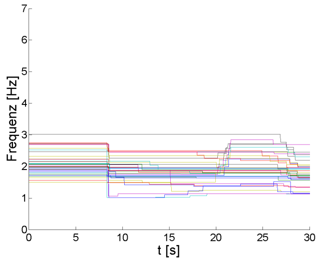
(c) Run 3



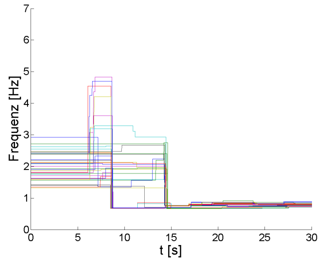
(d) Run 4



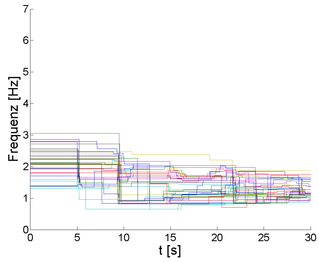
(e) Run 5



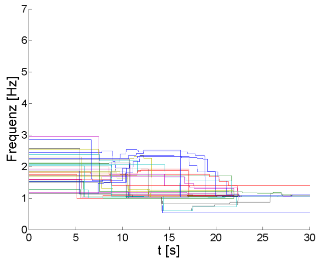
(f) Run 6



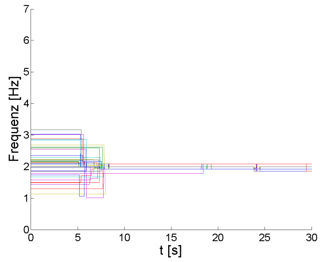
(g) Run 7



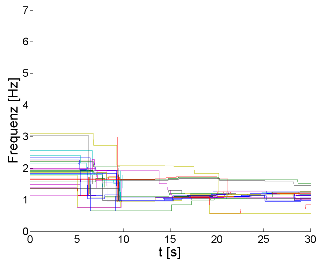
(h) Run 8



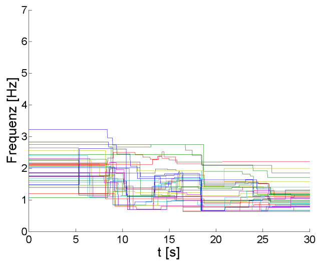
(i) Run 9



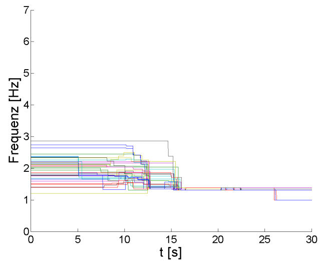
(j) Run 10



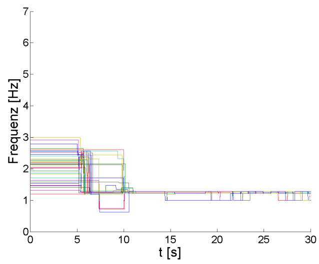
(k) Run 11



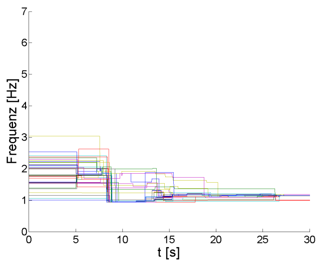
(l) Run 12



(m) Run 13



(n) Run 14



(o) Run 15

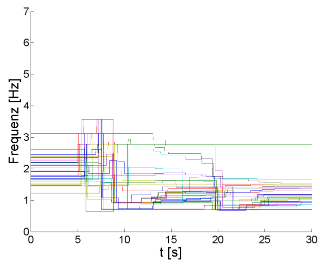
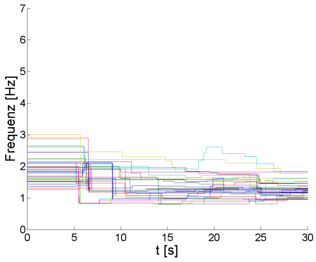
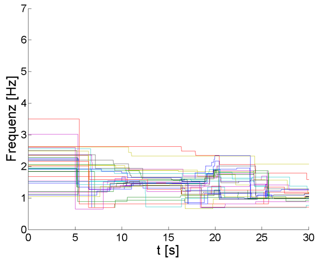


Figure 27: Frequencies configuration 3 (no synchronizers, low frequencies)

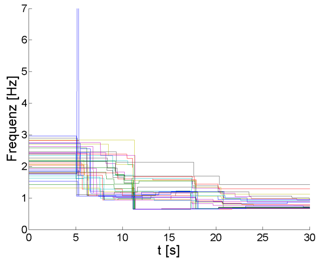
(a) Run 16



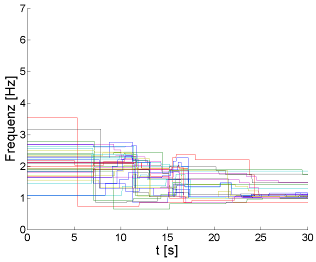
(b) Run 17



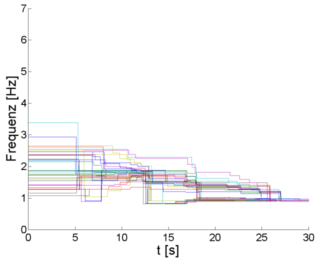
(c) Run 18



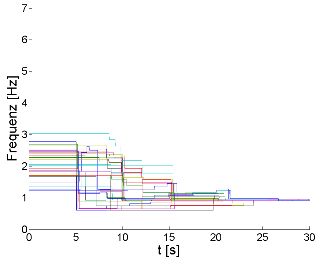
(d) Run 19



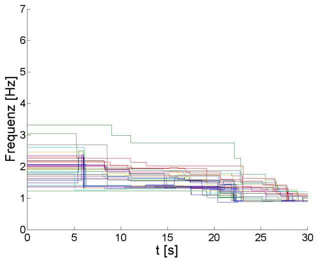
(e) Run 20



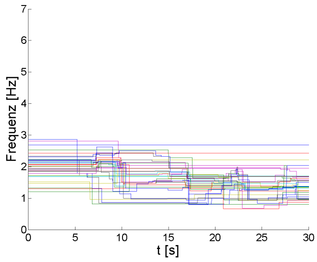
(f) Run 21



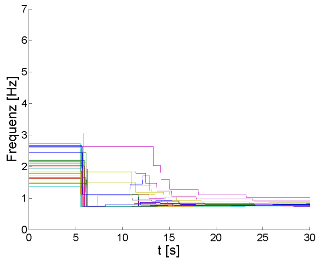
(g) Run 22



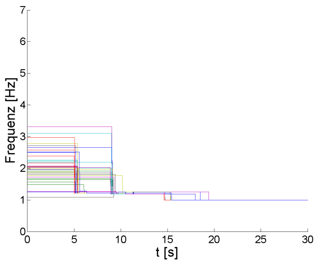
(h) Run 23



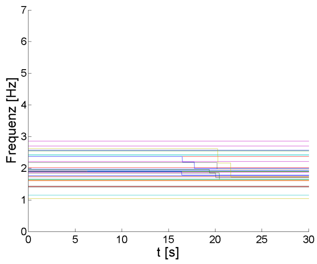
(i) Run 24



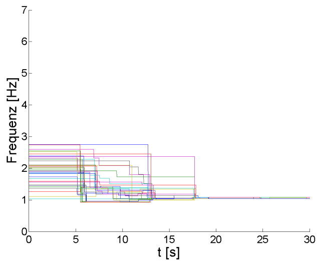
(j) Run 25



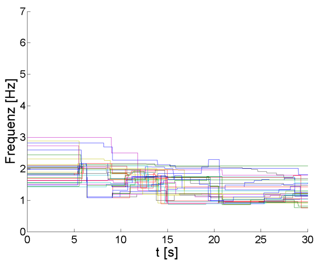
(k) Run 26



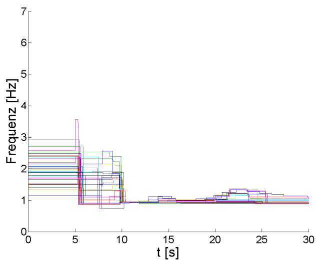
(l) Run 27



(m) Run 28



(n) Run 29



(o) Run 30

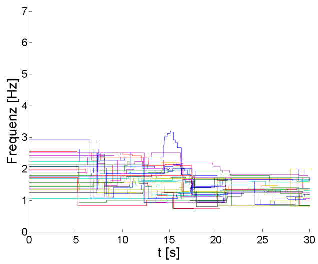
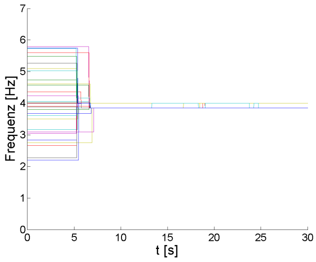
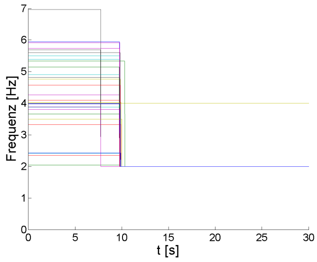


Figure 28: Frequencies configuration 4 (no errors, high frequencies)

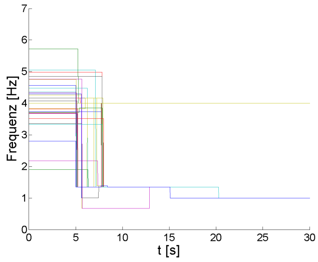
(a) Run 1



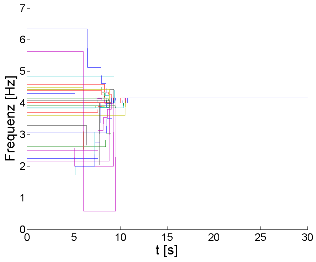
(b) Run 2



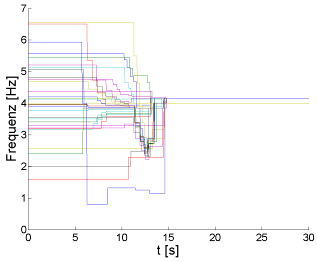
(c) Run 3



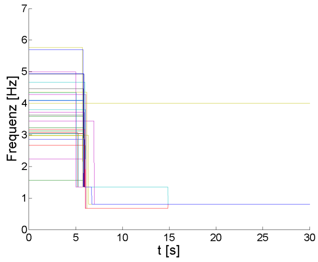
(d) Run 4



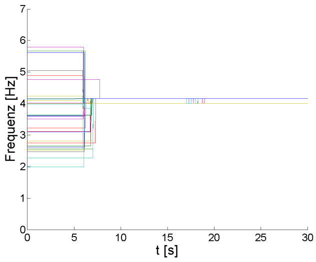
(e) Run 5



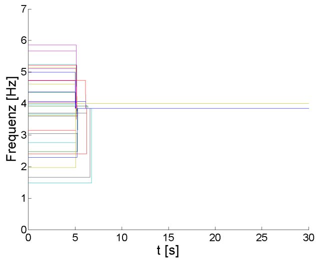
(f) Run 6



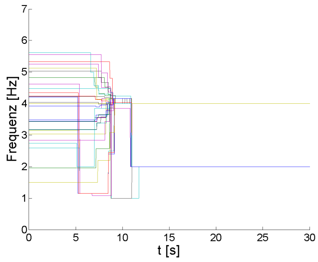
(g) Run 7



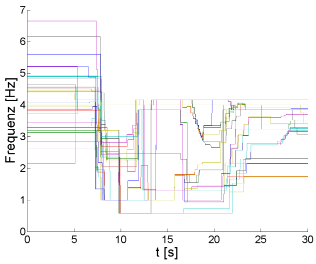
(h) Run 8



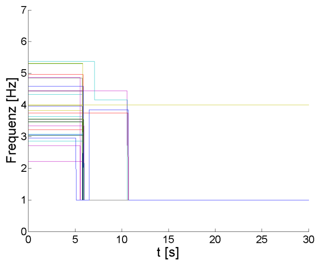
(i) Run 9



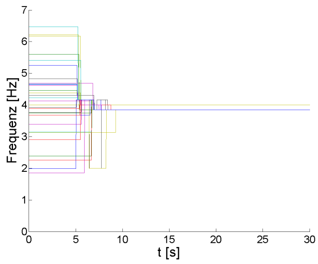
(j) Run 10



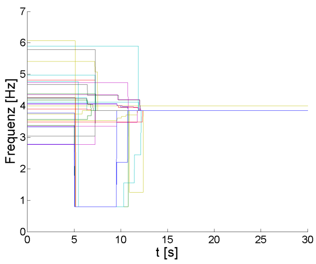
(k) Run 11



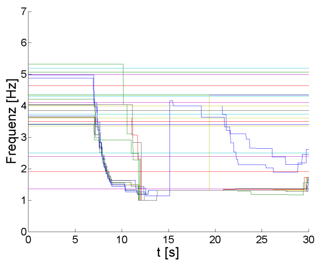
(l) Run 12



(m) Run 13



(n) Run 14



(o) Run 15

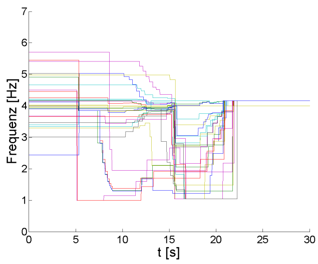
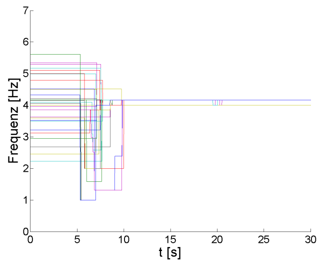
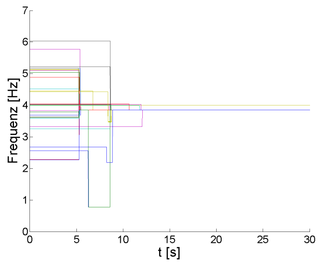


Figure 29: Frequencies configuration 4 (no errors, high frequencies)

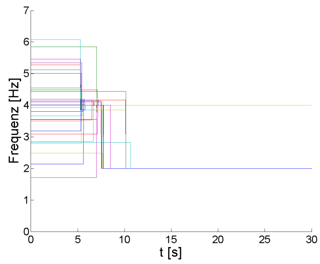
(a) Run 16



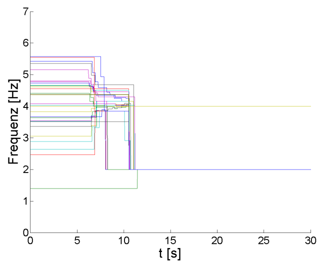
(b) Run 17



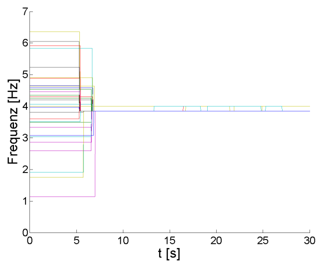
(c) Run 18



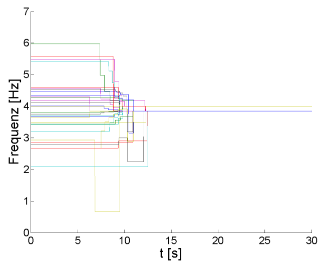
(d) Run 19



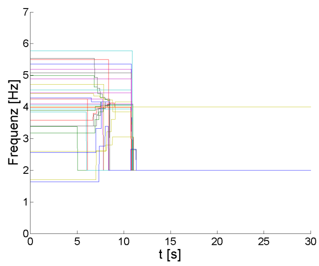
(e) Run 20



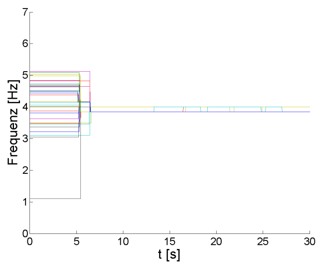
(f) Run 21



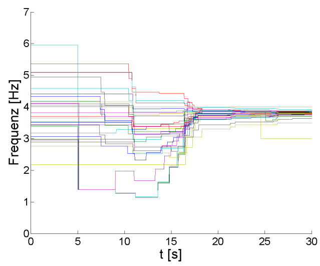
(g) Run 22



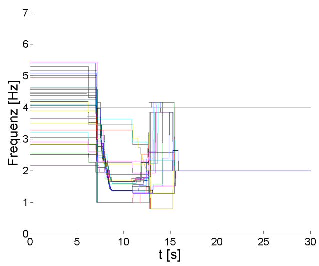
(h) Run 23



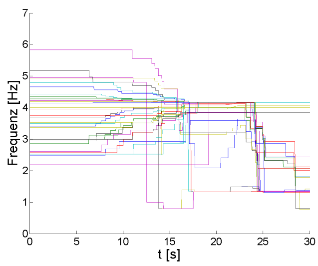
(i) Run 24



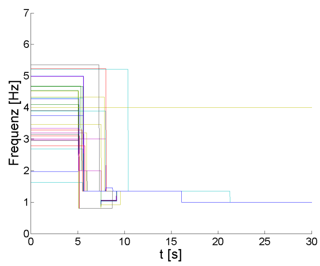
(j) Run 25



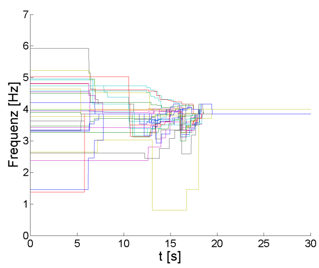
(k) Run 26



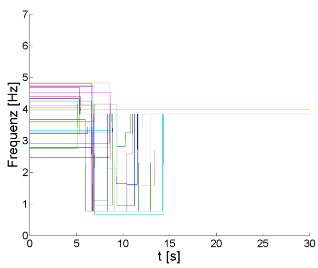
(l) Run 27



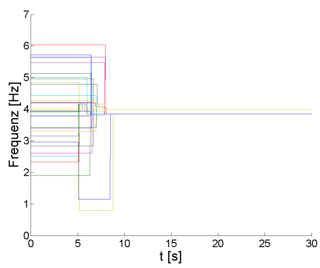
(m) Run 28



(n) Run 29



(o) Run 30



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