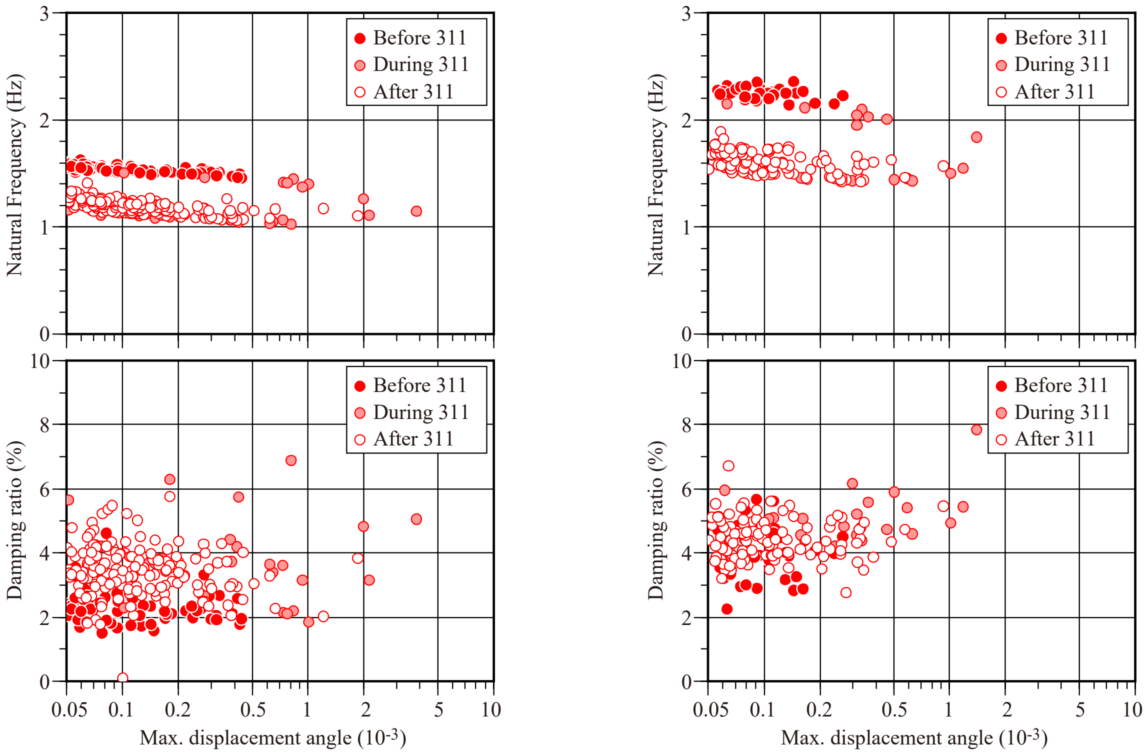
In order to discuss the amplitude-dependence of the dynamic characteristics, the maximum displacement angle $\theta_{\max}$ defined by Eq. (1) is adopted to represent the seismic response amplitude.

$$\theta_{max} = |x_{\mathrm{T}}(t) - x_{\mathrm{F}}(t)|_{max}/H \tag{1}$$

where, $x_{\mathrm{T}}(t)$ and $x_{\mathrm{F}}(t)$ are the time histories of the displacements on the eighth and basement floors, respectively (see Fig. 7), and H is the height of the eighth floor from the first floor level.

The relation of the natural frequency and damping ratio to the maximum displacement angle $\theta_{\max}$ of the main building is plotted in Fig. 5. In the figure, (a) and (b) indicate the results in the Y- and X-directions, respectively. In each of (a) and (b), the upper and lower plots correspond to the natural frequency and damping ratio, respectively. In all the plots, red, pale red and white circles (●, ● and ○) indicate values before, during, and after the Tohoku Earthquake. For values during the Tohoku Earthquake, the system identification was made for every 20 seconds. The natural frequencies in the Y- and X-directions of the main building were about 1.6 Hz and 2.2 Hz in the small amplitude range, respectively. Structural damage by the Tohoku Earthquake reduced the natural frequencies of the main building to 1.2 Hz and 1.6 Hz. The natural frequencies before the Tohoku Earthquake are stable and the amplitude dependence can be recognised slightly. The natural frequencies after the earthquake vary, especially in the X-direction. The damping ratios in the Y-directions are generally between 2% and 4%. The damping ratios in the X-direction are larger than those in the Y-direction and distributed between 3% and 6%. Generally, the damping ratios after the Tohoku Earthquake are slightly larger than before the earthquake. In addition, damping ratios tend to increase as the response amplitude increase.



(a) Y-direction (b) X-direction

Fig. 5 – Relations of natural frequency and damping ratio to maximum displacement angle ($\theta_{\max}$) of main building

The relations of the natural frequency and damping ratio to the maximum displacement angle $\theta_{\max}$ of the annex building is plotted in Fig. 6. The arrangement of the plots and the meaning of the symbols are the same as in Fig. 5. The natural frequencies in the X- and Y-directions are close and were distributed between 1.2 Hz and 1.8 Hz before the Tohoku Earthquake. The cause of the fluctuation is thought to be a decrease in the natural frequencies for seven years after the completion as shown in Fig. 4. After the Tohoku Earthquake, the natural frequencies in both directions dropped to about 1.0 Hz, and the variation became very small. Although the damping ratios vary widely, there is a tendency for the damping ratio to increase after the Tohoku Earthquake and to increase as the response amplitude increases.

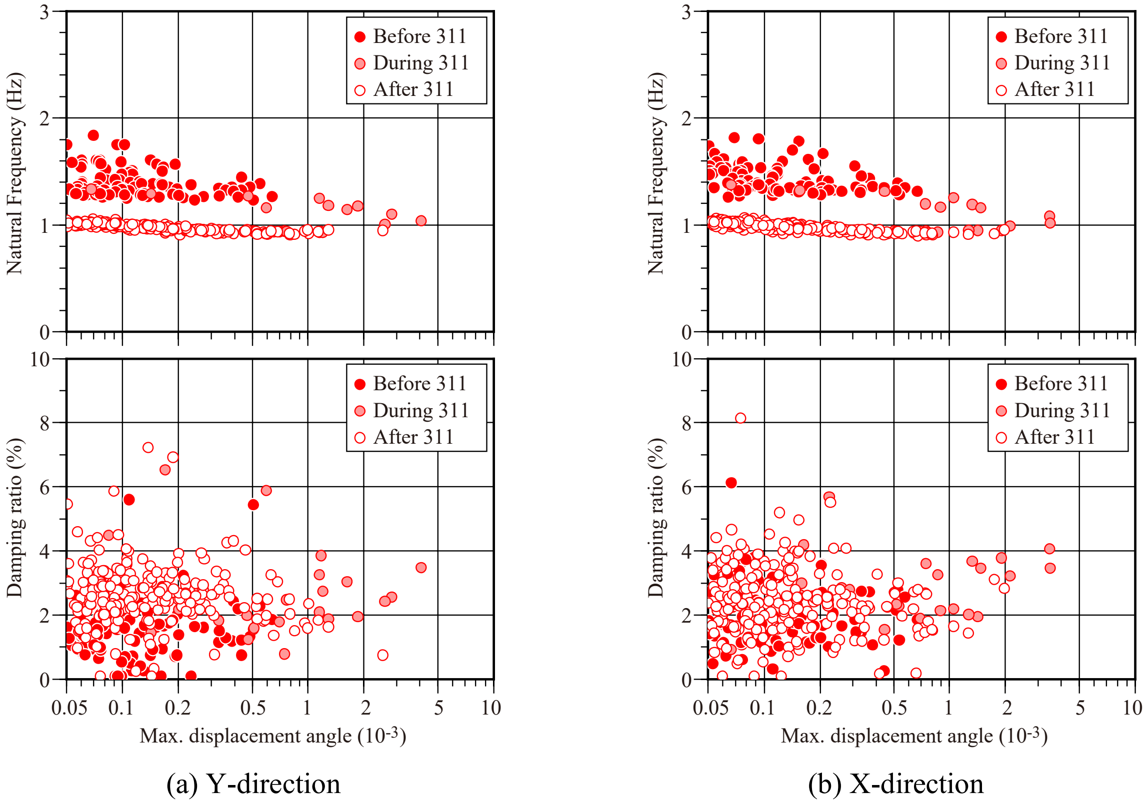


Fig. 6 – Relations of natural frequency and damping ratio to maximum displacement angle ($\theta_{\max}$) of the annex building

5. Effect of Soil-structure Interaction

Soil-structure interaction is one of the key issues to discuss the seismic response of buildings. The actual phenomenon of the annex building considering the soil-structure interaction effect is investigated using strong motion data in this chapter. The effect of the soil-structure interaction is often represented as the horizontal and rotation movements of a foundation. Since it is known that the horizontal translation of the annex building to be small [2], only the rotational movement is dealt with herein. A simple model having a spring and a damper of rocking (rotation) between the ground and foundation is illustrated in Fig. 7. The superstructure is modelled as an equivalent single-degree-of-freedom system. In this model, strong motion data at four measuring points (z_{L}, z_{R}, x_{F} and x_{T}) enable to separate the total displacement at the top floor into those caused by rocking (u_{R}), and building deformation (u_{B}) as shown in Eqs. (2) and (3). Based on this model, stiffnesses of the rocking and building (k_{R} and k_{B}) and damping coefficients of those (c_{R} and c_{B}) are identified from the strong motion data. To identify the parameters, the Evolution Strategies (ES) is adopted as an optimization algorithm. The ES algorithm, which simulates natural evolution, can be a powerful algorithm in nonlinear optimization [6].

The targets of the optimization are four parameters, k_{R}, k_{B}, c_{R} and c_{B}, and the fitness of the simulation is evaluated from the difference of displacements, u_{R} and u_{B}, to the observed ones.

$$u_{\mathrm{R}} = (z_{\mathrm{L}} - z_{\mathrm{R}})H/W \tag{2}$$

$$u_{\mathrm{B}} = x_{\mathrm{T}} - x_{\mathrm{F}} - u_{\mathrm{R}} \tag{3}$$

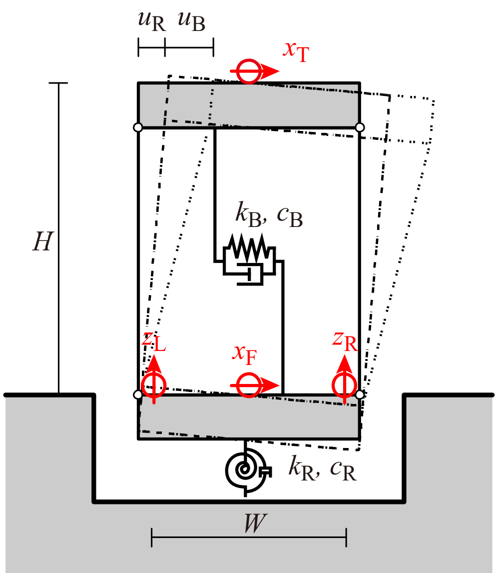


Fig. 7 – Rocking-building model

The parameter identification of the rocking-building model focuses on the Y-direction of the annex building using strong motion data having the maximum relative displacement ($u_{\mathrm{R}} + u_{\mathrm{B}}$) of 2.5 mm and larger. The optimised parameters are plotted in Fig.8 as a relation to time. In Fig.8(a), red circles and blue triangles correspond to the natural frequencies of the rocking-building model (f_{RB}) and building (f_{B}), respectively. The natural frequencies are calculated from the optimized stiffnesses k_{R} and k_{B}. Fig.8(b) and (c) show the stiffnesses of the rocking and building (k_{R} and k_{B}), respectively. Fig.8(d) and (e) show the damping coefficients of the rocking and building (c_{R} and c_{B}), respectively. The natural frequency ratio of the rocking-building model to the building model ($f_{\mathrm{RB}}/f_{\mathrm{B}}$) is plotted in Fig.8(f). The rocking ratio r_{R} is given by $r_{\mathrm{R}} = u_{\mathrm{R}}/(u_{\mathrm{R}} + u_{\mathrm{B}})$ is shown in Fig.8(g).

The rocking stiffness k_{R} can be considered as a constant value throughout the monitoring period, although there is some variation. The building stiffness k_{B} gradually decreased for seven years after the completion, and notably dropped by the Tohoku Earthquake. There has been no significant change in the building stiffness since the Tohoku Earthquake.

The rocking damping coefficient c_{R} varies greatly but does not seem to change significantly over the monitoring period. The variation in the damping coefficient of the building is smaller than that of the rocking, and there is no change during the monitoring period as well.

The natural frequency ratio ($f_{\mathrm{RB}}/f_{\mathrm{B}}$) increased from 0.93 to 0.97 in the first seven years and is around 0.98 after the Tohoku Earthquake. The rocking ratio r_{R} decreased from 0.1 to 0.07 in the first seven years and is around 0.04 after the earthquake. Both parameters indicate that the effects of the soil-structure interaction became smaller.

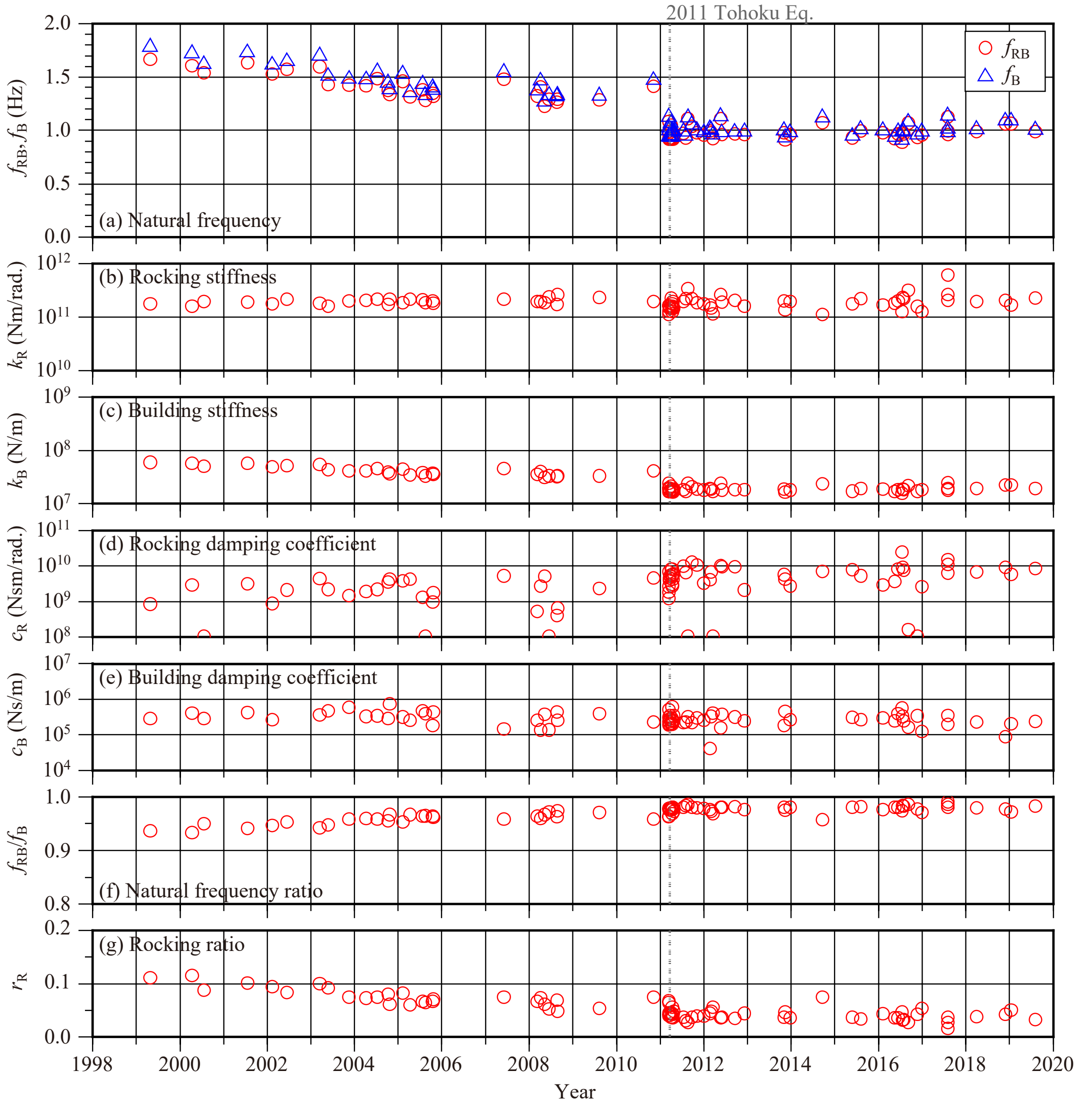
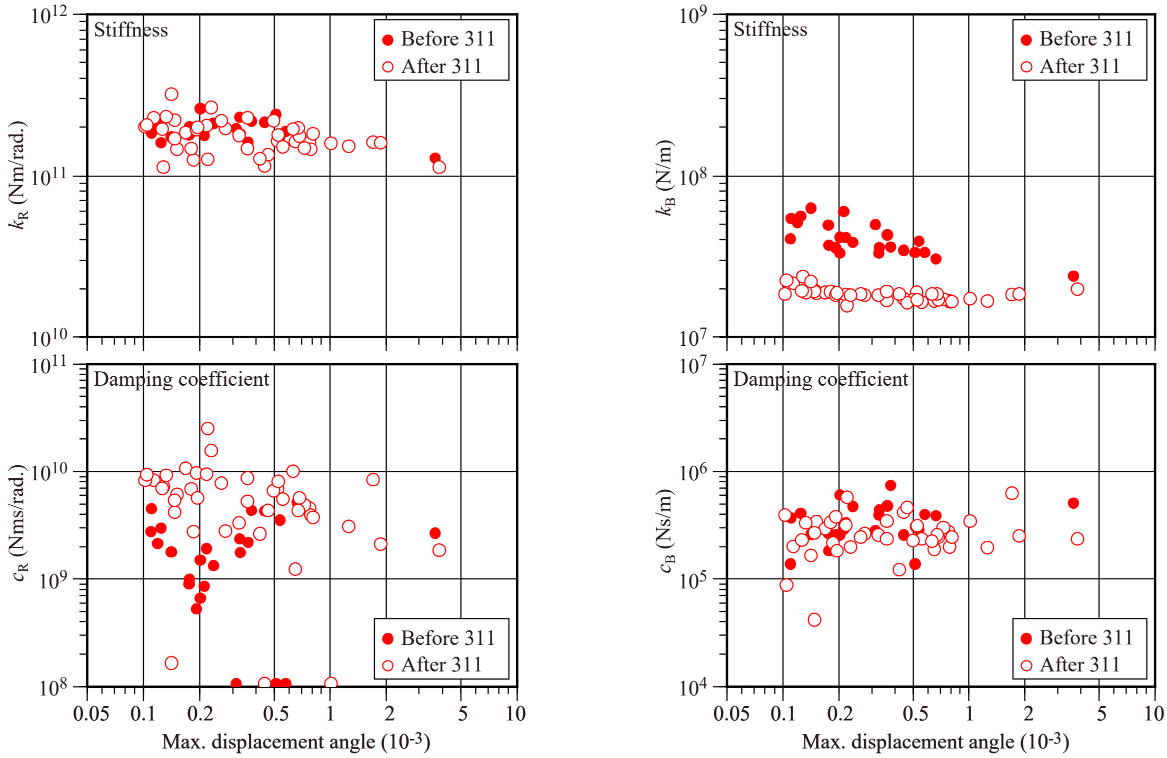


Fig. 8 – Change in natural frequencies (f_{RB}, f_B), stiffnesses (k_R, k_B), damping coefficients (c_R, c_B), natural frequency ratio (f_{RB}/f_B), and rocking ratio (r_R) with time

Fig. 9 shows the relations of the stiffness and damping coefficient to the maximum displacement angle. Fig. 10 shows the relations of the natural frequency ratio and displacement ratio to the maximum displacement angle. Solid and hollow circles (●and ○) in both figures indicate the values before and after the Tohoku Earthquake, respectively.

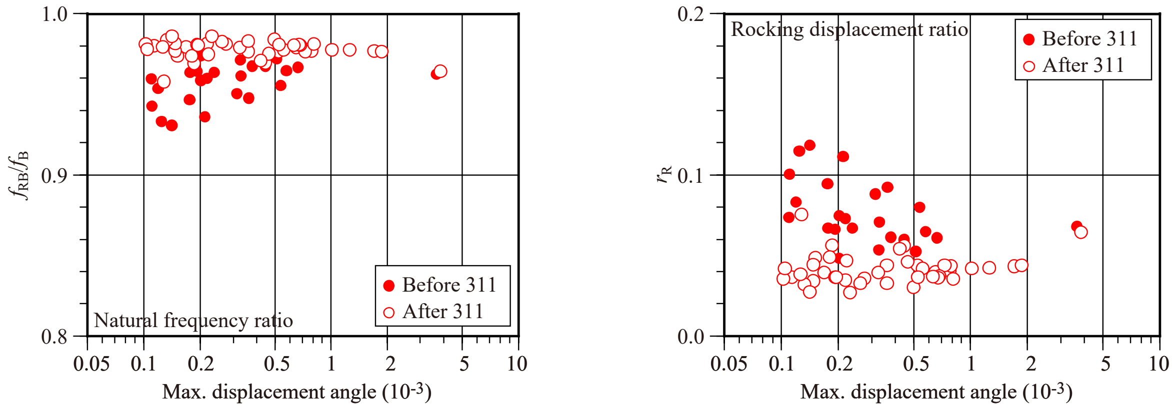
The rocking stiffness k_R varies somewhat and appears to decrease with increasing amplitude. The relation between the building stiffness k_B and maximum displacement angle θ_{max} is similar to the relation between the natural frequency and the maximum displacement angle shown in Fig. 6(a). The changes in the building stiffness before and after the Tohoku Earthquake are apparent.

The damping coefficients c_R and c_B widely vary, and there is no change due to the response amplitude. The natural frequency ratio (f_{RB}/f_B) ranges from 0.93 to 0.97 before the Tohoku Earthquake. On the other hand, the natural frequency ratio after the Tohoku Earthquake is stable at an average of about 0.98. The rocking ratio (r_R) before the Tohoku Earthquake varies widely between 0.06 and 0.12. The rocking ratio after the Tohoku Earthquake is about 0.04 on average, and there is some amplitude dependence. From the above results, it can be concluded that the decrease in natural frequency for several years after the completion and due to the Tohoku Earthquake was caused by the decrease in the building stiffness.



(a) Rocking (b) Building

Fig. 9 – Relations of stiffnesses (k_R, k_B) and damping coefficients(c_R, c_B) to maximum displacement angle (θ_{max})



(a) Rocking (b) Building

Fig. 10 – Relations of natural frequency ratio (f_{RB}/f_B), and rocking ratio (r_R) to maximum displacement angle (θ_{max})

6. Conclusions

The long-term seismic monitoring of the two buildings provided useful findings. The natural frequencies of the annex building were gradually decreased for seven years after the completion. Thereafter, the natural frequencies stopped decreasing. Although the cause is unclear, such phenomena should be kept in mind.

The 2011 Tohoku Earthquake caused some structural damage to both buildings and reduced those stiffnesses. As a result, the natural frequencies of the buildings dropped to about two-thirds. It can be pointed out that the stiffness of a building is considerably reduced due to the extent of damage that the structural members are cracked. Damping ratios of damaged buildings often increase slightly.

The amplitude dependence of the dynamic characteristics is an interesting phenomenon. In general, as the response amplitude increases, the natural frequency decreases. The degree of reduction depends on the structure. On the other hand, the damping ratio may increase or decrease as the amplitude increases. In the case of the BRI buildings, the damping ratios seem to increase slightly with the increase of the response amplitude.

The findings obtained above are considered useful for improving the accuracy of seismic structural health monitoring of buildings.

7. References

[1] Kashima T (2004): Dynamic Behaviour of an Eight-storey SRC Building Examined from Strong Motion Records, *13th World Conference on Earthquake Engineering (13WCEE)*, Vancouver, Canada.

[2] Kashima T and Kitagawa Y (2006), Dynamic Characteristics of an 8-storey Building Estimated from Strong Motion Records, *First European Conference on Earthquake Engineering and Seismology*, Geneva, Switzerland.

[3] Kashima T., Koyama S., Okawa I. and Iiba M. (2012): Strong Motion Records in Buildings from the 2011 Great East Japan Earthquake. *15th World Conference on Earthquake Engineering*, Lisbon, Portugal.

[4] Kashima T, (2014): Dynamic Behaviour of SRC Buildings damaged by the 2011 Great East Japan Earthquake based on Strong Motion Records. *Second European Conference of Earthquake Engineering and Seismology*, Istanbul, Turkey.

[5] Kashima T. and Kitagawa Y. (2006): Dynamic Characteristics of Buildings Estimated from Strong Motion Records. *8th U.S. National Conference on Earthquake Engineering*, San Francisco, United States.

[6] Michalewicz, Z and D.B. Fogel (2000): *How to Solve It: Modern Heuristics*, Springer.

