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Hybrid Genetic Algorithm for Packing Segments of Decommissioned Nuclear Reactor Components

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1. Introduction

- **Background**
  - **Permanent shut down for decommissioning : Kori unit 1 and Wolsung unit 1**
  - **Estimating the disposal amount of waste from decommissioned nuclear reactors has become a pressing issue**
  - **To reduce the storage cost of radioactive wastes in the disposal facility**
  - **desirable to maximize the volume utilization of the disposal containers**

- **Prior Studies**
  - **Waste disposal amount of Kori unit 1 reactor vessel was evaluated[1]**
  - **Segmentation and packaging plan for reactor vessel and reactor vessel internals of Kori unit 1 was proposed[2]**
  - **No. of segments of reactor vessels (RVs) : 17 - 172 pieces**
  - **Waste pieces in smaller sizes were advantageous for packaging with better volume utilization**

※1. Y. Choi, S.-C. Lee, and C.-L. Kim, Evaluation on Radioactive Waste Disposal Amount of Kori Unit 1 Reactor Vessel Considering Cutting and Packaging Methods, NFCWT, Vol.14, No.2 pp.123-134, 2016.

※2. Y. H. Hwang, et al., A Study on Segmentation Process of the K1 Reactor Vessel and Internals, JNFCWT, Vol.17, No.4 pp.437-445, 2019.

1. Introduction

- **Related Studies**
  - **Additive manufacturing (AM) or 3D printing**
  - **Optimal packing arrangements in the enclosed build container**
  - **Goal of AM is to maximize build volume utilization**
  - **Dominant strategies for packing problems in AM : the deepest bottom left with fill (DBLF) heuristic combined with genetic algorithm (GA)**

- **Focus of the Present Study**
  - **To propose a packing placement design method of waste segments from nuclear reactor components**
  - **To apply a hybrid genetic algorithm for cuboidal disposal containers**

2. Packing Placement Design Method

2.1 Problem Objective

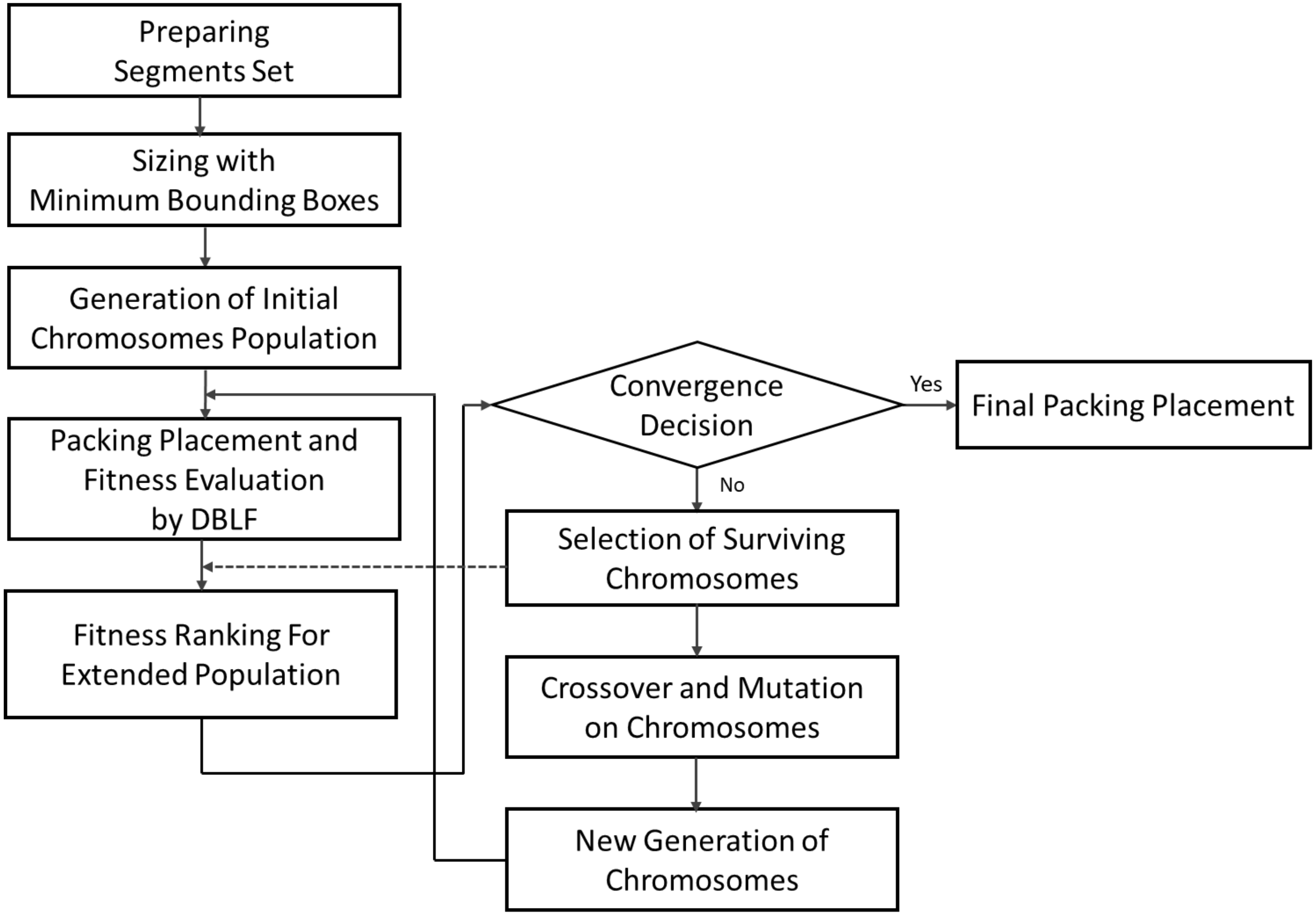
- 3D irregular packing problem
- Arbitrary volumetric items be placed into the given containers
  in such a way that the total empty space is minimized
- To minimize the number of containers to accommodate the given segments
- Minimum number of containers to be stored in the disposal facility

2.2 Hybrid genetic algorithm (HGA) method (1)

- HGA is combination of GA and a heuristic (DBLF)
- GA: diploid representation of individual boxes
  - chromosome 1 : packing sequence of boxes
  - chromosome 2 : rotations of the corresponding boxes
- DBLF : placing positions of boxes in the container
  such that each pair of packed boxes do not overlap
- Segments are modeled in STL file format
  and enclosed by orthogonal bounding boxes

2. Packing Placement Design Method

2.2 Hybrid genetic algorithm (HGA) method (2)



Preparing Segments Set

Sizing with Minimum Bounding Boxes

Generation of Initial Chromosomes Population

Packing Placement and Fitness Evaluation by DBLF

Fitness Ranking For Extended Population

Convergence Decision

Yes

Final Packing Placement

No

Selection of Surviving Chromosomes

Crossover and Mutation on Chromosomes

New Generation of Chromosomes

Fig. 1. Overall flowchart of packing placement design

2. Packing Placement Design Method

- **2.2.1. Deepest bottom left with fill (DBLF) heuristic**

Initial dimensions of box i : $(\Delta x, \Delta y, \Delta z)=(l_i, w_i, h_i)$
Deposited dimensions of box i with rotation r_i

2. Packing Placement Design Method

- **2.2.1. Deepest bottom left with fill (DBLF) heuristic (1st phase)**
  - **PP(potential position) generation started with (0, 0, 0)**
  - **box *i* in the sequence is placed with its left-bottom-back corner at (x_i, y_i, z_i) in the container**
  - **PPs are generated by projecting $(x_i+\Delta x, y_i, z_i)$ and $(x_i, y_i+\Delta y, z_i)$ on the boxes between the bottom of the container and box *i* or on the container bottom**
  - **If there is more than one box under box *i*, the position is projected on the nearest box surface**
  - **The third PP is generated at $(x_i, y_i, z_i+\Delta z)$**
  - **Additional position is obtained at $(x_i+\Delta x, 0, 0)$, if $(x_i+\Delta x)$ > any previous $(x+\Delta x)$**

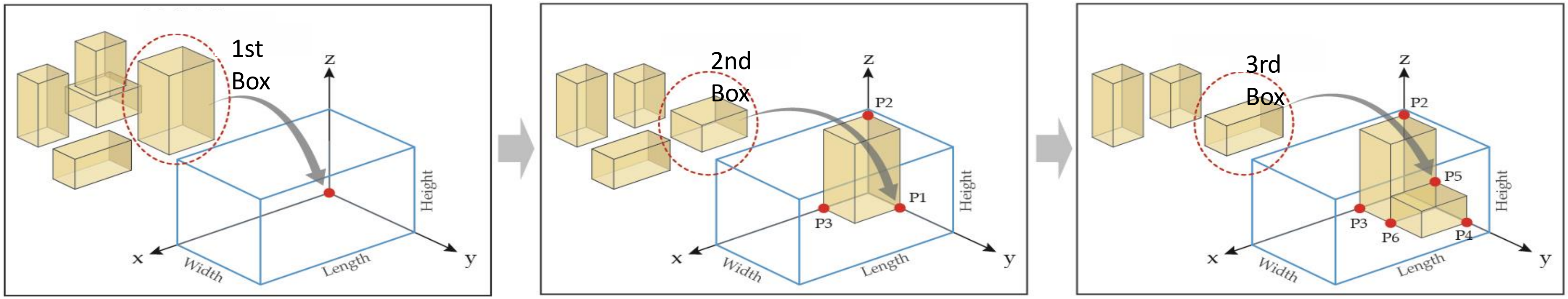


Fig. 2. Illustration of sequence of boxes and generation of potential positions in the container.

2. Packing Placement Design Method

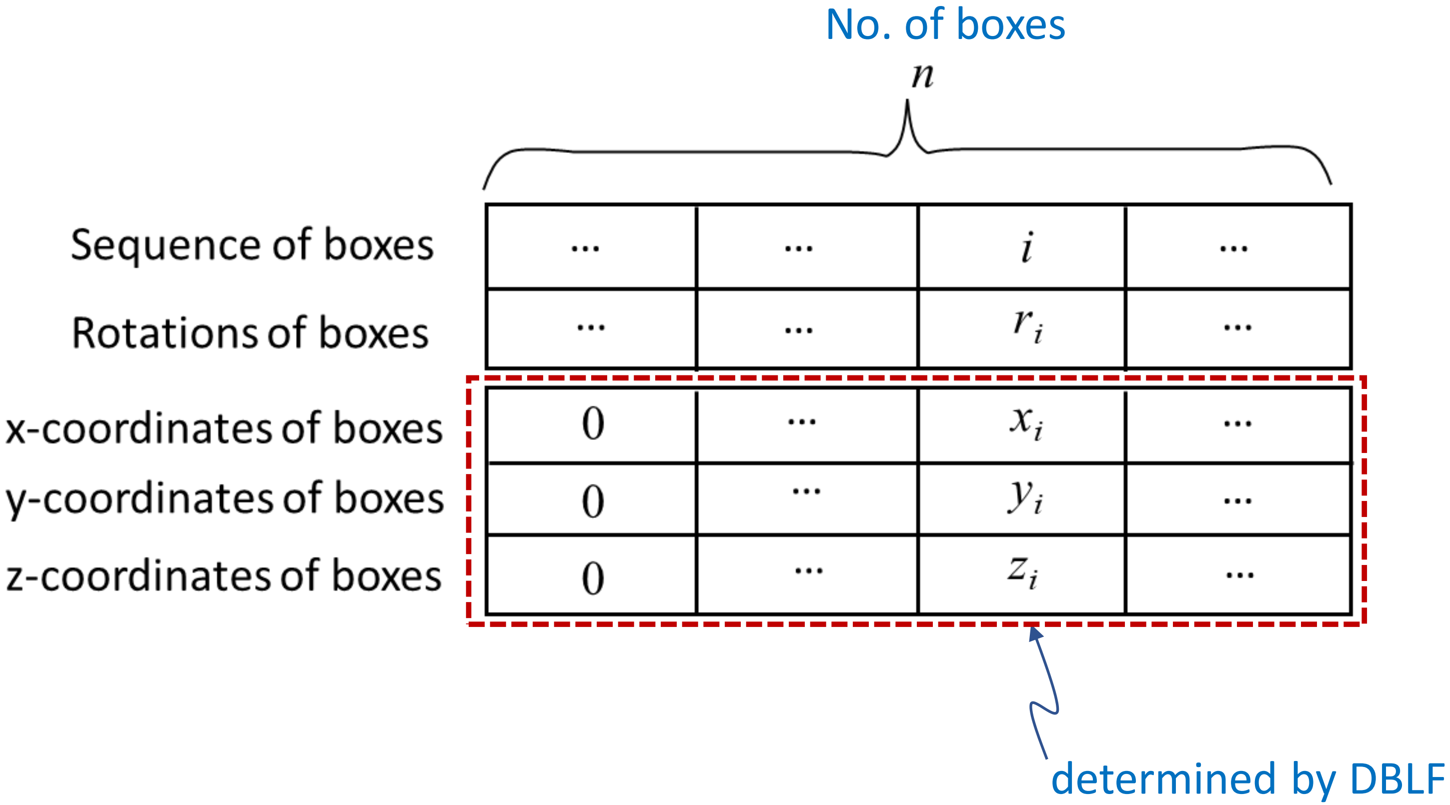
Illustration of Projection on the nearest box surface

- **2.2.1. Deepest bottom left with fill (DBLF) heuristic (2nd phase)**
  - Positions in the PP list are sorted in the deepest-bottom-left order
  - Box i is tried at potential positions of the PP list in ascending order
  - Box i is placed in a position, if it does not overlap any existing box in the container and does not penetrate the boundary surfaces of the container
  - When a box is placed at one position, that position is removed from the PP list
  - Placing process terminates when either all boxes are placed in the container or the current box finds no available positions in the PP list

2. Packing Placement Design Method

2.2.2. Genetic algorithm (1)

- Packing solution representation



No. of boxes

n

Sequence of boxes	⋯	⋯	i	⋯
Rotations of boxes	⋯	⋯	r_i	⋯
x-coordinates of boxes	0	⋯	x_i	⋯
y-coordinates of boxes	0	⋯	y_i	⋯
z-coordinates of boxes	0	⋯	z_i	⋯

determined by DBLF

Fig. 3. Illustration of a chromosome and the corresponding solution of placed positions

2. Packing Placement Design Method

- **2.2.2. Genetic algorithm (2)**
  - **The initial population of chromosomes is created by random permutations of {1, 2, …, n} for sequences and all rotations are set to 0**
  - **Special chromosomes by descending orders of volume, length, width, and height of boxes are added**
  - **Surviving chromosomes are selected based on the fitness rankings of the chromosomes**
  - **Crossover on parents, P1 and P2, from surviving chromosomes**

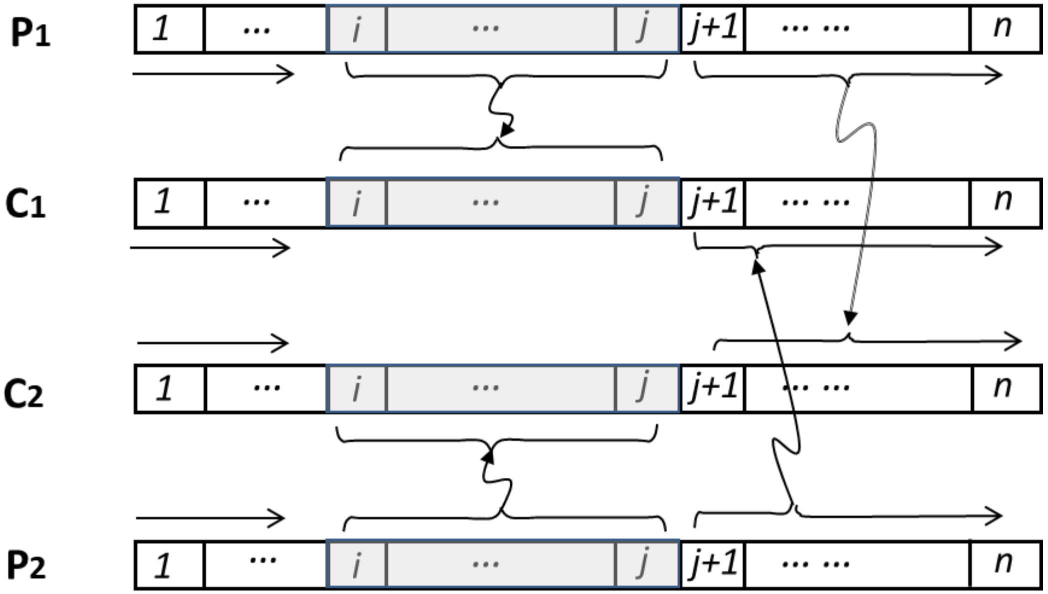


Fig. 4. Concept of crossover operated on a pair of parent chromosomes

2. Packing Placement Design Method

2.2.2. Genetic algorithm (3)

- Mutation
  - Swapping mutation: two random sites i and j are selected in C,
    genes C(i) ... C(j) are inversed with probability P_{m1}
  - Flip mutation : each rotation of C is changed randomly with probability P_{m2}
- Fitness ranking
  - New generation of population after crossover and mutation
  - DBLF determines packing positions and fitness values
  - Survivors are selected from the extended population (=old+new)
- Convergence evaluation
  - f: fitness (volume utilization rate of the container)
  - η: diversity index

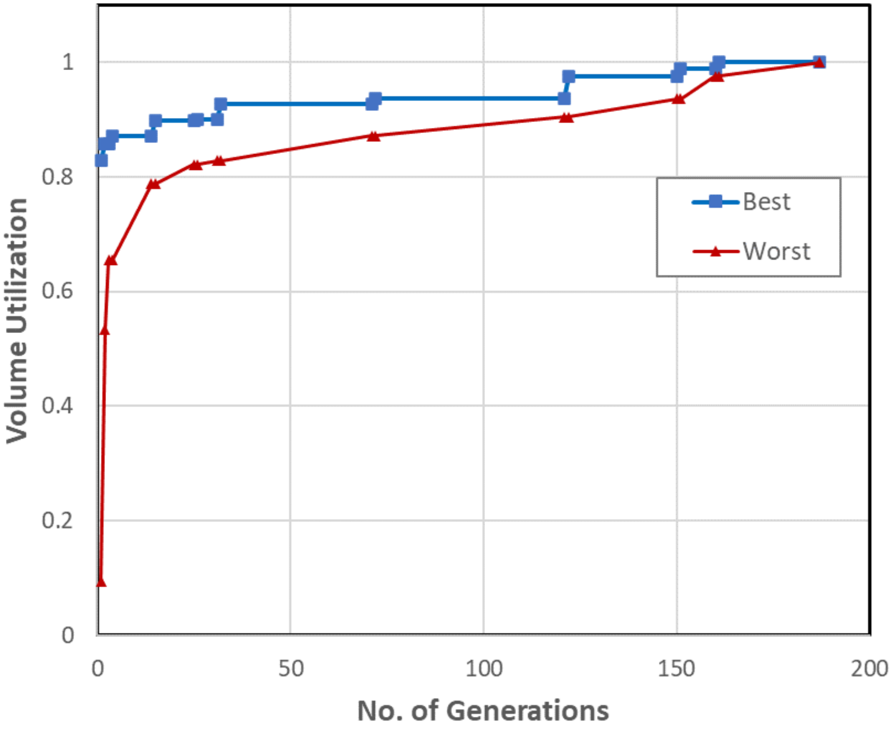
$$\eta = \frac{(f_{best} - f_{worst})}{f_{best}/2}$$

  - GA terminates with final packing solution, when η becomes small enough
- For new container
  - When boxes are left after packing a container,
    the same HGA is repeated for the next container with the remained boxes

3. Numerical Experiments

3.1 Verification of HGA method

- **Proposed HGA was verified against a known optimal solution of 100% volume utilization**
- **Population size : 400**
- **Mutation probabilities : 0.2 and 0.02 for P_{m1} and P_{m2}**



Reference case

Fig. 5. Convergence results of the reference packing problem

3. Numerical Experiments

3.2 Preparation of the segment packing test case (1)

- An RV model has been prepared in STL file format
- Subsidiary programs were developed for visualization and cutting
- RV were cut into 7x18 pieces, resulting in 126 heterogeneous segments
- The height of the model was set at 200 (unitless)
- Container was sized with 60x60x60

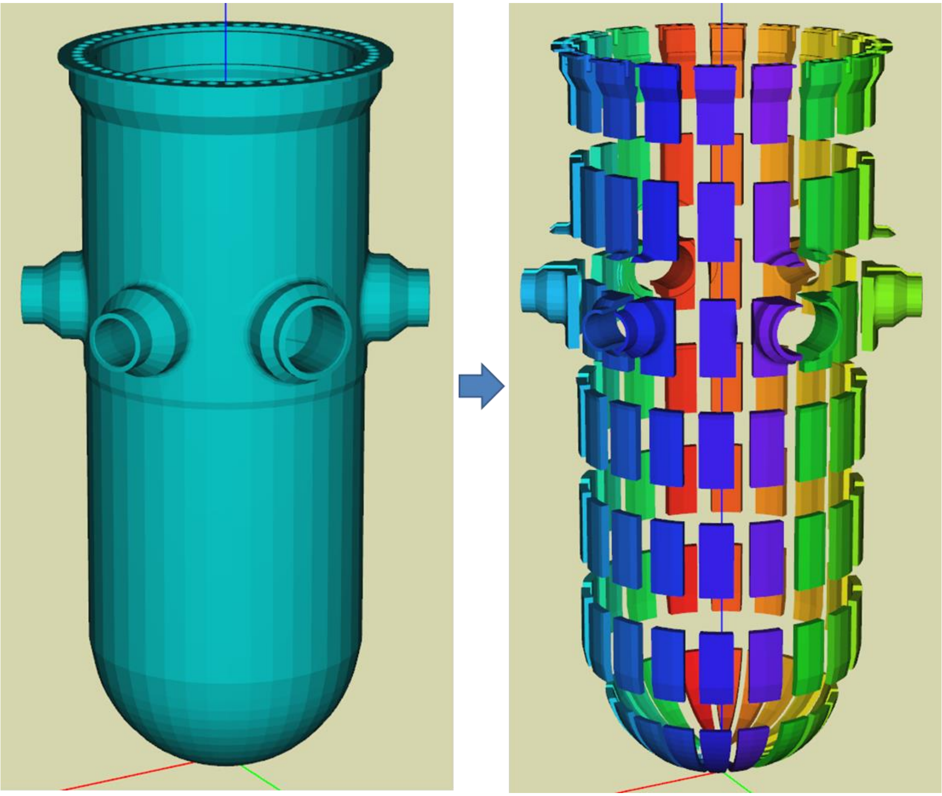


Fig. 6. A sample RV model and its cut segments.

3. Numerical Experiments

3.2 Preparation of the segment packing test case (2)

- Segments were encapsulated by minimum bounding boxes (MBBs)

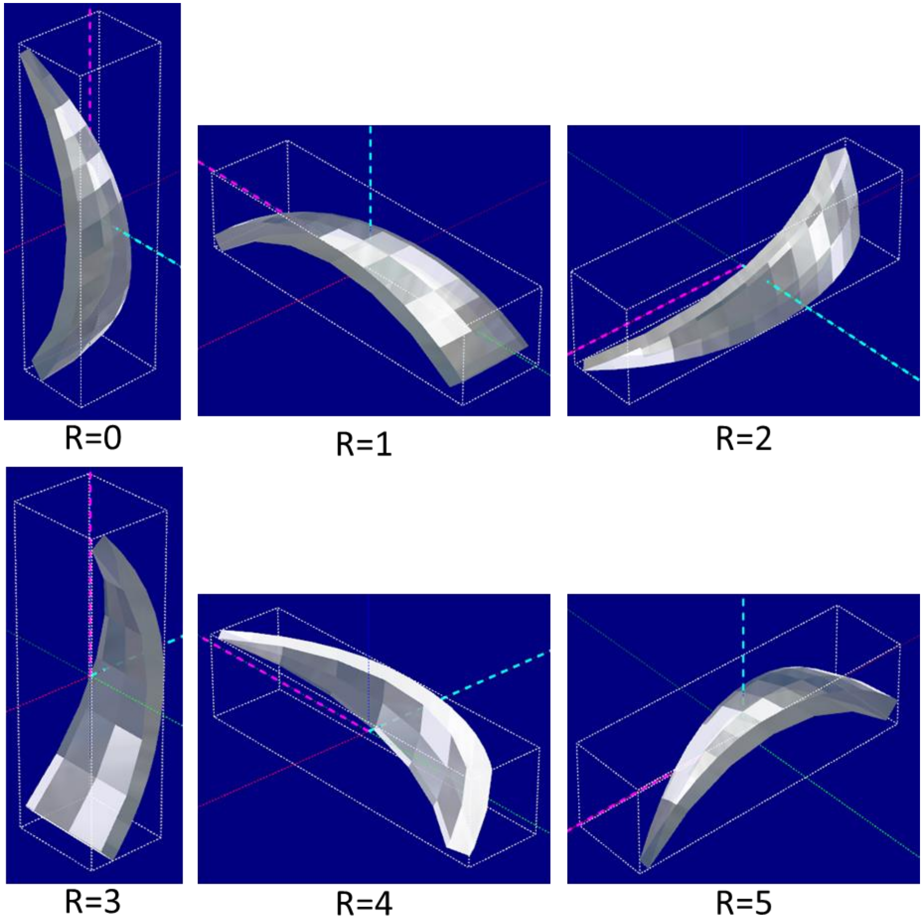


Fig. 7. Illustration of a segment with six rotations

3. Numerical Experiments

3.3 Test results and analysis (1)

- **Fitness of a solution was evaluated by the MBB volume utilization rate**

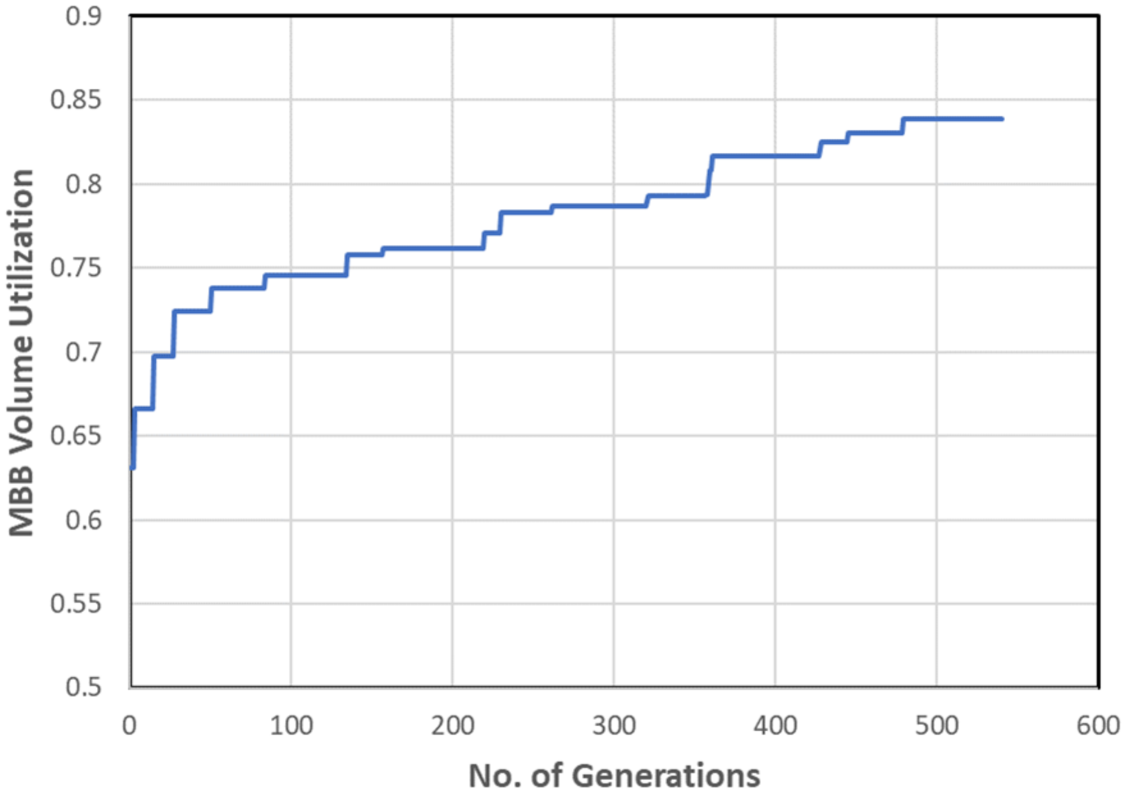
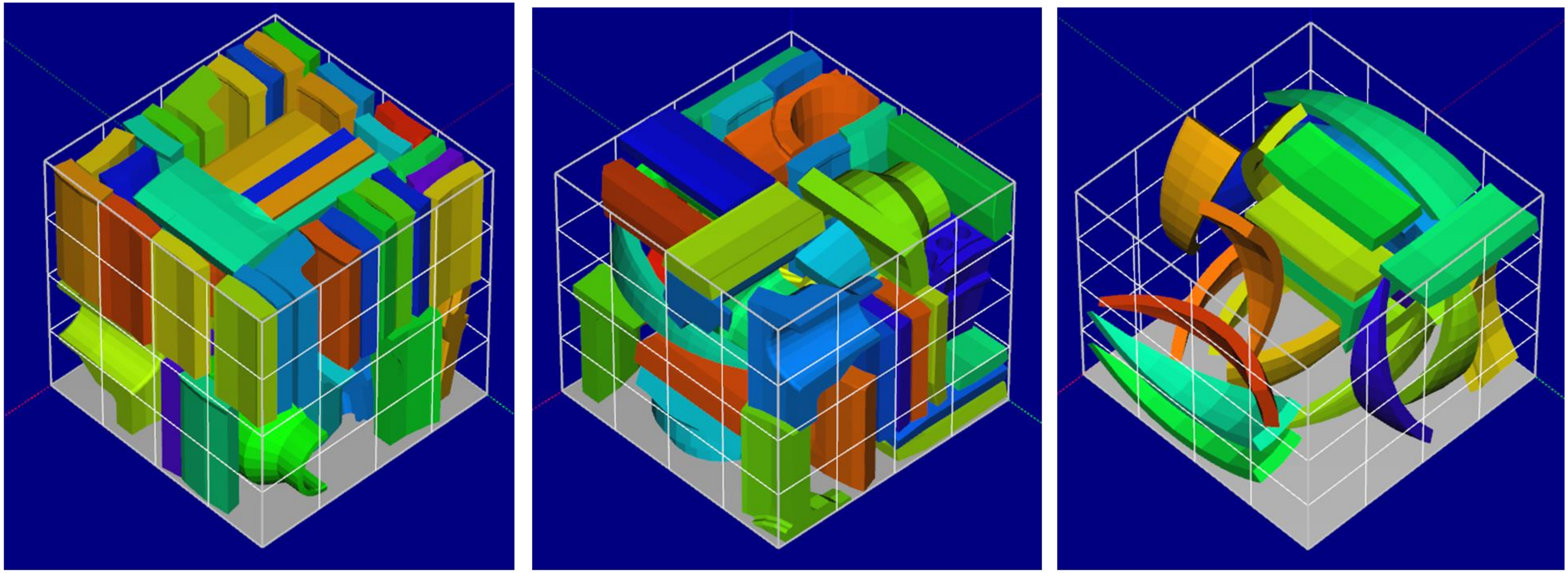


Fig. 8. Convergence results of the test case

3. Numerical Experiments

3.3 Test results and analysis (2)

- A final packing solution



First Container
No. of Segments =59
MBB Vol. Utilization =83.9%
Vol. Utilization by Segments =42.7%

Second Container
No. of Segments =42
MBB Vol. Utilization =84.4%
Vol. Utilization by Segments =33.7%

Third Container
No. of Segments =25
MBB Vol. Utilization =57.9%
Vol. Utilization by Segments = 12.7%

Fig. 9. A packing placement solution for the test case

3. Numerical Experiments

3.3 Test results and analysis (3)

- MBB volume utilizations were over 80% except the last container
- The volume utilization by segments of around 40% was generally far better than those of manual trials.
- The volume utilization by segments is expected to improve towards the MBB volume utilization, if cutting is more carefully planned to have higher solidity in MBBs.
- The packing solution for the last container was not quite optimized by the algorithm, because the container volume is sufficiently large compared to the volume sum of the remained segments and the fitness value was kept constant regardless of the packing placements.

4. Concluding Remarks

- This work provides a packing placement method for waste segments from nuclear reactor components based on a hybrid genetic algorithm
- The developed packing placement method was verified using a known packing problem and tested on a sample model of reactor vessel
- It was successfully demonstrated that the proposed method can provide near-optimal packing placement solutions for packing problems in nuclear reactor decommissioning
- The developed method is expected to be flexibly applicable for various cases of segments with different numbers and sizes and various containers
- It is expected to provide excellent solution guides in packing placement planning for decommissioning of nuclear reactors

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