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A Physical Internet-Enabled Container Loading Solution Leveraging Virtual Reality and Building Information Modeling

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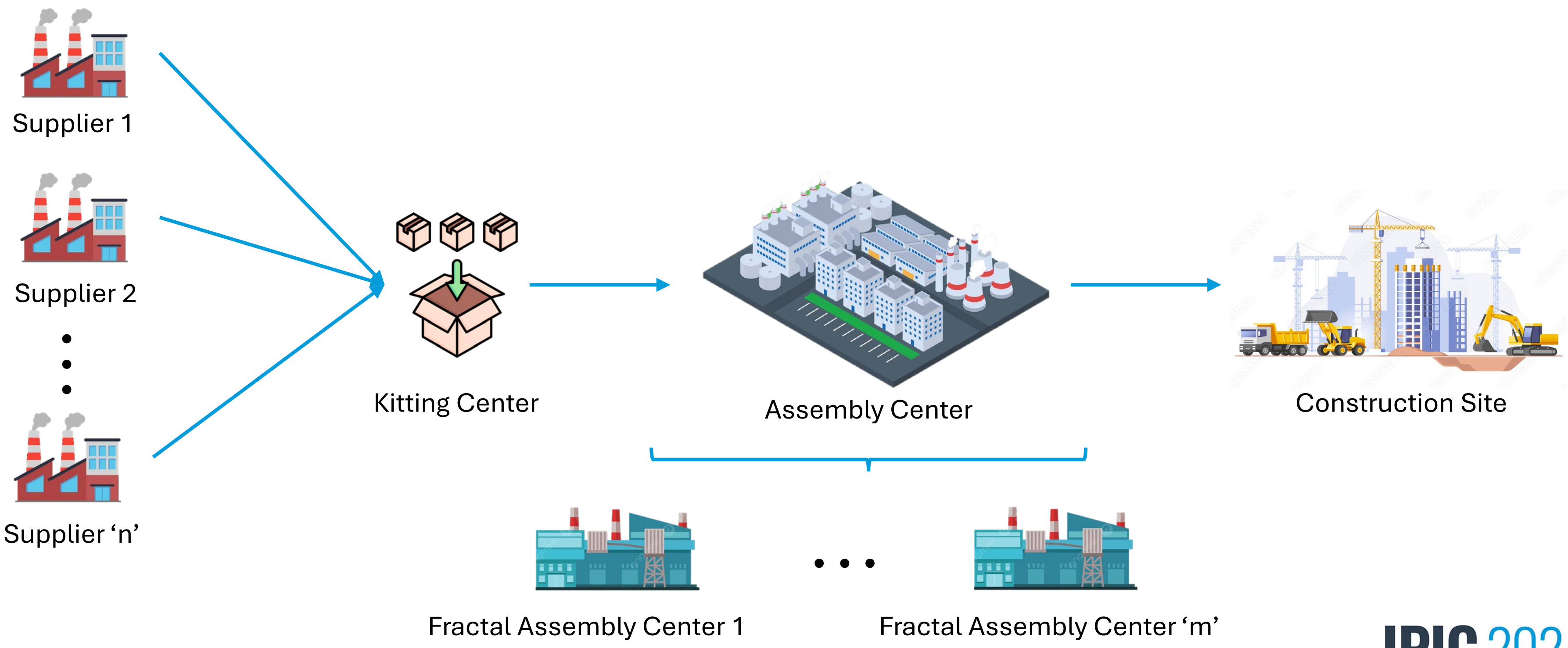
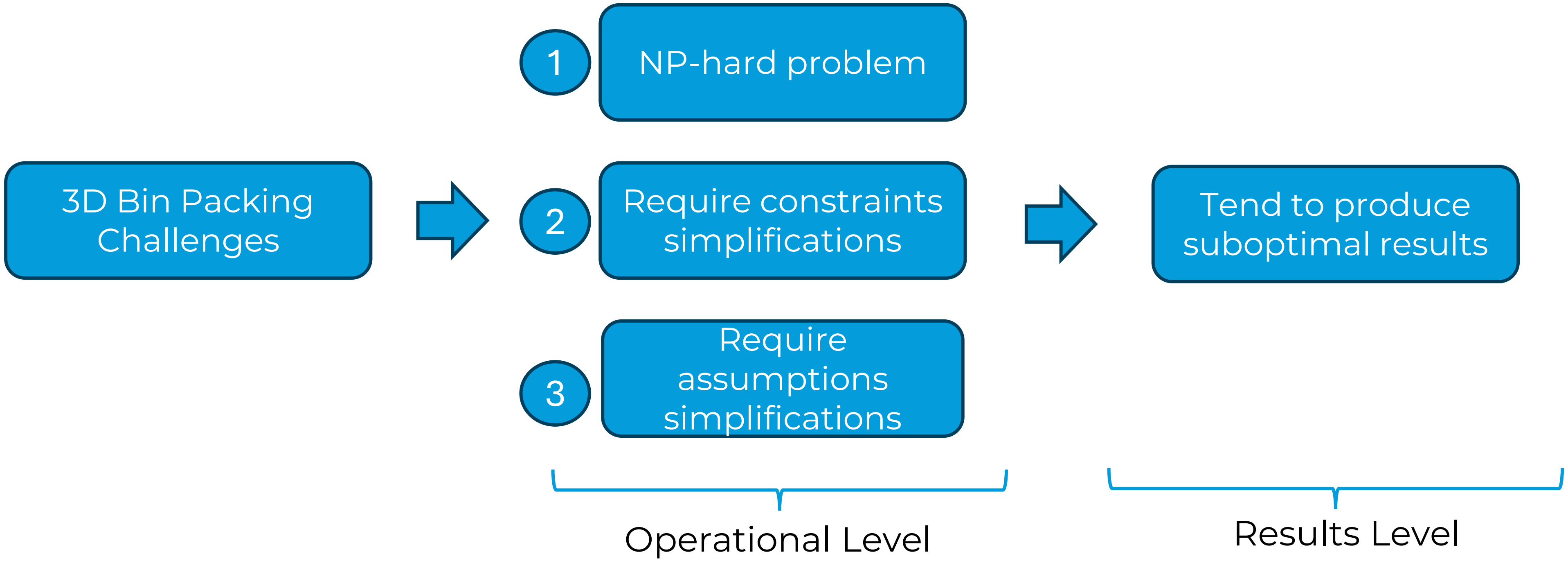
Industry and Setup Context

- Modular Construction (MC) is a construction method that parallelizes work between offsite and onsite locations.
- This parallelized method may vary among different companies, but for our analysis, we will consider a Distributed Modular Construction (DMC) which incorporates two actors: the Kitting Center and the Assembly Center.



Problem Description

- In the KC, items are consolidated into kits, bundling only the necessary parts for **specific assemblies** at **designated workstations** and **times**.
- The process of kit generation can be conceptualized as a 3D bin **irregular** packing problem and can be address with optimization model techniques.



Proposed Alternative

1 Incorporation of Virtual Reality into the Kit Containerization Design Process

2 The alternative is feasible and reasonable because in DMC, all components are digitally created (Digital Twin of the components)

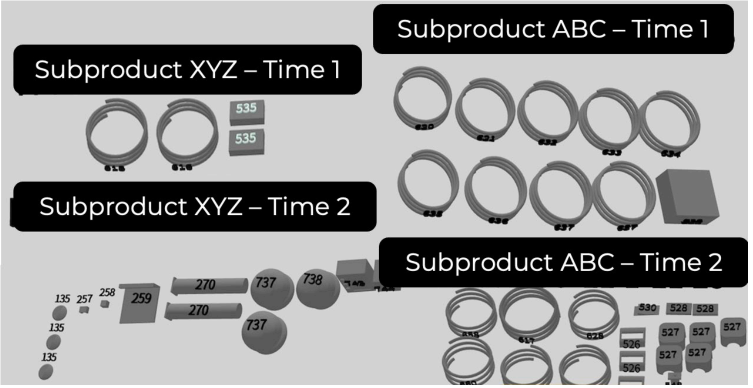


Fig. 1: Illustration of items with their corresponding labels

VR Approach

- A kit is considered complete when no more objects with the same label can be added
- If the kit is full but there are extra items, participants choose whether to split them into multiple containers or use a larger one
- If the largest container is not enough, then the participant will select an additional container to accommodate the remaining items

Optimization Model for Comparison

Item-to-container assignment

Parameters

l_i, w_i, h_i = $length, width\ and\ height\ of\ the\ item$

l_c, w_c, h_c = $length, width\ and\ height\ of\ the\ container$

f = $maximum\ fill\ percentage\ of\ a\ container$

m = $number\ of\ containers$ $\quad$ n = $number\ of\ items$

Decision Variables

$S_{ic} = 1\ if\ item\ i\ is\ placed\ in\ container\ c, 0\ otherwise$

$N_c = 1\ if\ container\ c\ is\ used, 0\ otherwise$

$$\boldsymbol{Minimize} \sum_{c=1}^{m} l_c w_c h_c - \sum_{i=1}^{n} l_i w_i h_i$$

st:

$$\sum_{c=1}^{m} S_{ic} = 1;\ \forall\ i = \{1,2, \dots n\}$$

Guarantee that every item is assigned to one container

$$\sum_{i=1}^{n} S_{ic} l_i w_i h_i \le f * l_c w_c h_c * N_c;\ \forall\ c = \{1,2, \dots m\}$$

Ensures that volume of all items in a container is within the limit of the maximum container volume

Optimization Model for Comparison (Item-in-container packing)

Decision Variables

$x_i, y_i, z_i = coordinates\ of\ back, left, bottom\ corner\ of\ item$

$l_{xi}, l_{yi}, l_{zi} = e_1, e_2, e_3\ if\ length\ of\ item\ i\ is\ parallel\ to\ x, y\ or\ z\ axis\ respectively$

$w_{xi}, w_{yi}, w_{zi} = e_1, e_2, e_3\ if\ width\ of\ item\ i\ is\ parallel\ to\ x, y\ or\ z\ axis\ respectively$

$h_{xi}, h_{yi}, h_{zi} = e_1, e_2, e_3\ if\ height\ of\ item\ i\ is\ parallel\ to\ x, y\ or\ z\ axis\ respectively$

$a_{ij}, b_{ij}, c_{ij}, d_{ij}, e_{ij}, f_{ij} = 1\ if\ item\ i\ is\ placed\ to\ the\ (left, right, behind, front, below, above)\ of\ item\ j\ respectively, 0\ otherwise$

$$x_i + l_i l_{xi} + w_i w_{xi} + h_i h_{xi} \leq x_j + (1 - a_{ij})M \quad \forall i, j, i < j$$

$$x_j + l_j l_{xj} + w_j w_{xj} + h_j h_{xj} \leq x_i + (1 - b_{ij})M \quad \forall i, j, i < j$$

Prevent overlapping between items 'i' and 'j' (*)

$$a_{ij} + b_{ij} + c_{ij} + d_{ij} + e_{ij} + f_{ij} \geq 1 - F \quad \forall i, j, i < j$$

Ensure non-zero values if items i , j exist in same container

$$x_i + l_i l_{xi} + w_i w_{xi} + h_i h_{xi} \leq l'_c \quad \forall i$$

Ensure that objects do not overlap with container (*)

$$l_{xi} + l_{yi} + l_{zi} = 1 \quad \forall i$$

Ensures that the length is only along one axis (*)

$$l_{xi} + w_{xi} + h_{xi} = 1 \quad \forall i$$

Ensures that one of the dimensions is parallel to x-axis (*)

(*) Similar constraints exist for the y-axis and z-axis

Note: e_k are three-dimensional vectors with 1 at position k and 0 elsewhere

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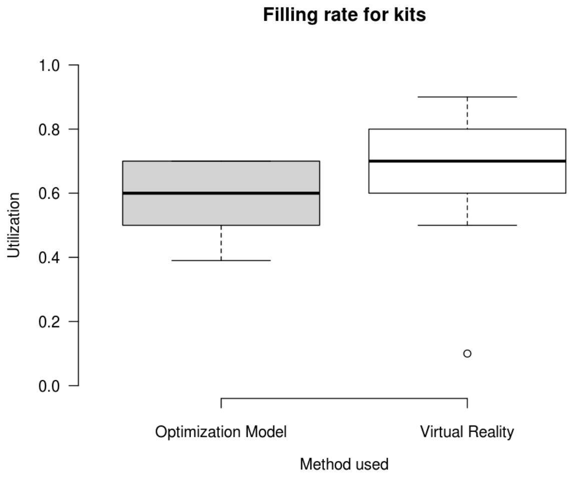
Results

1. Our findings show that the VR containerization strategy outperforms optimization methods (For this case) in terms of average and highest utilization.
2. The optimization model required either the same or more time to generate a feasible solution.
3. VR containerization provides visual insights and results that are easy to abstract, as illustrated in the low utilization image.



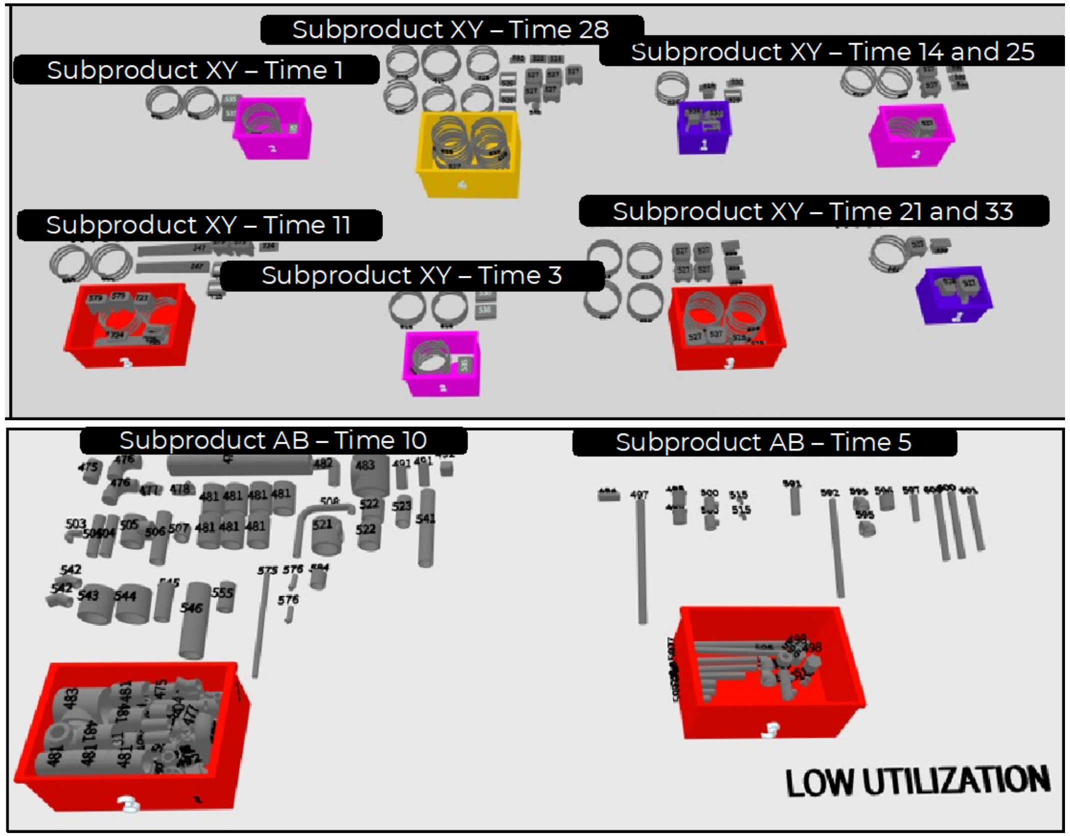


Fig. 2: Illustration of items containerized using VR Approach

Conclusions, Limitations and Future Research

1. It introduces a novel approach to address 3D irregular variants of the bin packing problem
2. The proposed method is flexible (applying to a broad spectrum of object shapes) and precise (not needing to discard important assumptions)
3. Relies heavily on human decision-making, introducing variability in containerization strategies
4. Acknowledges effectiveness at small scales but struggles at larger scales, suggesting potential for research in reinforcement learning techniques
5. Future research could explore training agents via crowdsourcing to collect diverse containerization strategies and optimize their performance

Questions

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