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

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Abstract: *The process of bundling items that need to be together in a container is known as kitting. In the context of Modular Construction (MC), kitting has the potential to streamline productivity since all the necessary parts to complete an assembly will be closed to each other. However, the kit generation process has associated challenges such as dealing with irregularly shaped objects and complex constraints. This paper explores the integration of Virtual Reality (VR) and Building Information Modeling (BIM) to overcome these challenges and develop optimal kitting strategies. Our value proposition involves a Human-VR-driven approach for efficient kit generation. Results indicate that our method not only has the potential to improve volume utilization rates compared to traditional optimization methods but also is capable to produce feasible solutions with less computational expense under specific scenarios. Lastly, this case opens new research opportunities to extend our findings to larger-scale applications.*

Keywords: *Physical Internet, Immersive Technologies, Modular Construction, Virtual Reality, Resilient Supply Chains, Sustainability.*

Physical Internet (PI) Roadmap Fitness*: Select the most relevant area(s) for your paper according to the PI roadmaps adopted in Europe and Japan:☒ PI Nodes (Customer Interfaces, Logistic Hubs, Deployment Centers, Factories),☒ Transportation Equipment, ☐ PI Networks, ☒ System of Logistics Networks, ☐ Vertical Supply Consolidation, ☐ Horizontal Supply Chain Alignment, ☐ Logistics/Commercial Data Platform, ☐ Access and Adoption, ☐ Governance.*

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1 Introduction

Modularity is a key principle in the concept of the Physical Internet (PI). Just as digital information can be partitioned into smaller and standardized units, physical goods can be broken down and then packaged into standardized containers, which can then be effectively routed (Montreuil, et al., 2014). By integrating this principle into Modular Construction (MC), a construction method that parallelizes work between offsite and onsite locations, it is possible to boost MC's strengths in executing parallel operations. Our proposal to enhance MC’s value proposition involves two key components: the Kitting Center (KC) and the Assembly Center (AC). Within the KC, elemental construction components are consolidated into kits, essentially containers carefully designed to bundle only the parts required for specific assemblies at designated workstations and times. This method facilitates their later use in the AC, where workers will only need to focus on performing assemblies with the kits received.

The process of kit generation can be conceptualized as a 3D bin packing problem; therefore, optimization techniques can be employed to obtain solutions. However, existing solutions are often based on numerous assumptions and constraints relaxations to make problems solvable. The aforementioned points are particularly pertinent when dealing with irregularly shaped items of varying weights and materials.

In this paper, we propose moving away from heuristic approaches that produce suboptimal solutions. Instead, we recommend leveraging Virtual Reality (VR) and Building Information Modeling (BIM), an approach commonly used in construction, where all elements necessary for the final product are modeled in a virtual environment using 3D modeling software such as Revit. These virtual assets can then be integrated into VR engines, allowing human agents to interact with them and propose containerization solutions. The human capacity to recognize patterns and employ spatial intelligence makes our feedback valuable for the kitting creation processes, especially when dealing with irregularly shaped objects that are challenging to model accurately with mathematical optimization.

2 Industry Context

To properly introduce the case study and our proposed VR driven containerization framework, it is crucial to understand the operations model to study. For realizing a modular construction project, the architectural team creates the designs, followed by the engineering team developing 3D representations of these proposals. These representations are constructed starting from their most elemental parts, such practice is known as Building Information Modeling (BIM). The information generated in this setting is fundamental because it is a precise representation of every single item that will be used in the construction process and provides details regarding the shape and geometry of the items.

The system to study in this paper consists of a modular construction manufacturing network which includes two main facilities: the KC and the AC. In the KC, one encounters the foundational 3D components utilized in assemblies, hereinafter designated as items. These items are classified into four different categories: i) Containerized, objects of relatively small size suitable for placement in containers like totes or boxes; ii) Sheeting, comprising drywall sheets used for subproduct cladding; iii) Bundle, predominantly consisting of plumbing pipes; and iv) Big, denoting objects with large dimensions like appliances. Our research focus revolves around elements within the 'Containerized' category, as they are the most abundant items and improving their containerization process is vital to improve the flows from the KC to the AC. Moreover, subsequent findings will show the robustness of the proposed framework and demonstrate how to extends these discoveries to the other categories.

Items are consolidated in the KC into containers, referred to as kits, before being shipped to the AC. This consolidation process cannot be arbitrary. To maximize efficiency at the AC, a smart kitting decision strategy must be employed, ensuring that items are logically grouped. One such logical approach is to include components in a kit that are part of a given subproduct (e.g., a wall) within a specified period, and to be assembled by the same team. This criterion, known as Kitting Containerization, is pivotal as it minimizes material handling costs at the AC, and enables transferring workload from the AC to the KC, easing the work of assembly workers which are subject to complex tasks. This strategy intends to improve the productivity in the AC.

Upon their arrival at the AC, the kits are received and processed at designated workstations, where they are transformed into subproducts. These subproducts form the building blocks for the subsequent stage, where they are volumetrically assembled into PODs. Finally, the PODs are combined to form the final modules. Figure 1 illustrates this multi-tiered structure.

Figure 1. Multi-tiered product structure. (a) Example of items designated for consolidation into kits (Source: BREAKA brackets) (b) Representation of Kits prepared for dispatch to AC (Source: Pengoodet shop) (c) An assembled subproduct utilizing its associated kits (Source: coloradosun) (d) Representation of a volumetric

assembly comprising multiple subproducts (Source: coloradosun) (e) Example of final module (Source: https://upsideinnovations.com/prefab-versus-modular-construction/)

3 Problem Description

The operational and logistical dynamics presented in MC propose two major challenges. Firstly, they require synchronizing operations between KC shipments and AC processing, to correctly parallelize manufacturing activities across onsite and offsite locations, propelling for time reduction and efficient space utilization. Secondly, they require the kit containerization plan to be strategically designed to balance the trade-off between maximizing volume utilization in a container and ensuring that only the appropriate items are dispatched within it. This trade-off will be the fundamental problem addressed in this paper.

Traditionally, a common strategy for managing this trade-off is through the application of optimization techniques. This challenge falls under the domain of the *Cutting and Packing Problems (CPP)*, whose three-dimensional variants are well-known for being NP-hard. Further complications in the construction sector include that the items inside a kit may have irregular shapes, such as interconnected tubes, valves, hoses, and connectors. Additionally, the elements required in each workstation can have dramatic changes in sizes, making each kit unique. These additional layers of complexity make conventional optimization techniques hard to solve and might require the adoption of heuristic approaches to obtain good quality solutions in a reasonable time.

These heuristics typically begin by relaxing certain assumptions. In the literature, practitioners who have similar problems often approximate the shapes of irregular items as rectangular prisms. If the resulting assortment is weakly heterogeneous, the problem can be addressed as a *Cutting Stock Problem (C&SP)*; on the other hand, a strongly heterogeneous assortment can be treated as a *3D Bin Packing Problem (3DBPP)*. However, this relaxation comes with a significant drawback: every feasible solution will be suboptimal. Usually, when the process is reversed from prisms to the original shapes, it is found that there is still more space that can be utilized inside the kits. Furthermore, object shapes can be leveraged to overlap pieces together, which is intuitive for humans but challenging to model in a mathematical optimization framework.

Given the NP-hard nature of the problems, it is possible that the previous relaxation is not enough to obtain solutions in polynomial time, and there is a need to further simplify some constraints. Common relaxations for the constraints in the literature include reducing the number of possible rotation orientations of the bins, suppose that all bins are strong enough and it is always possible to stack them vertically, keeping uniform priority among all bins, or assuming that all of them are unloaded at a single destination and that the order of unloading does not pose a problem (Poncelet, 2022).

Finally, one final challenge that arises when a kit containerization plan is obtained through an optimization-heuristic approach is that it becomes difficult to gain visual insights of the 'optimal solution'. Moreover, as we will show later, given that solutions to these approaches are suboptimal, incorporating the human factor is an easy but powerful way to enhance the solution. Under this setting, immersive technologies like Virtual Reality (VR) or Augmented Reality (AR) can play an important role in this regard, as enablers of the creation of virtual environments for testing and refining solutions without incurring additional expenses associated with acquiring and deploying a physical setup.

4 Literature Review

Cutting and packing problems (CPP) have been extensively studied in literature for various reasons, but primarily due to their wide-ranging real-world applications across numerous industries. Additionally, these problems present a high degree of versatility, as even minor variations introduce new and intriguing challenges. Any variant of the CPP will be termed from now on as a subproblem. Identifying the specific subproblem is key since any approach to solve this problem will heavily rely on the proper description of the subproblems. For this reason, it is important to introduce a systematic way to characterize any subproblem, and relevant literature accomplishes this by defining its typology and associated constraints.

4.1 Typology of Cutting and Packing problems

In any CPP problem is possible to identify two sets (Wäscher, et al., 2007):

- A set of large objects (for our case, the kits) that will contain the next set.
- A set of small items (for our case, the pieces used in a workstation).

Using this notion, the authors proposed five criteria to classify a CPP:

- Type of assignment: The primary objectives of any optimization problem are maximization or minimization. In a CPP, a maximization problem arises when researchers aim to allocate a set of small items into a limited (fixed) number of large objects. Conversely, a minimization problem occurs when practitioners seek to allocate the small items using the fewest (dynamical) possible large objects.
- Characterization of small items: According to this typology, small items can be categorized as identical, weakly heterogeneous, or strongly heterogeneous.
- Characterization of large objects: The typology for large items mirrors the one of small items: identical, weakly heterogeneous, or strongly heterogeneous.
- Dimensionality: The problem can be considered in one, two, or three dimensions. The case studied for this paper pertains to a 3D scenario.
- Shape of the small items: It is possible to identify an item with a geometric shape (rectangles, circles, etc.), or the object may have an irregular shape.

The combination of these five criteria generates the basic combinations that exist on a CPP. However, to fully characterize the problem, it is important to also consider the set of constraints.

4.2 Constraints in Cutting and Packing problems

In a literature analysis of the CPP's constraints (Bortfeldt & Wäscher, 2013), it was noted that the primarily focus was on small item's orientation and stability of the large objects, while other constraints such as weight distribution were often overlooked. Extending upon these findings, Ramos et al. (2018) proposed two key points: i) Most attempts to address the CPP have failed because the constraints considered, tend to oversimplify the real case scenarios; ii) the early literature lacked a comprehensive structure to categorize formally the constraints of a CPP. To address this last issue, the authors proposed the constraints classification described below.

4.2.1 Safety constraints

As the name suggests, this type of restrictions is related to conditions that guarantee the well-being of the workers and other actors while loading, handling, and unloading the cargo. At the same time, these limitations are designed to maintain cargo integrity. In this group the following constraints are considered:

- Weight limit constraints: Indicate the maximum weight capacity of a large object.
- Weight distribution constraints: Detail how weight should be spread within the large object. Typically, the weight is evenly distributed across the floor, but this may vary based on the object that works as a container.
- Orientation constraints: Specify permissible orientation variations for small items. This could range from allowing six different orientations (any rotation in 3D) to disallowing any single orientation change (preloaded pallets for example).

- Stacking constraints: Limit the number of small items that can be placed on top of each other.
- Physical positioning constraints: Restrict the placement of specific small items within the large object, for example placing the largest small item at the bottom of a bin.
- Stability constraints: Designed to ensure the safety of cargo operators during loading/unloading operations by ensuring that small items are fully supported by the bottom side of the large object when stacked.

4.2.2 Logistic constraints

These restrictions pertain to operational decisions rather than the physical properties of the objects. Within this set, the following are considered:

- Loading priorities constraints: In this setting, the number of large objects is fixed and limited, but there is a degree of priority among the small items. The overall solution assigns various levels of importance when creating the loading plan.
- Complete shipment constraints: Assume that either all items will be loaded in the same shipment or none at all. This is useful to ensure that all items for a company are placed together.
- Allocation constraints: Prevent small items from being placed in the same large container because of their nature.
- Customer positioning constraints: Facilitate bundling a set of small items together or within a predefined distance to expedite the unloading process, assuming all these objects belong to a specific company.
- Complexity constraints: Related to the level of difficulty that represents for a robot or a worker to learn the loading pattern.

As shown, the universe of subproblems that may exist is extensive and is given by the combination of typology and the two sets of constraints. However, the subset of problems studied in literature has primarily focused on safety constraints and variations of the first three criteria of the typology (Bortfeldt & Wäscher, 2013). For the fourth criterion, most studies only analyze the 1-dimensional and 2-dimensional problems. Regarding the fifth criterion, typically, the objects involved are considered with a well-defined geometric shape. It is precisely in these last two points where the literature presents a significant gap since the study of irregular and 3-dimensional objects remains underexplored.

To tackle the problem of 3-dimensional and irregular objects, practitioners typically begin by studying the 2D case and then attempt to extend these heuristics. In this line, one of the earliest proposals to address this problem was the no-fit Polygon (Art, 1966). This method performs effectively with convex objects, and several updates of this method were introduced to address the non-convex case, although they come with significant computationally costs (See Bennell, et al., 2001 and Dean, et al., 2006). Another common method is the Raster Method (Oliveira & Ferreira, 1993), where objects are represented by a grid and leverage binary variables to indicate if a cell is part of the piece or not. This method can address non-convex cases more effectively, but the trade-off is the inability to accurately represent an object, being memory-intensive, and remaining computationally expensive.

Since the previous alternatives require approximating the object, other methods have been developed aimed to preserve their true geometry. One such method is the D-function (Konopasek, 1981) which computes distances using the relative position of a point P, that corresponds to one object, with respect to an edge AB from another object. Based on the resulting distance, several cases are considered along with an algorithm indicating how to proceed while placing both items. Another widely used method in literature is the Phi-function method, leveraging the concept of ‘phi-objects’ in topology. Under this premise, phi objects can be primary or composed (where the composed can be described as the union of primary objects). Objects are then described using linear, non-linear, and piecewise inequalities. The proper placement is defined trying to minimize the Euclidean distance (Leao, et al., 2020).

All these approaches can be extended to the 3D case, but the results often tend to be suboptimal (Huwei, et al., 2023). Addressing the non-polyhedral case then implies the need to explore new alternatives that, instead of relying on restrictive rules based on geometry—which is challenging to represent—adopt a more self-optimizing strategy. It is within this line of thought that the most recent publications are emerging. Harrath (2022) proposed a three-stage heuristic algorithm for packing 'n' different items into the least number of boxes, considering the rotation of objects in any direction and balance constraints. Shuai et al. (2023) introduced a novel algorithm allowing for the self-correction of packed items using various sensors. Zhao et al. (2021) approached the 3D bin packing problem as a MDP and employed deep reinforcement learning techniques to obtain a solution. It is evident from these recent studies that technology plays a crucial role in seeking innovative solutions, and the subsequent literature section will be related to the approach proposed in this study: Virtual Reality for the 3-dimensional and irregular objects case.

4.3 Virtual Reality for irregular shaped objects containerization

Traditionally, VR literature has focused on the potential of VR for training, especially in cases where real-life scenarios are expensive, difficult to replicate, or pose significant risks. However, researchers have recently expanded their analysis of VR to other settings. Among these, the logistics processes have emerged as promising candidates due to its potential in the traditional lines of VR research - such as training for warehouses and design of assembly lines (Lucas & Thabet, 2008) - but also it offers opportunities in non-traditional lines of VR research - such as exploring the potential in item containerization and performance analysis.

Among the non-traditional applications of VR in logistics, this paper focuses on analyzing the implications of employing this technology in the containerization of irregularly shaped 3D objects. Since this idea is relatively new, the existing literature on this topic is scarce. Moreover, literature predominantly explores the use of another immersive technology, Augmented Reality (AR). For instance, Poncelet (2022) developed a method utilizing AR to visualize the proper placement of items within a container, ensuring compliance with stability, weight, and orientation constraints. Jaoua et al. (2023) generated a more comprehensive approach, first developing an optimization module that identifies the ideal location for each item while respecting constraints related to stability, weight, and dimensions. Leveraging this optimization module, a visualization module in AR was created to verify the placement. It is worth noting that both solutions are specifically designed for items with regular shapes.

To the best of our knowledge, the only paper addressing the 3D irregular shape problem using VR is found in Zhao et al. (2021), the authors proposed a comparison of packing efficiency when training individuals to pack both regular and irregular objects using VR. It is important to note that their primary concern was not to optimize containerization, but rather to understand the nuances while training for packing different shapes. Lastly, it is important to highlight that the 3D bin packing problem in the context of construction has remain understudied.

5 Methodology

In this paper, the formulation introduced in (Grover & Montreuil, 2021) serves as the starting point. This formulation proposes a two-stage optimization approach. In the first stage incoming parcels are assigned to a departing vehicle. Once this initial step is completed, the second stage focuses on loading parcels in containers which then are loaded into the assigned vehicle. Is important to highlight two considerations of this formulation: i) It assumes regular-shaped 3D items, and ii) The overall objective of this model aims to minimize empty volume and does not consider other aspects such as the placement of items that need to be together.

From the outset, our objective has been to address the issue of containerizing irregularly shaped 3D items while considering a kitting strategy, neither of which have been considered in the previous formulation. However, it is important to note that solving the second stage of the problem offers a solution for our case when relaxing the constraints of irregular shapes items and permitting items that need to be together (in a kit) to be spatially separated. The rationale behind initially allowing this relaxation stems from our literature review findings, which suggest that methods attempting to replicate the specific geometry of items often result in overly constrained models or situations that are nearly impossible to model. Doing this relaxation does not imply that we will overlook these challenges; rather, it means that we will approach them from a distinct perspective.

Since the studied company leverages on BIM technology, all components associated with a modular unit have been meticulously modeled in a CAD software named Revit, this ensures exact virtual replicas of every item. Furthermore, it is possible to perform a virtual decomposition of each modular unit into subproducts and generate a list of items associated with each one, this capability enables to define which items need to be placed together in a kit. Another advantage is that these virtual items can be easily exported to any VR engine compatible software such as Unity or Gravity, this allows to represent and interact with any kitting solution in an immersive environment. The final advantage is that all these items can be converted into 3D regular shape objects without difficulty, allowing us to use the initial formulation and obtain an initial solution. Once we have this solution, we can further refine it with the original items in a safe virtual environment generated in VR. Figure 2 provide a schematic representation of this loop.

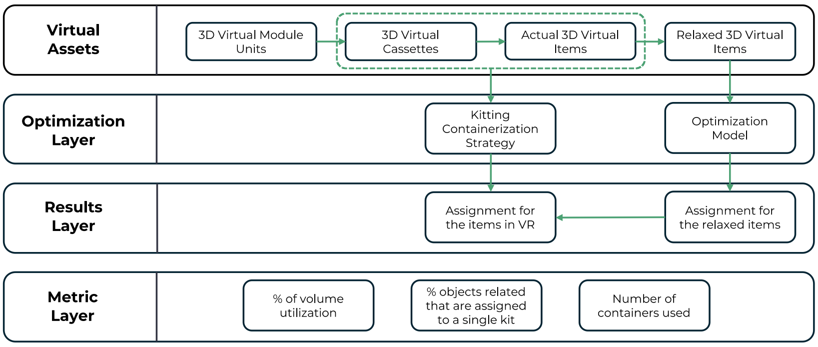

Figure 2. Proposed framework for the improved assignment using VR.

6 Experimental setup and results

6.1 3D Objects (Items)

Items are fundamental for the study; they determine the optimization model's performance and play a crucial role when interacting in VR. Information from an industry partner regarding all the constituent elements of a modular unit was used for this study exported from Revit. The next step involved decomposing this unit until we reached the level of items. From this disassembly, artificial labels were generated to help us track which elements should be grouped together, as they are part of the same subproduct and are used in a certain time (See Figure 3).

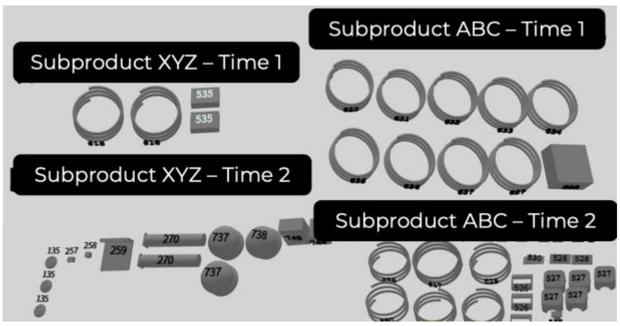

Figure 3. Illustration of containerized items associated with different subproducts and used at various times

Additionally, during this decomposition, we encountered several types of items. For the purposes of this study, we excluded ‘Sheeting,’ ‘Bundle,’ and ‘Big’ items, focusing exclusively on items in the ‘Containerized’ category.

Another important aspect to highlight is that, as previously explained, a simplified representation of each item was used, while maintaining the geometry of the object. To achieve this, we considered the farthest points on each side of the object and constructed a face from them. The resulting prism is the union of these six faces.

6.2 Virtual Reality Setting

Given that all the 3D models of the items were accessible in Revit, the following stage was to make them available on a VR appropriate platform. We opted for Gravity Sketch (GS), an immersive environment tool recognized for its versatility, user-friendly interface, and compatibility with Revit. The next step involves exporting the items in. fbx format and importing them into GS.

In the VR environment, a 30-year-old male participant, with prior experience in using immersive tools, begins by manually grasping objects whose labels indicate they belong together in a kit. These objects are then placed into a container chosen by the participant based on their understanding of what constitutes the correct container size. A kit is considered complete when there are no more objects to add that share the same label. If there are additional objects but the kit is full, the participant decides if the kit will be split in multiple containers or to use a bigger container. If the container picked was the largest available, then the participant will select an additional container to accommodate the remaining items. The experiment concludes when there are no more remaining items to add to any kit.

6.3 Results

Our findings demonstrate that it is possible to generate a reasonable kitting containerization strategy exclusively using VR. The subject only knows the label and must make decisions about which container to use from a set of available containers by visually matching items to containers based on his experience. The instance used consisted of 747 items to be organized into 96 kits for which the required time to containerize did not exceed 4 hours for the first iteration, resulting in 108 containers being used for the containerization, including Bundle, Big, Containerized, and Sheeting kits. This suggests that with more training, practice, and knowledge, this time could be further reduced.

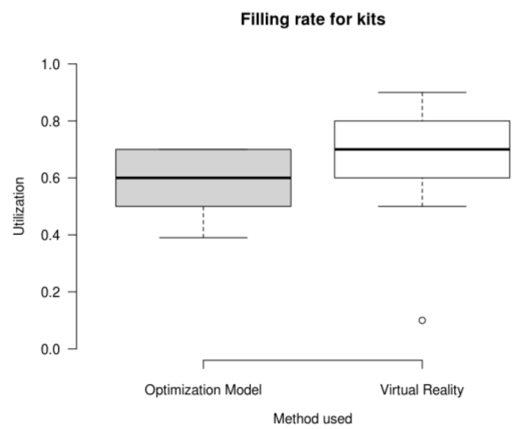

Figure 4: Comparison between the two containerization methods

In various scenarios, using the optimization model described in section 5, the model exceeded by far the time used by the human, only to package 457 ‘Containerized’ items into 38 containers. To reduce the time required by the optimization model, an optimization-based heuristic was implemented. This heuristic involves manually splitting kits containing more than 14 items into multiple kits before running the optimization model based on the shapes of the items. It was identified that for this number of components, splitting the container load didn’t significantly impact the container utilization. Additionally, the model still took a considerable amount of time to find suitable containers, but there was a reduction in the model's runtime from hours to minutes. However, it is important to remember that the model uses a simplification of all items and assumes that all objects are prisms, which compound the impacts of the low utilization of the kits.

Regarding this last point, when comparing both methods, our approach using VR significantly outperforms the optimization approach. This superiority is evident not only in terms of average utilization but also in the kits with the highest utilization, reaching up to 93% utilization in some cases, whereas the results of the optimization model never exceeded 70% utilization. Even when comparing the weakest performers (first quartile), better results are observed.

It is worth mentioning that there are cases where VR shows kits with low utilization. A deeper analysis identified that the set of available containers was not efficient for elongated objects, such as pipes (Refer to Figure 5 Kit Subproduct AB-Time 5). Additionally, the Kit Subproduct AB-Time 10 which was containerized in two of the red boxes with the optimization model could be packed in a single container given the opportunity to overlap items due to their shape. These types of insights were also an advantage of using the VR methodology, which are way harder to achieve from the results of the optimization model or even nor reachable at all.

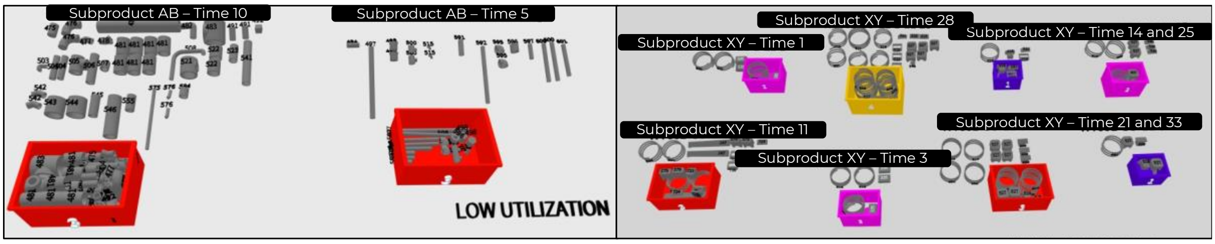

Figure 5: Results of VR containerization kits

7 Conclusions

In this paper, the primary contributions are as follows: Firstly, it introduces a novel perspective for addressing the 3D irregular variants of CPP problems by integrating VR and BIM (which strongly leverage modular principles of PI) into the containerization process. Furthermore, it demonstrates that incorporating available technology notably improves cargo consolidation, which serves as a strong incentive for companies to decide to invest in new practices.

Secondly, the method presented distinguishes itself for its flexibility and precision. It is deemed flexible because it can be applied to a broad spectrum of object assortments, encompassing both regular and irregular shapes, as well as identical, weakly heterogeneous, or strongly heterogeneous types of objects. Its precision is asserted by its independence from constraint relaxations or the need to discard important assumptions. The utilization metric obtained through our VR method will be reliable, as it closely mirrors real-world settings.

Another noteworthy aspect is the research avenues proposed by this paper. An immediate extension is the application of this framework to analyze other types of items not included in the study. One interesting case is the ‘Bundle’ category, where arranging tubes within other tubes is possible - a task challenging for optimization approaches but straightforward for humans.

However, our approach also has limitations. It heavily relies on human decision-making, and while the decisions have proven to be correct in our case study and have improved utilization, this may not hold true for another individual. In other words, the human element introduces variability that complicates extrapolating results. Additionally, even with exceptional human performance, it is challenging to envision a person creating hundreds or thousands of kits—a common scenario in other industries that are part of hyperconnected networks serving multiple clients. Nonetheless, this limitation offers a promising avenue for research, which involves integrating reinforcement learning techniques. Specifically, an agent could be trained to learn from human decisions. Once trained, this agent could autonomously make containerization decisions, likely resulting in more efficient outcomes on larger scales.

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