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Shipping Configuration Optimization with Topology-Based Guided Local Search for Irregular Shaped Shipments

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SHIPPING CONFIGURATION OPTIMIZATION WITH TOPOLOGY-BASED GUIDED LOCAL SEARCH FOR IRREGULAR SHAPED SHIPMENTS

For the degree of Doctor of Philosophy

Is approved by the final examining committee:

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SHIPPING CONFIGURATION OPTIMIZATION WITH TOPOLOGY-BASED GUIDED LOCAL SEARCH FOR IRREGULAR SHAPED SHIPMENTS

A Dissertation
Submitted to the Faculty
of
Purdue University
by
Xinyue Chang

In Partial Fulfillment of the
Requirements for the Degree
of
Doctor of Philosophy

May 2015
Purdue University
West Lafayette, Indiana

Dedicated to my beloved family, friends, and all those who helped me in my life

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ABBREVIATIONS

AABB	Axle-Aligned Bounding Box
CAD	Computer-Aided Design
CFR	Collision Free Region
CKD	Complete-Knockdown
CLP	Container Loading Problems
COG	Center of Gravity
CPU	Central Processing Unit
EDM	Evaluation Decision Method
FDM	Forced Decision Matrix
FEA	Finite Element Analysis
FIFO	First-In-First-Out
GLS	Guided Local Search
GPU	Graphics Processing Unit
HC	Heavy Core (shipment modules)
HM	Heavy Minor (shipment modules)
IFP	Inner-Fit Polygon
ISO	International Organization for Standardization
KDK	Knockdown Kit
KPI	Key Performance Indicator
LC	Light Core (shipment modules)
LM	Light Minor (shipment modules)
max.	Maximize/ Maximization
min.	Minimize/ Minimization
MOI	Moment of Inertia

NASA	National Aeronautics and Space Administration
NFP	No-Fit Polygon
OBB	Oriented Bounding Box
P-Module	Pallet Module
SKD	Semi-Knockdown
TEU	Twenty-foot Equivalent Unit
TRL	Technology Readiness Levels
USDOT	United States Department of Transportation

ABSTRACT

Chang, Xinyue Ph.D., Purdue University, May 2015. Shipping Configuration Optimization with Topology-Based Guided Local Search for Irregular Shaped Shipments. Major Professor: Haiyan H. Zhang.

Manufacturer that uses containers to ship products always works to optimize the space inside the containers. Container loading problems (CLP) are widely encountered in forms of raw material flow and handling, product shipments, warehouse management, facility floor planning, as well as strip-packing nesting problems. Investigations and research conducted two decades ago were logistic orientated, on the basis of the empirical approaches. Starting from the late 1990s, researchers and experts in disciplines, such as mathematics, computer science, and industrial engineering, actively participated in the developments of solutions to CLP. Their contributions are mainly in the areas of typological analyses, heuristic methods, and optimization. However, even in the mid-2010s, the gaps between those research contributions and the applicable level of problem-solving methods for industry are still tremendously huge. Especially, the majority of existing theoretical solutions fall short in the real-world applications due to the incapability of handling irregular shapes in three-dimensional space. To tackle this shortcoming, this research presents a topology-based metaheuristic approach that simplifies both the irregular shapes and the optimization process. Real-world data and constraints are applied to test the validity of this metaheuristic approach, such as compatibility between commodities, orientation limitations, etc.

This research is a project of Center for Technology Development (CTD), sponsored by American Axle Manufacturing, Deere & Company, Eaton, and

Faurecia. Within the work scope of this research, two distinctive CLP scenarios are constructed. One scenario is the Shipping Configuration Optimization (SCO), targeting the containerization processes of shipping raw materials and irregular shaped Semi-Knockdown (SKD) modules. The generalized constraints of this scenario are custom and highway regulations, availability of the facilities, labor cost, easiness of loading and unloading, etc. The other scenario is Warehouse and Facility Optimization (WFO). The goal of this scenario was to enhance the efficiency of shelf usage, reduce the floor occupation, corresponding to the change of demands, production plans, regulations, et cetera.

The developed metaheuristic approach utilizes topological spatial optimization to handle the complexities related to the three-dimensional irregular shapes. Those irregular shaped items are pixelated into three-dimensional envelop shapes, in which some clearances are added onto the original shapes to ensure the final plan is free of interference. In order to deal with the huge amount of combinations of shipping configurations, this approach applies topology-based category optimization and path optimizations to the existing guided local search (GLS). Topology-based category optimization and path optimization significantly reduce the total number of the possible configuration combinations that need to be analyzed, evaluated, and validated.

To test the metaheuristic approach, a proof-of-concept end-user program for engineers that implement the heuristic method is designed and developed.Pilot tests using real world data and conditions from the industrial members of CTD are conducted. The proposed heuristic method satisfactorily takes the constraints into account and generated optimal shipping configurations which cannot be obtained from previous research.

CHAPTER 1. INTRODUCTION

In Chapter 1, the background of this research will be presented, along with the motivations behind this research. This chapter will also construct the foundations of this particular research, including objective, limitations & delimitations, and several assumptions that support the validities of this research. Moreover, definitions to several terms that are either core terms or frequently used ones will be provided as references to the later chapters regarding to the exact meaning of them. Last but not least, the structural layout of this dissertation will be illustrated in the last section in this chapter.

1.1 Background

Since early-1990s, the intense globalization and technology development rapidly increased the demand of shipping commodities across the world for nearly every industry. Due to industry's elevated dependency of shipping, the cost of shipping products takes away a significant portion of the monetary profit (Angeli, 1995; Silay, Dehollain, & Declercq, 2011; B. J. Singh, Krasowski, & Singh, 2011; B. J. Singh et al., 2011; Smith, 2003; Zhao, 2007). The profit of a product is a part of its price by taking away production cost. Operation & maintenance cost is a part of life period cost, which may generate follow-up values to the manufacturer, such as the ink cartridges from printer manufacturers. The rate of cost increment associated with shipping reflects the characteristic of shipping activities to some extend, for example, adding large scale of cost in the relatively short time period compared to the manufacturing process (B. Y. Wang et al., 2010). It is understandable and reasonable that manufacturers are desperate to save more on shipping.

Figure 1.1 illustrates the general cost compositions during the life cycle of a product. In this plot, one should distinguish the differences between the regions marked as profit (on the left-hand-side) and operation & maintenance cost (on the right-hand-side).

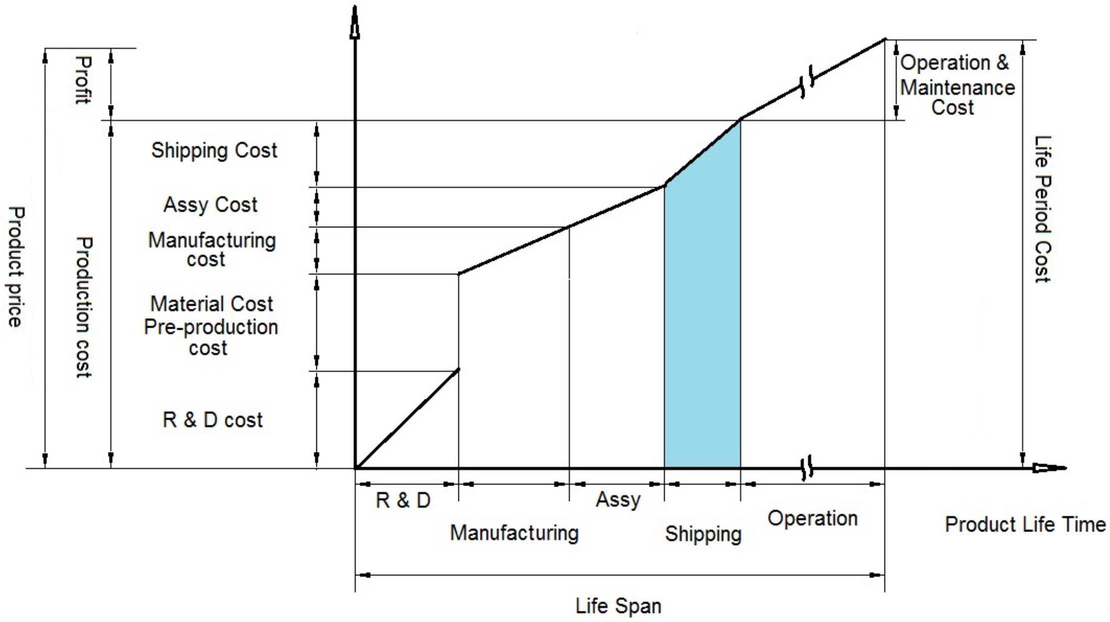
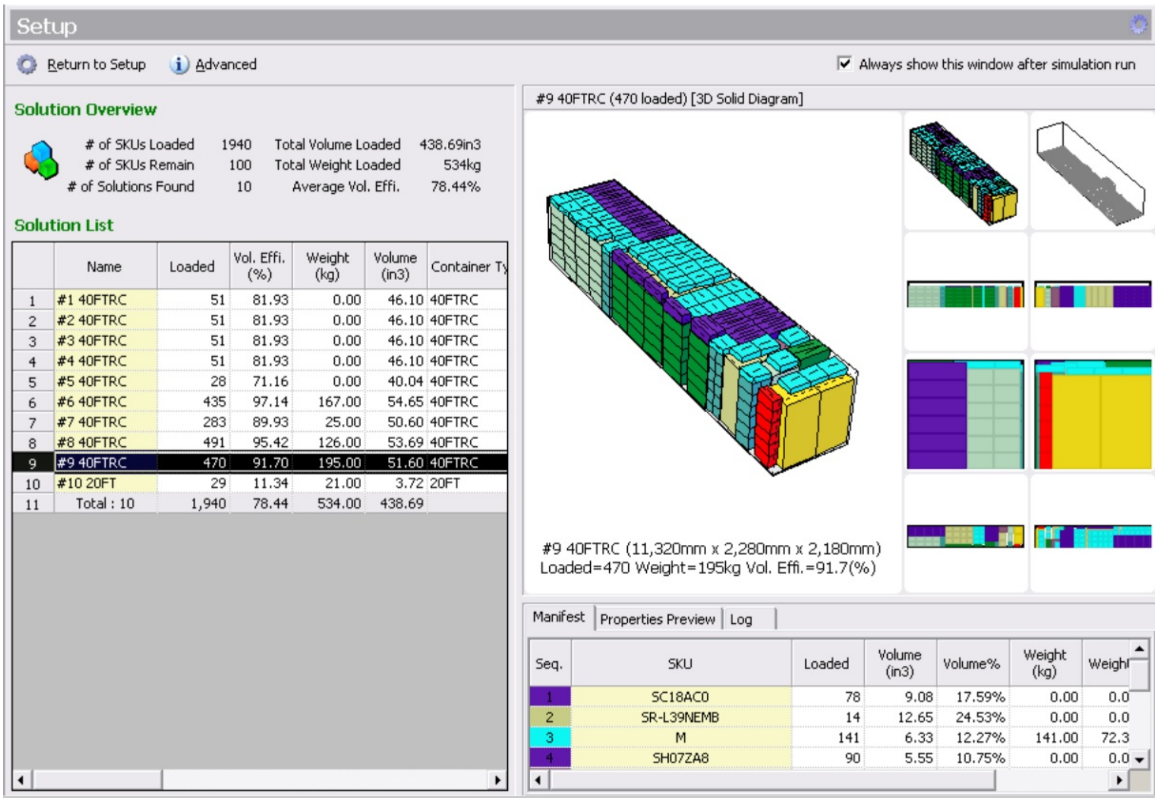


Figure 1.1. The compositions of product cost through the product life cycle.

There are large numbers of software tools available in the market, which put as many regular shape shipments as possible into shipping containers. In general, regular shape shipments are referred to those with relatively simple contour. Figure 1.2 shows a screen shot captured from the user guide of CubeMaster Professional, one of the leading container loading software programs, developed by Logen-Solutions (2008, 2011).

However, dilemmas that companies become concerned are far more complicated than what the available software tools can accomplish. According to the shipping configuration experts from Deere & Company, there are huge amounts of factors that make the dilemmas extremely difficult to be addresses, such as highway axle loading limitation, port custom regulations, insurance, container



Solution Overview

# of SKUs Loaded	1940	Total Volume Loaded	438.69in3
# of SKUs Remain	100	Total Weight Loaded	534kg
# of Solutions Found	10	Average Vol. Effi.	78.44%

Solution List

	Name	Loaded	Vol. Effi. (%)	Weight (kg)	Volume (in3)	Container Ty
1	#1 40FTRC	51	81.93	0.00	46.10	40FTRC
2	#2 40FTRC	51	81.93	0.00	46.10	40FTRC
3	#3 40FTRC	51	81.93	0.00	46.10	40FTRC
4	#4 40FTRC	51	81.93	0.00	46.10	40FTRC
5	#5 40FTRC	28	71.16	0.00	40.04	40FTRC
6	#6 40FTRC	435	97.14	167.00	54.65	40FTRC
7	#7 40FTRC	283	89.93	25.00	50.60	40FTRC
8	#8 40FTRC	491	95.42	126.00	53.69	40FTRC
9	#9 40FTRC	470	91.70	195.00	51.60	40FTRC
10	#10 20FT	29	11.34	21.00	3.72	20FT
11	Total : 10	1,940	78.44	534.00	438.69	

#9 40FTRC (11,320mm x 2,280mm x 2,180mm)
Loaded=470 Weight=195kg Vol. Effi.=91.7(%)

Seq.	SKU	Loaded	Volume (in3)	Volume%	Weight (kg)	Weigh
1	SC18AC0	78	9.08	17.59%	0.00	0.0
2	SR-L39NEMB	14	12.65	24.53%	0.00	0.0
3	M	141	6.33	12.27%	141.00	72.3
4	SH07ZA8	90	5.55	10.75%	0.00	0.0

Figure 1.2. It is obviously shown in this figure that only cuboid, rectangular shapes are optimized by CubeMaster (Logen-Solutions, 2008).

loading labor cost, loading facility cost, and hazardous regulations, etc. Taking the all real world factors into consideration, a shipment of million-dollar products may finally make no profit to the manufacturer or even loss money. Shipping configurations can be considered as valid only if they manage to satisfy all required constraints. Figuring out a valid shipping configuration with high enough container loading density is a time consuming and tedious process. For instance, according to the statistical date from industrial partners of this research, the shipping configurations are determined by trial-and-error process for each model of their entire product family. Moreover, engineers need to perform the same processes again if any modifications were made to the products, or even regulations involved. Including negotiations between the engineers and custom authorities, the total time needed for nailing down a shipping configuration can range from 3 to 8 weeks, depending on the complexity of the product.

Therefore, methods that can help the engineers to tackle the real world scenarios should at least manage to

- recognize irregular shaped shipments as non-regular equivalences,
- generate container layout that utilize the container's volume,
- satisfy all given constraints database including all regulations, physical and company defined constraints, and
- shorten the time consumed when finding out valid configurations.

From a manufacturer standpoint, shipping unassembled parts should reduce the difficulties encountered than shipping the whole product units. Miller (2000) mentioned that knockdown (KD) is a supplying method that including all necessary parts as kits in the shipment back from the World War II. Upon introducing KD, automobile and aircraft industries actively adopted a form of KD called complete knockdown (CKD). In the shipments of CKD, parts are never previously build up, freshly from suppliers. That is to say, engineers and workers in the shipment destinations need to assemble the product literally from scratches. Manufacturers soon revealed that large number of specialists related to assembling were needed in destination regions. Moreover, the intellectual properties and assembling quality of core subassemblies were difficult to retain (Miller, 2000). Starting less than two decades ago, manufacturers who have very large products experimented the method of shipping products in subassemblies instead of unbuilt parts. Semi-knockdown (SKD) are subassemblies sufficiently small to be placed in containers, and large enough to minimize the disassembling and reassembling costs. Semi-knockdown modules are disassembled from fully assembled products, with test run performed prior to disassembling actions. By working in this way, over-sized products can be transported inside the containers with a significant lower price, compared with on specifically designed over-sized carriers. Furthermore, SKD modules are SKD that designed to be interchangeable within or across the models of a family of products.

The above background information, comparison of what industry needs and what the current shipping configuration software tools can provide, demonstrates obvious mismatches between demand and supply. Therefore, the statement of the problem can be formed in order to initiate the discussion of shipping configuration optimization with irregular shaped shipments.

1.2 Statement of the Problem

The problem this research targets is a comprehensive one, coupling several sub-problems. Due to the lack of previous research in taking irregular shapes into account of container loading problem (Bortfeldt & Wäscher, 2012), there is no systematic overview of heuristic methods focusing on irregular shapes, especially in three-dimensional space. Container loading software tools in the market deal with boxes and sometime cylinders. The cut-off rule for regular and irregular shapes is not clear enough for engineers and researchers to choose suitable methods for tackling container loading problems. Shipping experts from industrial partners reveal several more constraints that had not been mentioned in previous research, such as compatibility of commodity code. Therefore, whether there are more commonly encountered constraints unrevealed appears to be another problem. In industry, planning loading schemes of containers in involves trial-and-error searching performed by engineers. Those trial-and-error searching experiences are very similar to paths from topology standpoint (Bendsoe & Sigmund, 2003). Intuitively, topology might be able to simplify the repetitive trial-and-error searching, as well as handling irregular shapes. Topology also provides a different thinking pattern compared to the previous research in container loading problem. Similar to using topological invariant to verify the homeomorphic relationship between spaces, engineers may utilize topological properties to categorize the searching paths in purpose of reducing to searching efforts (Armstrong, 1983).

1.3 Research Objective

According to the problems that pointed out above, this research sets the scope to the following objectives.

1. Review all available heuristic methods which focus on irregular shapes.
2. Clarify the criteria for distinguishing regular and irregular shapes, in both two- and three-dimensional spaces.
3. Understanding container loading problem constraints and their mechanisms, especially for irregular shapes.
4. Represent container loading problem from topology aspect.
5. Apply the topological invariant concept to the optimization process of container loading problem.
6. Generate metaheuristic approach for handling irregular shapes in container loading problem.
7. Use the industrial cases to verify the metaheuristic approach.

1.4 Assumptions

In this research, there are several assumptions need to be stated in advance. These assumptions indeed simplified the scenario in this research from the real world conditions. However, these assumption are widely accepted in industry (World-Trade-Press, 2008), that the significance of this research should still hold.

- The edge of the containers inner boundaries are considered as straight, instead of corrugated one. This reason for setting this assumption is that the possibility of utilizing those space generated by corrugating straight edge is too small in real world practice.

- Due to considering irregular shaped SKD modules as irregular shapes, this research assumes there are enough pallets, boxes, or other dunnage available whenever there is a need.

- It is assumed that pallets and racks are strong enough to hold SKD modules on a given pallet or rack.

- When placing SKD modules into containers, engineers need suitable dunnage and fasteners to hold the modules in place. Because of focusing on placing irregular shapes, this research assumes there exists suitable pallets, racks, boxes, and fasteners available for engineers. Therefore, this research does not cover designing dunnage in detail.

- This research takes one real product, the 9000R tractor, from Deere & Company and corresponding shipping constraints into investigation. With consensus from Deere & Company, this research uses three-dimensional computer-aided design files of SKD modules that involved in 9000R tractors for all image manipulations required for the meta-heuristic approaches.

- The computational time that involving computer programming and calculations are assumed to be obtained from the desktop computer in the Multidisciplinary Design Lab (MDL) supervised by Prof. Haiyan Zhang. The desktop computer has the following specifications: Intel® Core™ i7-3770 CPU @ 3.40 GHz with 8.00 GB installed RAM.

1.5 Limitations

The lack of previous research on involving multiple real world constraints along with irregular shape container loading problems was pointed out by Bortfeldt and Wäscher (2012). The developed meta-heuristic method holds a novel approach that handling constraints before placing irregular shaped items. That is to say, the boundary conditions for the optimization approach used in this research will be nulled if container empty space is the only constraint. Also, this research will base on algorithms in previous research and modify those algorithms corresponding to the approach. The major modification to the existing algorithms is enabling them to perform optimization with compiled multiple real world constraints as boundary conditions, which those existing algorithms did not capable to consider. Therefore, comparisons of algorithm speed between proposed algorithm and existing ones are meaningless

This research mainly focuses on simplifying irregular shapes and search paths. All constraints that considered in the metaheuristic approach are industry oriented. In other words, this value of this exact approach is limited if one encounters constraints or search paths that are different from those mentioned in this approach.

Loading stability is one of the most complicated constraints in container loading problems. Situations involve both static and dynamic stability of the loaded pallets, as well as containers, under different transportation conditions. Due to the limit of time and experiences, handling dynamic stability constraints will not be investigated in detail. However, general information and concerns are provided as a reference for future research.

In order to consider a three-dimensional space constraint, this research uses rectangular close top containers as examples. Discussions are simplified by using only rectangular close top containers.

1.6 Delimitations

The three-dimensional rectangular container shape represents not only shipping containers, but also any rectangular shape with three-dimensional size constraints. Therefore, the proposed approach can be generalized to any two- and three-dimensional rectangular empty space.

Recognition and simplification of SKD modules can be expanded to other companies or industries involving shipments of large and complicated shapes. The spatial loading approach can be applied to all the logistic related industries, dealing with various objects. The custom and highway regulations that the researcher has access to are from United States and Russia. However, constraints database can be expended by including other countries. Future research may embed more customized algorithms or heuristic methods into the one proposed in this research in order to fulfill other unique tasks.

1.7 Significance & Purpose

From the starting point of this research, systematically reviewing container loading problem from the irregular shaped shipment perspective not only emphasizes the lack of attention to this area, but also points out the possible future research directions. Clarification to the criteria of distinguishing regular and irregular shapes will provide in depth understanding of the underlying differences between regular and irregular shapes. Moreover, due to the status of definition of irregular shape, the proposed criteria may be used as references to establish a more advanced typology of shapes, especially for research in container loading problem field.

The concept of topological invariant may lead to wider applications of topological thinking in other interdisciplinary and multidisciplinary problems. Visual topology and intuitive topology can be used in product appearance design and functional design (Fesanghary & Khonsari, 2012; Gupta & Dally, 2006; S. Huang & Cheng, 2012). Algebraic topology can be employed to express spatial or physical problems in algebraic words, which may be able to find the solution much easier than in original domain.

The result of this research benefits the industrial partners who often ship SKD modules in containers by cutting shipping and time related expenses, reducing potential damages due to interferences between SKD modules, enlightening further development of proposed approach to fit customized needs (Chikwendu, Emenonye, & Nwankwo, 2014; Hofstetter, Gupta, Bitting, & U.S. Army Research Laboratory., 2010). On one hand, the metaheuristic approach enables generating optimized shipping configuration that satisfies all predefined constraints without physical trial-and-error. On the other hand, even if the shipping configuration generated by the metaheuristic approach was the same as the one by trial-and-error, the lead time saved by adopting this approach indirectly increase the profit margin for the products.

1.8 Summary

In this section, the reasons for conducting this research and its significance are discussed. Multiple questions are raised when looking into the current mismatch condition between the industrial needs and container loading software tools' performance. Potential development direction of this research is also introduced, including topological simplifications and multidisciplinary concepts. Several by-products of this research should be able to explain confusions in the process of loading SKD modules overseas. Expectations and assumptions, as well as all limitations, are listed in this chapter at the authors best knowledge. The author also explains some of the key terms that frequently occur in this field, such as semi-knockdown modules.

1.9 Dissertation Outline

Chapter 2 reviews the relevant literature in the field of container loading problem, with attention focusing on handling irregular shaped shipments. Before diving down into the existing algorithms, typology of container loading problem will be introduced in detail in the purpose of providing clear definitions to the different types of container loading problems. Research efforts paid on dealing with irregular shaped shipment and other container loading problem (two- and three-dimensional) will be investigated in order to specify usable approaches.

Chapter 3 decomposes the shipping process in detail from disassembling to SKD modules to containerization. General ideas of image manipulations which simplifying the irregular shaped shipments will be discussed. Moreover, an evaluation system with key performance indicator and forced decision making process will be used to evaluate the shipping configurations.

Chapter 4 experiments using topological concepts to represent irregular shapes and container loading problem, which will be used in Chapter 5 to enable the construction of envelop shapes for irregular objects using topology-based pixelation. The topological representation also helps modify existing guided local search to topology-based guided local search with sextuple-tree model and industrial constraint oriented seeding search.

In Chapter 7 and Chapter 8, the metaheuristic approach is adopted to solve real world cases of shipping configuration optimization with John Deere and warehouse optimization with American Axle Manufacturing.

Last but not least, chapter 9 points out the original contribution of this dissertation towards the research and industry. Chapter 9 concludes the dissertation with a conclusion and the illumination of future research directions.

CHAPTER 2. REVIEW OF LITERATURE

Modern steel reusable containers were first introduced in 1956, while the concept of containerization was published even earlier (Notteboom & Rodrigue, 2008). Container loading problem (CLP) did not significantly draw attention from different sectors in the industry until the recent 20 years (Bortfeldt & Wäscher, 2012). CLP is more and more crucial because that people has been asking the question of how containerize can be more efficiently to adapt the increasing shipping cost since the world political and economic patterns changed dramatically in early 1990s.

Also in this chapter, the historical research road map will be discussed, such as the steps of diving into more specific problems in the field and the consequential problems. During the recent two decades, major achievements were focused on developing algorithms that dealing with regular shaped shipment items. Bortfeldt and Wäscher (2012) statistically measured that only 1.8% of a total number about 200 articles in the field from 1980 to 2011 that particularly investigated irregular shaped shipments in CLP. Compared with regular shaped shipments, irregular shaped objects are more challenging in terms of their complex contours and the non-geometrical centered locations of their center of gravity (CoG). Bortfeldt and Wäscher (2012) mentioned that there were several related works that adapted irregular shape fitting in two-dimensional cases in other fields, which provided inspirations to this research.

Even the container in CLP represents a certain empty space with well-defined dimensions, familiarizing the actual steel reusable containers should build a better foundation for later discussion. Then, discussions will continue on achievements that were accomplished in the field of CLP, where a lot of heuristic methods found to be very important for this research.

2.1 Familiarize with Sea Containers

Sea container is a broad name that refers to those reusable containers carried by container vessels around the world. Because of introduced for sea transportation, the name retains even those containers are used for nearly all kinds of transportations (Miller, 2000). Containers can be categorized by their size. Commonly used containers are listed in Table 2.1, with information provided by Hapag-Lloyd (2008).

Table 2.1: External dimensions of the common containers for shipment

Size	Length (m)	Width (m)	Height (m)	TEU
20’	6.1	2.44	2.59	1
40’	12.2	2.44	2.59	2
40’ High Cube	12.2	2.44	2.90	2
45’	13.7	2.44	2.59	2.25
45’ High cube	13.7	2.44	2.90	2.25
48’	14.6	2.44	2.59	2.4
53’	16.2	2.44	2.59	2.65

The listed sizes follow International Organization for Standardization (ISO) standards, which should be acceptable for all international container ports in the world. Being the smallest commonly used standardized container, twenty-foot ISO sea container is adapted as units, twenty-foot equivalent unit (TEU), approximately measuring the amount of cargo. Twenty-foot and forty-foot sea containers are most commonly used for transportation (Drummen, Wu, & Moan, 2009; Notteboom & Rodrigue, 2008). Shown in Figure 2.1, forty-five-foot, forty-eight-foot, and fifty-three-foot containers are actually extensions from the forty-foot container, sharing the same frame dimensions. The mounting poles in container vessels, fastening locks on container trucks and trailer, and port loading cranes are utilizing the dimensions of forty-foot containers to carrier containers with larger sizes.

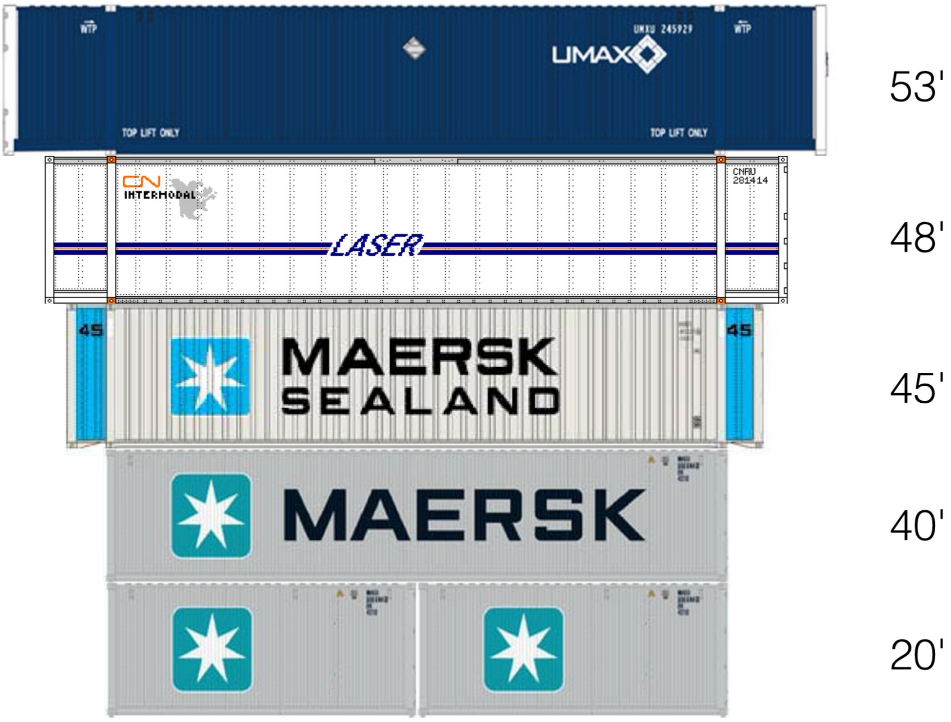


Figure 2.1. Visual comparison of ISO standard shipping containers World-Trade-Press (2008).

There are several types of containers categorized by the purposes of those containers. The following list is summarized from Hapag-Lloyd (2008) with short explanations.

- *Dry storage container*

  The most commonly seen containers for all general purpose dry shipment items

- *Flat rack container*

  Sides of the container can be folded and acts as a giant pallet

- *Open top container*

  Convertible top that can hold theoretically unlimited height of the shipment items

- *Tunnel container*

  Doors on both end of the container for quick loading and unloading

- *Open side storage container*

  Relatively wide opening doors on the sides of the container for large size of shipment items

- *Double doors container*

  Provides side doors with the opening even much wider than open side storage container

- *Refrigerated ISO container*

  Inner insulations and powerful refrigerator installed to provide control temperature while hauling to the destinations

- *Insulated/ thermal container*

  Inner insulations and temperature regulator installed to provide higher inside temperature than the ambient temperature

- *Cargo storage roll container*

  Installed rollers underneath the container for easier movement

The sizes and purposes of the containers are important constraints that engineers have to take them into considerations. More constraints will be discussed in Section 3.1.

2.2 Historical Achievements on Typology of Container Loading Problems

According to the literature, most efforts were dedicated to new algorithms targeting the conditions that placing regular shaped shipment items (cuboid boxes or cylindrical items) into containers. Irregular shaped shipment items are those with complex contours and much more challenging for optimal container loading problems. According to statistical results, there were only three papers that considered irregular shaped shipment in the CLP, from 1980 to 2010 (Bortfeldt & Wäscher, 2012).

Situations that involve irregular shaped shipments are actually encountered in many industries, from semi-conductive industries to heavy-duty agricultural and industrial equipment manufacturers. Figuring out the best shipping configuration using the original irregular shapes is a natural thinking path. However, as the matter of fact, those industries often ship these products either as regular shaped items in the loading scheme generated by container loading software, or as irregular shaped items packed in the experience designed container loading scheme. Even though it can save a significant amount of cost of shipment by recognizing and placing the products as irregular shapes, over 78% of the companies still choose to treat them as regular shapes due to the elevated difficulties of dealing with irregular shaped products (Frank, Gilgenbach, & Maltenfort, 2010; Hapag-Lloyd, 2008; Wever, 2011). Therefore, there is a huge potential market for optimal container loading algorithms that can handle irregular shaped items with sufficiently high accuracy and efficiency.

Dealing with irregular shaped shipping items is always a more troublesome condition compared with the handling regular shaped items. For example, when planning the placing scheme, overlap control for regular shaped items are much simpler than irregular shaped items, especially for those shipment items with strength, various weights, and various locations of the center of gravity (CoG). Moreover, if considering the possibilities of stacking and racking, the optimization process is even more challenging by shifting from two- to three-dimensional space with dunnage, such as racks. This paper discusses the above conditions and constraints in detail in order to guide the future research efforts focusing more on irregular shaped items CLP.

Soon after introducing SKD modules for shipment, another problem appeared: SKD modules are normally in much more complex shapes. Shipping irregular shaped SKD modules directly caused the overall low packing density inside containers, which dramatically lowered the profit per container. Moreover, regulations started preventing some certain combinations of SKD modules placing in the same container, due to hazardous limitation and other conditions. Different states, countries, ports have their own dynamic regulation systems, which means those regulations keep modifying as time goes by.

A recent publication, Bortfeldt and Wäscher (2012) mentioned that CLP started to get attentions since 1995. The initial idea of CLP was simply involving placing boxes into predefined space with geometric constraints. There were approximately 170 publications in total addressing different CLP, among those there were fourteen major directions, with more than seventy minor directions, of researches related to CLP (Bortfeldt & Wäscher, 2012). Those major directions had two orientations: input minimization problems (using as few containers as possible with a set of predefined cargo) and output maximization problems (fitting as many sets of cargo as possible into predefined types or number of containers). However, Bortfeldt and Wäscher (2012) pointed out that the rectangular small items (referred as boxes) were still the type of cargo considered for CLP for almost all publications, with very few exceptions. In order to make placing objects into containers as defined problem, there must be at least one constraint to limit the possibility of placing. Bortfeldt and Wäscher (2012) summarized all constraints discussed in CLP related publications, involving both regular and irregular shaped shipments. Table 2.2 lists the 10 of those constraints with brief explanation along with them.

Wäscher, Hauß ner, and Schumann (2007) introduced the very first systematic typology to cutting and packing problems (C&P) and categorized them into two major types: input minimization and output maximization. Input minimization stands for packing a defined set of objects into a set of containers, such that the number of containers is minimized. Output maximization means

Table 2.2: Ten generally encountered constraints in container loading problems, regardless dealing with regular or irregular shaped shipments. Brief explanations to each of them are provided in the right-hand-side column

Types of Constraints	Brief Explanations
Weight limit	Total net load allowance
Weight distribution	Distribution of load to the container floor and distribution of weight on each axle
Loading priority	The priority of shipment items and loading sequence
Cargo orientation	The way of setting the shipment items in containers
Stacking	(loading-bearing constraints) The way shipment items placed on top of others
Complete-shipment	The requirement that items belonging to the same set must be in the same container
Allocation	The subsets of cargo should be in same container or not
Positioning	Where a particular item is restricted to a certain region of the container
Stability	The static and dynamic stability of items inside the container, as well as the stability of container as a whole
Complexity	All constraints not suitable for manual or automatic loading techniques

filling a defined set of containers with a set of objects, such that the number (value) of the objects is maximized. Based on the similarity of the shapes, Wäscher et al. (2007) characterized an arbitrary set of shapes into two different categories, weakly heterogeneous and strongly heterogeneous. A set of shapes is called weakly heterogeneous if the shapes can be grouped into several types (identical or very similar in shape and size) with relatively large number items in the same type.

Strongly heterogeneous describe a set of shapes if none or limited them are identical or very similar in shape and size. Bortfeldt and Wäscher (2012) consolidated the aforementioned typology of C&P into generalized CLP, covering both two- and three-dimensional placing problems. Table 2.3 shows the detailed typology of input minimization CLP, while Table 2.4 shows the detailed typology of output maximization CLP.

Table 2.3: Typology of input minimization CLP with common abbreviations and definitions (Bortfeldt & Wäscher, 2012), where input minimization stands for packing a defined set of objects into a set of containers, such that the number of containers is minimized.

Abbr.	Types of CLP	Definitions
SSSCSP	Single Stock-Size Cutting Stock Problems	Weakly heterogeneous set of cargo into identical containers
MSSCSP	Multiple Stock-Size Cutting Stock Problem	Weakly heterogeneous set of cargo into weakly heterogeneous set of containers
RCSP	Residual Cutting Stock Problem	Weakly heterogeneous set of cargo into strong heterogeneous set of containers
SBSBPP	Single Bin-Size Bin Packing Problem	Strongly heterogeneous set of cargo into identical containers
MBSBPP	Multiple Bin-Size Bin Packing Problem	Strongly heterogeneous set of cargo into weakly heterogeneous set of containers
RBPP	Residual Bin Packing Problem	Strongly heterogeneous set of cargo into strongly heterogeneous set of containers
ODP(W/S)	Open Dimension Problem	(Weakly/ Strongly heterogeneous) set of cargo into single container with at least one dimension as variables and minimizing the container volume

Table 2.4: Typology of output maximization CLP with common abbreviations and definitions (Bortfeldt & Wäscher, 2012), where output maximization means filling a defined set of containers with a set of objects, such that the number (value) of the objects is maximized.

Abbr.	Types of CLP	Definitions
IIPP	Identical Item Packing Problem	Identical cargo into a single container
SLOPP	Single Large Object Placement Problem	Weakly heterogeneous cargo into a single container
MILOPP	Multiple Identical Large Object Placement Problem	Weakly heterogeneous cargo into a set of identical containers
MHLOPP	Multiple Heterogeneous Large Object Placement Problem	Weakly heterogeneous cargo into a set of weakly or strongly heterogeneous containers
SKP	Single Knapsack Problem	Strongly heterogeneous cargo into a single container
MIKP	Multiple Identical Knapsack Problem	Strongly heterogeneous cargo into a set of identical containers
MHKP	Multiple Heterogeneous Knapsack Problem	Strongly heterogeneous cargo into a set of weakly or strongly heterogeneous containers

In this research, the real world scenario involves optimization that placing a set of SKD modules, various in shape and weight, into a set of containers, various depending on the shipments. Therefore, according to the aforementioned typology of CLP (Wäscher et al., 2007), the scenario that this research focuses can be categorized as Residual Bin Packing Problem (RBPP) with allocation and positioning types of constraints.

2.3 Current Research Status Irregular Shaped of CLP

There were more than thirty different algorithms proposed or tested related to the CLP topic (Eley, 2002; Pinson, 1986; Wäscher et al., 2007). Since the CLP deals with placing a number of objects into a number of containers, the placing of the objects needs to follow a sequence, which creates the situation that decisions and choices are nested together for the container loading scheme. Therefore, a nested metaheuristic approach should be needed. Both allocation and positioning constraints need to be considered for both inner and outer nested algorithms. The inner nested algorithm is placing several SKD modules onto the sample pallet to form a pallet module, by using topological convex optimization methods. This inner algorithm is widely used in structural design engineering field, and was introduced by Boyd and Vandenberghe (2009); Fujiyoshi (2007); Hoeppner (2008). This research takes this method and uses it to deal with container loading problem. The basic idea of this algorithm was identifying empty or open spaces according to certain specifications, and then placing several objects to those open spaces determined by predefined criteria.

The outer nested algorithm aims to place pallet modules into different containers, depends on the actual geometry and loading capabilities of the each containers (Che, Huang, Lim, & Zhu, 2011; Fujiyoshi, 2007). This algorithm was modified based on dynamic space decomposition method proposed and virtually verified by Fukunaga and Korf (2007); George (1996); Z. Wang, Li, and Levy

(2008). Z. Wang et al. (2008) used tertiary-tree model to represent the three largest blocks of space remaining after placing a box-shape object to the corner of container. Their dynamic search was based on two aspects: there were multiple decomposition ways regarding the same actual space; after placing any rectangular shape object to the current space, there were multiple decomposition ways regarding to the different placement locations.

2.4 Current Achievements Regarding to Overlap Detection and Elimination

Depending on the different requirements and concerns, SKD modules may be allowed to be stacked, racked inside the containers, or both. Otherwise, SKD modules have to be fastened onto pallets or into boxes, which have relatively easier loading, unloading, and in-site transportation. Pallets can be made of wood, plastic, steel or other low cost metals. Pallets can also be disposable or reusable. Disposable pallets are usually wooden with certain metal or plastic fasteners. Reusable ones are designed for enhanced durability and flexible fasteners (Mehrabi, Ulsoy, & Koren, 2000; Mehrabi, Ulsoy, Koren, & Heytler, 2002). In recent 5 years, engineers started to apply the idea of reconfigurability to the reusable container design (B. J. S. Dai, Medland, & Mullineux, 2009; J. Dai & Caldwell, 2010; J. S. Dai & Jones, 2002, 2005; Liu & Dai, 2002; Nordin & Selke, 2010; Teng, Wu, Cheng, & Sung, 2010; Wei, Zhang, & Dai, 2010; Wikström & Williams, 2010; Yao, Cannella, & Dai, 2011; Yao & Dai, 2008; Yao, Dai, Medland, & Mullineux, 2010). By embedding proper mechanisms, the pallets can be featured with reconfigurable structures, which enable the pallets changing the fastening structures to fit different loading objects (Jain, 2011; Jiang, 2011; Li, n.d.; Lidwell, Holden, & Butler, 2010). The ability of reconfiguring the pallets reduces the cost of manufacturing individually designed pallets (J. Dai, Taylor, Liu, & Lin, 2004; Svanes et al., 2010; Takahara, 2008). Moreover, it is possible to ship the pallets back to the origin factories with compact shapes, which cuts the cost of two-way shipping of the reusable pallets.

Another deterministic issue in the CLP is the loading sequence, which needs to take a lot of parameters into considerations. For instance the overall CoG of the container, the moment of inertia (MoI) of the container after loading, static and dynamic stability of the shipment items, buffering space left between shipment items, and easiness of loading/unloading process operated by workers or fork-lifts (Jäger & Krebs, 2003).

Small SKD modules or protection enhanced SKD modules can be packed into wooden boxes before loading into containers. Under other conditions, SKD modules are fastened onto pallets or stacked on the racks. No matter using either type of packing, in order to achieve maximum loading density, irregular shaped items must be treated as irregular shapes or simplified irregular shapes. Thus, an idea of placing several SKD modules together on the same pallet or rack is the intuitive solution. The difficulties following the above idea appear during the planning process of the CLP. Some of the SKD modules can stand on multiple sides, which means having multiple axis-aligned orientations or even free-rotation positions. Some other SKD modules are limited by the weights or the CoG locations, which indicates they can only be placed on one side.

Moreover, the overlap detection and elimination process for irregular shapes took over 100 times more of the total computing time for the worst case (Bortfeldt & Gehring, 2001; Burns, White, & Krause, 2012; Jackson, 1996; Lamb, Rouillard, & Sek, 2012). For the three-dimensional CLP, there are two major methods to measure the overlap between items, depth of overlap and area/volume of overlap. That is to say, if using this measuring method, the goal of overlap elimination is to place items into the container with the depth of overlap of all items equal to zero for all directions. Similarly, area or volume of overlap method measures the overlap area of the items in two-dimensional placing and the overlap volume of the items for cases of three-dimensional fitting.

Now the question is how to search for the local or global minimum of the overlap? Egeblad, Nielsen, and Odgaard (2007) suggested that searching the whole space along axis-aligned paths, showing in Figure 2.2. Egeblad et al. (2007) used a method combing guided local searching and simulated annealing approaches to solve the two-and three-dimensional overlap minimization nesting problem. However, for the two dimensional method, the spacing between each path needs to be determined, and it determines the time consumed for calculation significantly. Especially for three-dimensional searching and placing, this process can be frustrating even for computers (Alidaee, 2014).

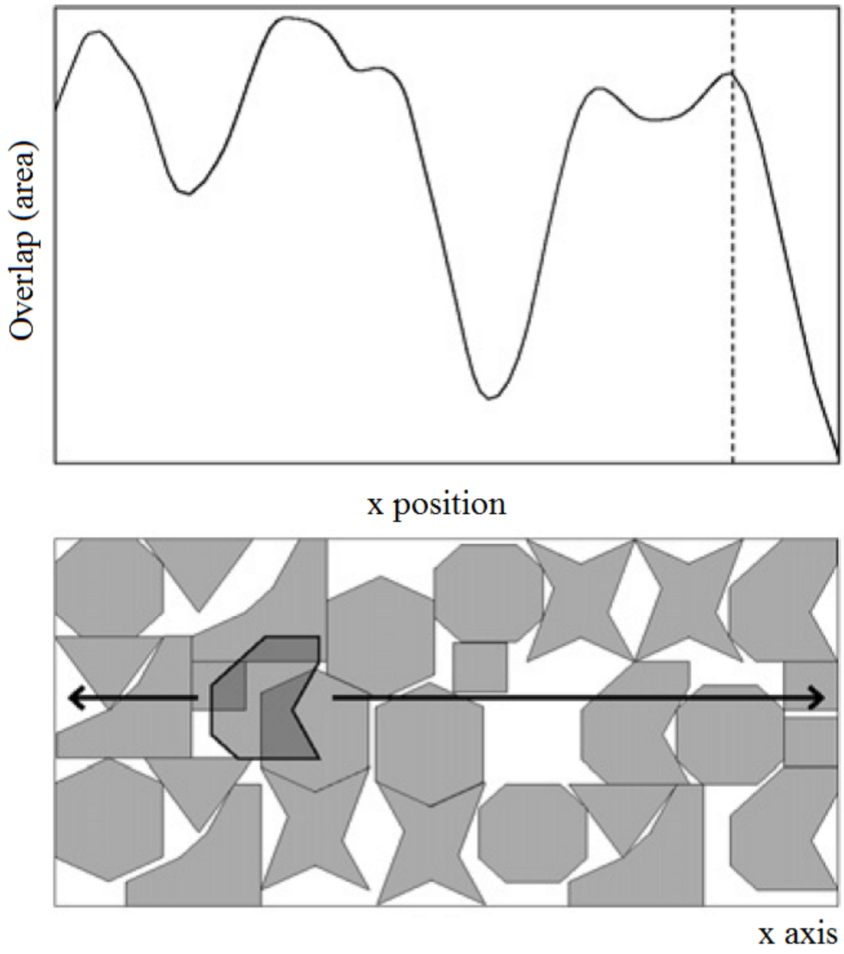


Figure 2.2. Demonstration of guided local search for the overlap on x-axis. (Egeblad et al., 2007) The vertical dash line on the upper part of the figure indicates the right-most limit for searching the least overlap position, which prevents placing the object outside the defined region.

The algorithm that developed by Dees and Bahar (2010); Egeblad et al. (2007) had the ability to search the space around the current position in polynomial time. The same algorithm found a sequence of translational movements that can be applied to the given polygon with the goal of minimizing the overlap. The algorithm was tested and verified with standard cases by Egeblad et al. (2007). They claimed that this new algorithm has high flexibility in the aspect of adapting various issues and conditions with different types and levels of constraints. This two-dimensional solution is expended to the three-dimensional applications. Egeblad et al. (2007) utilized the stencil cutting process, a two-dimensional irregular shape Open Dimension Problem (ODP) with additional commonly seen constraints. Cases in the textile industry were selected as examples to demonstrate the feasibility, efficiency, and flexibility of this algorithm. On one hand, even this algorithm is generalized to the three-dimensional condition, it is not verified to be as efficient as two-dimensional condition under real-world oriented pilot test. On the other hand, this new algorithm is highly valuable to the problems of placing irregular shape items into containers — searching the container space and placing shipment items with translational movement only for minimum overlap.

There are two commonly used overlap detection methods mentioned by Bortfeldt and Wäscher (2012): detecting overlapping area and detecting intrusion depth. Figure 2.3 is included for further clarifications to those two methods.

Irregular shaped SKD modules can be grouped together into a number of irregular or regular shaped sub-shipments, which are easier for the container-wise overlap detection and elimination processes. The grouping action may not need predetermined characteristics. For example, the small SKD modules can be placed around the large SKD modules on the same pallets to utilize the space. Therefore, this metaheuristic approach suitable for this compact palletization process with reasonable efficiency need to be developed to handle irregular shaped objects.

Sato, Martins, and Tsuzuki (2012) applied another method to search for the legal position for irregular shaped items — collision free region (CFR), no-fit

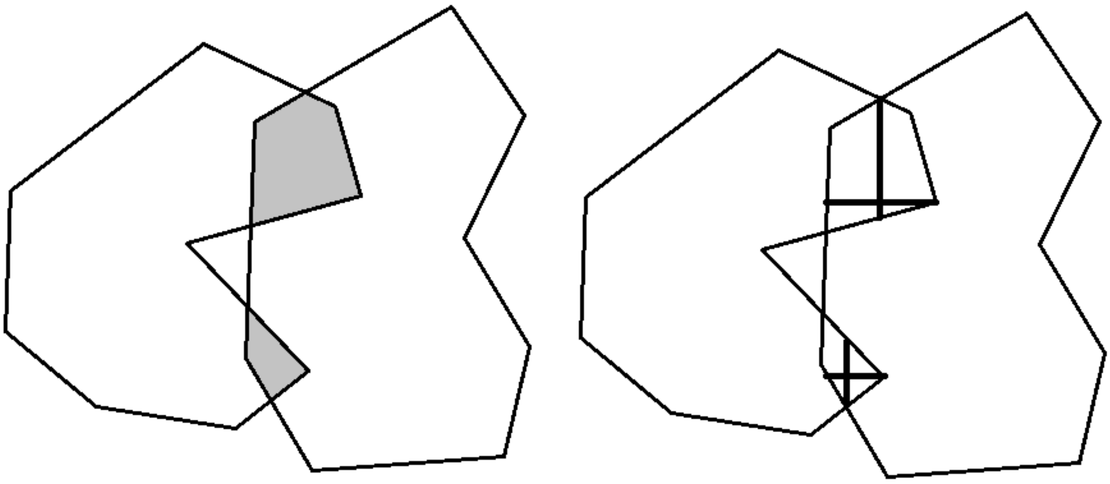


Figure 2.3. Two commonly used overlap detection methods: measuring intersection area (left) and measuring intrusion depth/ width (right)

polygon (NFP), and inner-fit polygon (IFP). Hassan, Angelopoulos, Rempp, Endler, and Burghartz (2010); Sato et al. (2012) used this method to figure out the above two dimensional polygon as the suitable regions and overlapping regions. However, this method needs a lot of modifications and refinements before it can be used for three-dimensional placement searching process.

Irregular shaped SKD modules, especially with complicated contours, are handled in different ways to achieve different goals in not only overlap detection and elimination processes, but also in the steps related to the security of shipment items. Next section, the methods of dealing with irregular shaped items are discussed from the aspects of recognition of irregular shapes and orientations of the items when placing.

2.5 Dealing with Nested Decision Making Process

There must be a placing sequence as the shipment cannot be placed at the same time. Then, after successfully placing one object, the decision of choosing which to be the next object, and where it should be places affect the later decisions. At this stage, nested decision making process is formed regarding to the placing sequence (Hu & Lim, 2014; Jäger & Krebs, 2003; Ren, Tian, & Sawaragi, 2011; Sun, 2011).

However, choosing the next spot for placing can also create decision making process. Illustrated in Figure 2.4, a tertiary-tree type decision making process was extracted from the container loading problem at the stage of finding remaining spaces (Gonçalves & Resende, 2012; N. Wang, Lim, & Zhu, 2013; Z. Wang et al., 2008).

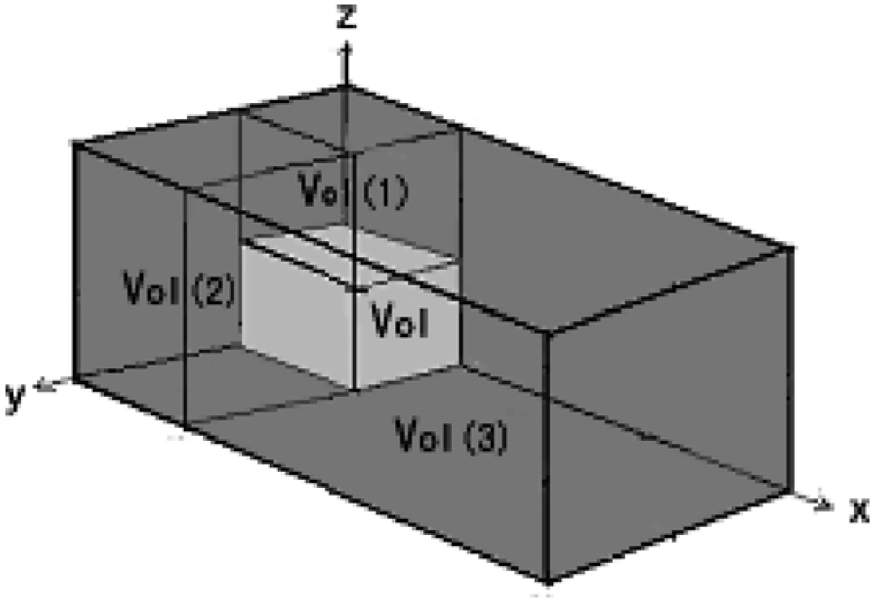


Figure 2.4. Tertiary-tree model of decomposition of stages for the remaining space in container after loading one object. (Z. Wang et al., 2008)

Z. Wang et al. (2008) also pointed out that the possible decompositions of remaining container space itself is a tertiary-tree. Showing in Figure 2.5, there are actually three approaches of decomposing the remaining space into three empty blocks for a single placement of object. That is to say, there are 8 different combinations of the remaining space with one object at a corner.

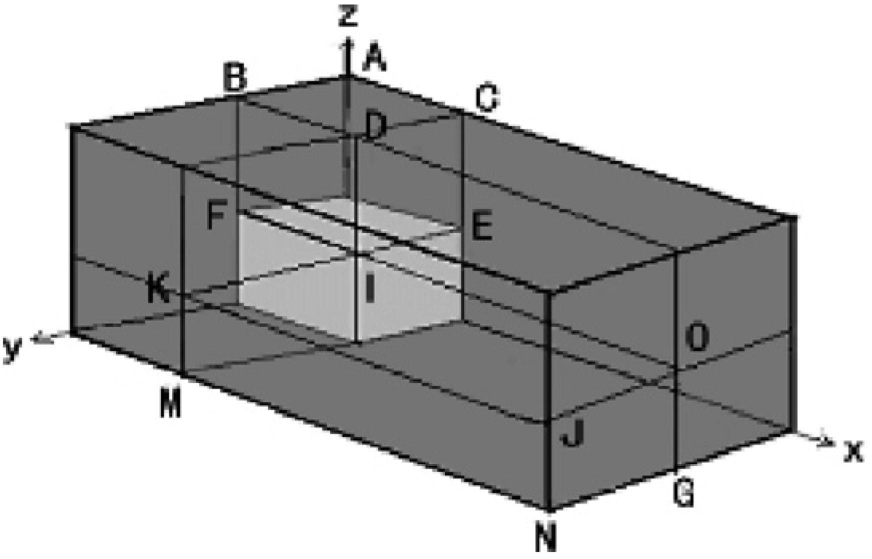


Figure 2.5. Tertiary-tree model for a tertiary-tree decision making process when defining the remaining space in containers. (Z. Wang et al., 2008)

2.6 Recognition of Irregular Shapes

The first step of handling the irregular shaped items is accurately representing the characteristics of irregular shapes. There are two major approaches for recognition of shapes. One is exact recognition by three-dimensional mesh and the other is approximated recognition by reducing certain less important details of the irregular shapes. Omitting those unnecessary details, the irregular shapes are simplified to the reduced shapes for less computational efforts required.

Miller (2000); SCAI (2010) mentioned the most used method of exact recognition was the meshing by using polygons, such as triangles. Meshing represent the surfaces of the object in the way that is very similar to the meshing before performing finite element analysis (FEA). After meshing, there are two choices of utilizing the meshed object: vertex-edge-extraction, which is taking information only related to the vertexes and edges of those polygons; and surface-extraction, which means taking information only related to the surfaces (Mukundan, 2012; Nam, 2002). Information that can be extracted from the surfaces normally contains the normal vector of the surfaces, the vectors pointing towards the vertexes of the surface that originated from the surface normal vector, and the coordination of the starting point of the surface normal vector (Warren & Weimer, 2001). When handling irregular shaped shipment items with relatively large surfaces, the surface-extraction of post-meshing method cost less computational efforts than using vertex-edge-extraction method.

Egeblad, Nielsen, and Brazil (2009) generalized their solution method to placing d-dimensional polytopes into a polytope container. Guided local search was employed in this algorithm to handle the local minimal with the exact one-dimensional translation for searching minimum overlap volume. Moreover, according to the author, this algorithm can deal with non-convex polytopes and interior holes without any difficulties. The amount of overlap was controlled by the one-dimensional translation. They had proved the validity of using this algorithm under the conditions of both two- and three-dimensional placements by experimental verifications. They claimed this algorithm is suitable for even higher dimensional placement, however, since it was not applicable to construct test for verifications, the correctness and the possible applications were not clear yet.

For some cases, the requirements of the precision of the recognition is not crucial or the irregular shaped SKD modules are too complicated to be efficiently loaded into the algorithm, approximate recognition is a reasonable approach. Currently, the most commonly used approximate recognition approach was adopted from the Raster Model from geographic fields (Bortfeldt & Wäscher, 2012). Shown in Figure 2.6, it is similar to the process that placing the irregular shapes onto a chessboard. Originally, if a cell was covered by the shape, that cell was considered as occupied (Allahdadian, Boroomand, & Bareketein, 2012).

Egeblad (2009) illustrated a heuristic solution for placing the irregular shaped items into containers. They applied the method of optimizing balance and inertia moment without overlap between items by iteratively removing overlaps. The technique they proposed was based on the bin-packing problem with

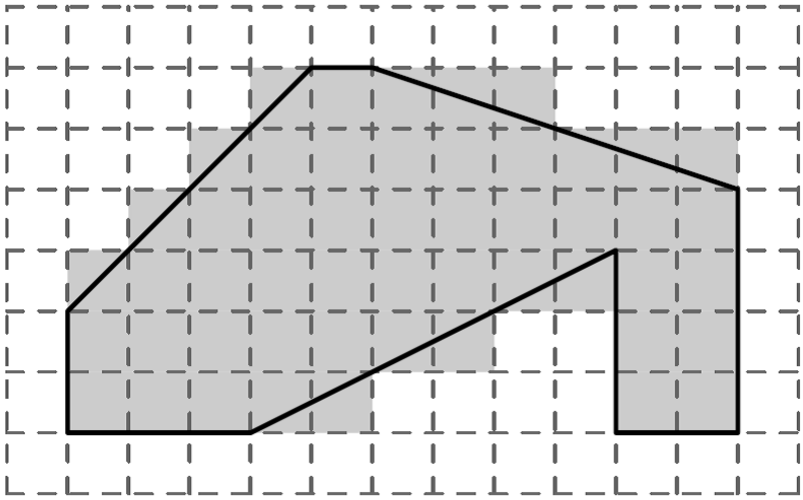


Figure 2.6. Representation of the Raster model for approximating and simplifying irregular shapes. (Egeblad et al., 2007)

rectangular objects and strip-packing problems with irregular shaped items, which were proven to be effective in his another paper (Egeblad et al., 2007).

After the image manipulation processes of irregular shaped SKD modules for shape recognition, the next multi-option step is the orientation of the SKD modules when placing.

2.7 Prioritizing Placing Sequence

Egeblad and Pisinger (2009); Sarkar, Batta, and Nagi (2007) tested the idea of subset when dealing with CLP for loading irregular shape furniture items. The shipment items were firstly grouped into subsets with highest total profit that could be transported with the given size containers. The profit of each item was different depends on the items. The heuristic used to solve the subset loading problems one by one. The protection of the large shipment items during the transportation was also considered by using different grouping scheme. Egeblad and Pisinger (2009) mentioned that the situation was set as loading furniture into containers with different level of desirability associated to the furniture, which determined the relative priorities of the loading process of each item. It was categorized to the strongly heterogeneous three-dimensional single knapsack problem (SKP) with irregular shapes according to the typology published by Wäscher et al. (2007). The placing assumption in this study employed the axis-aligned rotation based orientations and smaller items on top of larger items. Besides, larger items were more desirable than smaller items when determining the loading priority.

In the process of recognition of the shapes, triangle-mesh method is used to the represent the surfaces of the items and no inner structures were considered. However, according the loading scheme example (Egeblad et al., 2007), when placing a sofa onto another, the deformation of the furniture was not considered. Also, the successful result proved its validity towards rigid items. The algorithm may need modification for loading relatively soft items. Moreover, the deformation of the soft items due to dynamic loading may change the stability of the subset items in a significant amount, even with dunnage/ strip fastener protection (Allen, 2011; Chien, Lee, Huang, & Wu, 2009; J.-l. Lin, Chang, & Yang, 2006).

Egeblad and Pisinger (2009) firstly used a tree-search heuristic to allocate the intermediate solution for large items by placing them following the quad-wall building process. After refining the placing for better stability, Greedy algorithm was applied to place medium-sized items. Finally, small items were placed following the wall building process with Greedy algorithm.

Following the idea of grouping the shipment items into subsets and placing the items subset by subset, Egeblad and Pisinger (2009) suggested a new algorithm for two- and three-dimensional Knapsack Packing Problem (KPP) for regular shape items and regular shape container, with the assumption of orthogonal packing. Their proposed algorithm was an iterative heuristic based on sequence pair representation. Egeblad and Pisinger (2009) applied a very-large-scale integration (VLSI) module placing originated from the rectangle-packing by the sequence pair. There was another algorithm named sequence triple designed for handling three-dimensional KPP using similar strategies, which was tested with computational experiments and proved to be much more efficient dealing with both two- and three-dimensional cases (Chikwendu et al., 2014). In addition, this algorithm was able to placing items with rotational poses, which may also be utilize for irregular shaped container loading problem.

2.8 Research on Stability

The approach proposed by Egeblad (2009) was able to reduce the augmented objective function related to balance, inertia moment and overlap, by applying the Guided Local Search (GLS). They focused on balance, by measuring the difference between the center of gravity (COG) of the items and a predetermined COG target, and controlling the moment of inertia (MOI) of the placement to be minimized. However, by setting one of the goals to be minimizing the moment of inertia of the placement, there were two concerns. Firstly, placing the items with relatively large mass makes requirement of controlling the MOI of the placement easier, which significantly simplifies the placing process with the goal of minimizing the difference between COG of the items and predetermined COG target (Davies & Bischo, 1999; Fasano, 2004, 2007; J.-l. Lin et al., 2006). It means there is no guarantee of the current placing algorithm can work effectively or even properly without the assumption of minimizing the MOI of the placement. Secondly, even placing the items with relatively small MOI can enhance the safety of road transportation, especially with semi-trucks, minimizing the MOI is not favorable or researchable in real world (Junqueira, Morabito, & Sato Yamashita, 2012; Yan, Shih, & Shiao, 2008). The floor pressure limit of containers and the semi-truck chassis limit may not allow the carrier to place all heaviest items in a specific spot. Moreover, placing a whole container of relatively heavy items is not possible to minimize the MOI to a level that easy enough for the COG placement algorithm. Thus, controlling of the

MOI to fall into a certain region is more practical and real-world oriented for industry.

2.9 Technology Readiness Levels

Technology readiness levels (TRL) are used to measure the development stages for a critical technology in certain applications. Determined by technology readiness assessment, technology elements are categorized depending on the maturity of them. National Aeronautics and Space Administration (NASA) introduced TRL in 1980s with the scale from 1 to 9. Research institutions and government agencies in both North America and Europe were actively adopting the new concept of TRL in the recent 15 years (Graettinger, Garcia, Siviy, Schenk, & Syckle, 2002). The definitions had been modified by those organizations according to their needs. The original definitions from NASA (Mankins, 1995) are shown in Table 2.5.

According to the definitions of levels in TRL scale, mature methods that are ready for commercialization are of TRL8 to TRL9 (Graettinger et al., 2002). The heuristic methods of existing container loading problem are of TRL3 to TRL 4 due to only simulations performed onto mock data (Bortfeldt & Wäscher, 2012). The TRL scale can also be applied to non-physical technology elements, such as the optimization methods in operational engineering and data manipulation techniques in computer network field.

Table 2.5: The 9 levels scale of the technology readiness level (TRL) were summarized by Mankins (1995).

Levels	Meanings corresponding to TRL
TRL 1	Basic principles are observed and reported.
TRL 2	Technology concepts/applications are formulated.
TRL 3	Analytical and experimental critical function/characteristic are performed for proof-of-concept.
TRL 4	Components/breadboards are validated in laboratory environment.
TRL 5	Components/breadboards are validated in relevant environment.
TRL 6	System/subsystem models or prototypes are demonstrated in a relevant environment.
TRL 7	System prototypes are demonstrated in an operational environment.
TRL 8	Actual systems are completed and qualified through tests and demonstration.
TRL 9	Actual systems are proven through successful application operations.

2.10 Summary

The history of irregular shaped shipment of CLP is significantly shorter than the general CLP, which is only 20 years. There were three previous works that illuminated a clear and solid mainstream of the research direction. The phenomenon of scattered research directions and various approaches of the heuristic methods expresses that researchers in this field are still working on exploratory method. Therefore, the detail approaches for this research involve several different ideas and techniques without precedents to follow. However, the main idea of this research is to investigate and experiment on the feasibility of using topology-based guided local search algorithm.

CHAPTER 3. FRAMEWORK AND METHODOLOGY

Chapter 3 is dedicated to explain the approach of working on this research after reviewing all relevant literature. The literature review is a bridge connecting the questions raised in Chapter 1 and the present research One major research problem is the incompleteness of the collection of constraints known by the researchers. Therefore, in purpose of addressing this problem, this chapter will start with the detailed investigation of constraints of container loading problem (CLP). Thereafter, the steps of the metaheuristic approach will be introduced as the sequence of the process flows: spatial optimization with topology, constraints handling optimization, and placing objects, and evaluations to the shipping configurations. At the end of this chapter, a summary will briefly cover the crucial steps in the metaheuristic approach.

3.1 Understanding the Constraints of CLP

Constraints are rules or regulations that restrict people from performing a certain action (Wu & Hamada, 2013). Similarly, constraints in container loading problem are a set of rules or facts that prevent engineers to pack the container with objects freely. To fully understand the constraints, one should start with getting familiar with the whole process of container loading problem, rather than only focusing only on loading process. The following subsections will be arranged as the flow of shipping SKD modules, step by step based on the observations the author performed in the shipping facility of Deere & Company (located in Waterloo, Iowa, US). Constraints encountered in each step will be pointed out with the underlying relationship with the whole process. Thereafter, with an aftermath of the shipping process, those constraints will be compiled into a mind-map.

3.1.1 Determination of Shipments

For shipping product, engineers need to know the components that are to be included in the shipments. Said differently, the set of shipment for the container loading problem needs to be decided (Chiu, Ting, & Chiu, 2005; Yiangkamolsing, Bohez, & Bueren, 2010). Observations show the first piece of information is product orders gathered from the sales department from the destination region. Taking the John Deere 9000R tractor as an example, engineers need to determine the trims associated with the order, even the model of the product is the same. Customers normally select optional trims when making their order. Therefore, the base components and the trim parts of the ordered product, in terms of SKD modules, are known and ready to use for planning. At this time, the SKD modules listed in the bill of material form a set of shipments.

Imagine the scenario that the customer ordered 6 tractors shipping from one location to another. Two 40' containers are needed for each tractor, estimated by the preliminary assessment or previous experiences. Therefore, this customer order with 6 tractors will need 12 forty-foot containers. When considering all SKD modules of these tractors are in one set, grouping same SKD modules in the same container is very convenient for loading and unloading. Since SKD modules need to be disassembled from the finished and tested products, shipping facility at the origin location has to disassemble all 12 containers before getting ready for loading. Also the SKD modules that disassembled before other SKD modules need to be placed (or loaded onto pallets) inside the facility, occupying lots of facility floor area. Moreover, the shipping facility at the destination location has to wait for the arrival of all 12 containers to be able to assemble a complete product. While waiting for being loaded, materials (SKD modules) and containers sitting in the facility are counted for expenses without profit generated.

Therefore, SKD modules in the set of shipments need to be grouped into subsets and shipped group by group. The grouping constraint needs to be determined by the estimated volume of the shipment and the facility availabilities for both origin and destination. Empty space in a non-fully filled container may be used for other SKD modules not belongs to this set of shipments, such as spare parts also requested by the destination region (Mahata & Goswami, 2009). However, engineers need to group those spare parts as a set of shipment with lower priority when designing the loading scheme in the containers. That is to say, not all the spare parts can be placed into containers for this shipping order.

3.1.2 Determination of Containers

There are several types of containers that engineering can choose from. Certain types of containers may not be accepted by different ports or even the ground transportation conditions in particular country or region. Because of keeping the SKD modules in the same container from origin to destination, the compatibility of certain sizes of containers needs to be assessed thoroughly.

Another factor of choosing containers is the shipping rate for different size of the containers. While comparison shipping rates between sizes is straightforward to think of, the price-performance (or cost-benefit) ratio may be neglected when choosing container sizes (Zhu, Huang, & Lim, 2012). The price-performance ratio here means the comparison between the weight of shipments and the overall cost for shipping, including carrier rate, port surcharges, insurances, fuel efficiency, and so on. World-Trade-Press (2008) suggested that the 40' and 45' containers normally have higher price-performance ratio for both ground and sea transportations.

Having more than one size of containers capable may provide benefits on enhancing shipping efficiency, in other words, reducing total cost. For instance, there is a set of SKD modules needs to be shipped in containers. According to the preliminary volume estimation, those SKD modules take a little more space than one 40' container, but less than two of them. The manufacturer may waste significant amount of space and monetary profit if using two 40' containers. If have

20’ containers also available, one can use a 40’ container combined with a 20’ container to fulfill this shipping order.

3.1.3 Determination of Space-wise Loading Plan

The set of shipments and the set of containers are figured out for planning the loading layout inside the containers. The first constraint when planning loading schemes is the compatibility between shipment items in the same container. The compatibility issue mainly regulated by border controls of each government or other authorities. Regulations were formed to restrict the types of commodities entering their region in a very detailed well-written manner. There is a code associated with each commodity, which is different from port to port, country to country. According to the shipping experts from Deere & Company, import taxes for complete products are higher than parts from the same product. Therefore, shipping SKD modules is more preferable then the whole product. Manufacturers seek ways to lower tax, by regularly negotiating with authorities on which categories that a particular SKD module should fall into.

There is an underlying mechanism of the tax rate restricting the possible combinations of the SKD modules in the same container. Shipping a whole product is the same as shipping all necessary parts and components in the same container, as being able to be assembled as a whole product. For instance, axles and chassis from the same tractor have their own commodity codes. If placing axle SKD module and chassis SKD module in the same container, the ability of assembling them create a new commodity, chassis & axle assembly. The import tax associated with this new commodity may be elevated as much as 30%, according the shipping experts. Shown in Figure 3.1, the SKD modules A, B, C, D, and E, can be assembled in the illustrated way. The two SKD modules nearby with each other, for example A and B, are incompatible from the above discussion from the aspect of reducing tax. Those two SKD modules that cannot be assembled directly, such as A and C, are compatible in the same container.

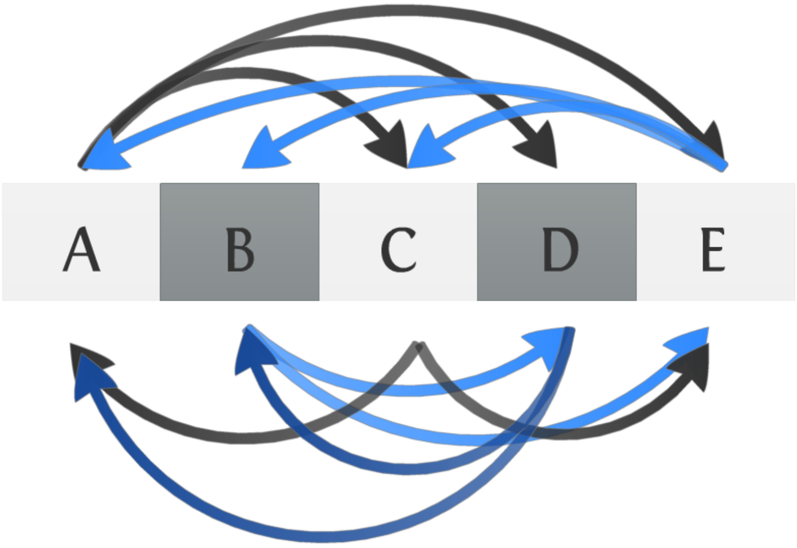


Figure 3.1. Illustration of compatibility between SKD modules regarding to the ability of being assembled together

Apart from the tax related restrictions, hazardous regulations are also strictly enforced for both sea and ground transportations. For example, the engine SKD module and cabin SKD module are prohibited to be placed in the same container. Being mentioned in Section 1.1, SKD modules were built into product before being disassembled. Therefore, there must be certain amount of fuel remaining in the combustion cylinders of the engine SKD modules. The cabin SKD modules of the tractor contains electronics and fabrics from panel and seats, respectively. Placing engine SKD modules and cabin SKD modules in the same container means putting flammable substance along with combustible substance.

Spatial interference is the condition that shipping engineers desperately want to avoid. For the container loading problem, spatial interference is also referred as overlaps, which was discussed in Chapter 2. In real life, spatial interferences are not only those between SKD modules, but also include

- between SKD modules and pallets,
- between pallets,
- between SKD modules and container walls,
- between pallets and container walls,
- between SKD modules and fasteners from pallets,
- between SKD modules and fasteners or rings (for cargo straps) from containers, and
- between pallets and fasteners or rings from containers.

3.1.4 Determination of Dunnage and Pallet Loading Sequence

Starting from disassembling the test products to finishing loading all pallets into containers, the SKD modules have to sit in a certain temporary place or a pallet in a static location (Bischoff & Ratcliff, 1995). The idling time is due to the impossibility of disassembling all SKD modules at the exact same moment, as well as the impossibility of loading all pallets into containers at the same time. Of important note, there exists a circumstance that the SKD module disassembled first, may not be the first when placing on pallets, or loading into containers. The equipment and temporary space occupied are cost associated with shipping from the operational engineering standpoint. Therefore, the pallets, racks, and other dunnage need to be designed in the way that suitable for the loading plan that determined above. Moreover, the sequence of loading SKD modules onto pallets, racks, or other dunnage, must be carefully designed to minimize the idling time, space occupied, and potential interference when loading.

3.1.5 Determination of Container Loading Sequence

Loading pallets into containers needs proper equipment, such as forklift. The base line for placing pallets is being able to access the door opening of the containers. Noticeable, the rotating axis for each door is located inside the main frame of the container. Therefore, considering the thickness of the main frame, the door opening size should be smaller than the interior dimensions of the container, which affects the design of pallets and loading process. Table 3.1 lists the internal dimensions and door opening size, along with volume and floor area, corresponding to a few sizes of containers.

Table 3.1: Internal dimensions of the common containers for shipment

	Internal Dimensions				
Type	L, W, H (m)	Vol. (m^3)	Area (m^2)	Door W. (m)	Door H. (m)
20’	5.87, 2.33, 2.35	32.85	13.93	2.28	2.26
40’	12, 2.33, 2.35	66.83	28.33	2.28	2.26
45’	13.56, 2.33, 2.65	86.10	31.88	2.28	2.56

A typical interior floor of the sea containers is made of wooden board (over 1” in thickness) with reinforced supporting beams underneath the floor. Even using the wood, such as oak, basswood, and marine plywood, there still exist load limitations restricting the positioning of SKD modules and the pallet loading process. For the load distribution of SKD modules on pallet, the maximum load for 20’ container floor is 4.5 tons per running meter, and 3 tons per running meter for 40’ containers (Hapag-Lloyd, 2008). Running meter stands for an area covering a one-meter long (along lengthwise direction) section of the container floor, with the whole internal width of container. Hapag-Lloyd (2008) emphasized the load restrictions of operating forklifts inside containers, listed in Table 3.2.

Table 3.2: The load restrictions for loading cargo in containers.

Restriction Item	Limit
Load front axis (forklift + cargo)	max. 5,460 kg
Contact area per tire	min. 142 cm^2
Width of tire	min. 18 cm
Wheel spacing (on one axis)	min. 76 cm

The gross weight of the loaded container should not exceed its certified value. The payload weight is the value subtracting tare weight, self-weight of the container, from gross weight. Apart from keeping the weight of loaded container lower than the allowed gross weight, the load that exerting on the road from each axle of the truck is also restricted by transportation authorities in purpose of protecting road and keeping the maneuverability of the truck (Lim, Ma, Qiu, & Zhu, 2013). Table 3.3 lists the restrictions, by United States Department of Transportation (USDOT), on the gross weight of trucks and maximum axle load corresponding to various types of axles (World-Trade-Press, 2008).

Table 3.3: Weight allowances of truck regulated by USDOT

Limitation Type	Maximum Allowed Load (*lb.*)
Gross Weight	80,000
Steering Axle	12,000
Trandem Axle	34,000
Tridem Axle	42,000

Steering axles are those control the traveling direction of the vehicles. Normally, each axle has its own suspension system connect to the chassis and separated from suspension systems of other axles, If two axles have their suspension systems linked together, the new suspension system with two axles is called trandem axle. If three axles have their suspension systems linked together, the new suspension system with three axles is called tridem axle. Linking the suspension system with ones from nearby axles will greatly enhance the structural strength of the trussed system. Moreover, the load to the road can be more evenly distributed, allowing higher load on the trucks (Chen & Wang, n.d.).

3.1.6 Determination of On-the-way Possibilities

While being transported around the world, SKD modules and container have to experience climate changes, in terms of different combinations of temperature and humidity. Also, the chemicals in vaporized sea water corrode the metallic parts in the containers. The wooden pallets or other fixtures in the containers absorb moisture when setting in a high humidity region. Moisture will put extra weight onto the containers resulting possible overload and corresponding fine.

When riding on the road, the vertical vibration induced can have a frequency up to 10 Hz with amplitude up to 0.5 m (Garcia-Romeu-Martinez & Rouillard, 2011; S. P. Singh, Saha, Singh, & Sandhu, 2012). The conditions on sea are far more difficult to predict. With high sea condition, Delgado, Jensen, Janstrup, Rose, and Andersen (2012); Drummen et al. (2009); Mitra, Wang, Reddy, and Khoo (2012) pointed out that the average frequency is as low as 0.5 Hz, but the amplitude can be over 20 meters. Moreover, the container vessels have rotation movement in roll direction as much as 40 degrees on each side, while in pitch direction as much as 10 degrees on each side (Aguiar, Souza, Kirkayak, Watanabe, & Suzuki, 2013; Buckingham, 2005). Table 3.4 compares the potential acceleration during road, rail, and sea transportation that a container may experience. The letter “g” stands for gravitational acceleration, 9.81 m/s^2. The actual acceleration may be higher than the values listed in Table 3.4 due to impacts or vibrations.

Table 3.4: Possible acceleration exerting on containers during various transport (Hapag-Lloyd, 2008; Otari et al., 2011)

Type of Transport	Lengthwise	Transverse	Vertical
Road	±1.0 g	±0.6 g	±1.5 g
Rail	±4.0 g	±0.4 g	±0.4 g
Sea	±0.4 g	±0.8 g	±2.0 g

Associated with the potential accelerations mentioned above, the center of gravity (CoG) location is also being restricted for loaded containers, shown in Table 3.5. The lengthwise restriction is a range regulated by the distance deviated from center of the container.

Table 3.5: Center of gravity (CoG) restrictions for loaded containers (Hapag-Lloyd, 2008)

Axis of CoG	20' ISO Containers	40' ISO Containers
Lengthwise	max. 60 *cm* from center	max. 90 *cm* from center
Transverse	in center of container	
Height	below or at half height of container	

The possibilities of human error and unexpected incidence are also travel along with the containers (Baker, 1999). For example, the container may be accidentally dropped on to ground during unloading from the ship; side way impact may occur if the container sways onto another; or an SKD module strikes onto another when loaded onto pallets/ containers, or unloaded from pallets/ containers, due to tight spatial arrangement. Sufficient spacing or cushion should be provided whenever needed. Therefore, engineers should plan on the certainties and uncertainties through the whole trip for the shipment.

3.1.7 Compiling Constraints

Several constraints with the corresponding circumstance of occurring were covered in the above discussions. The relationships between each of them seem to be messy and interrelated, coupled. Figure 3.2 shows the mind up of constraints coupled with shipment uncertainties.

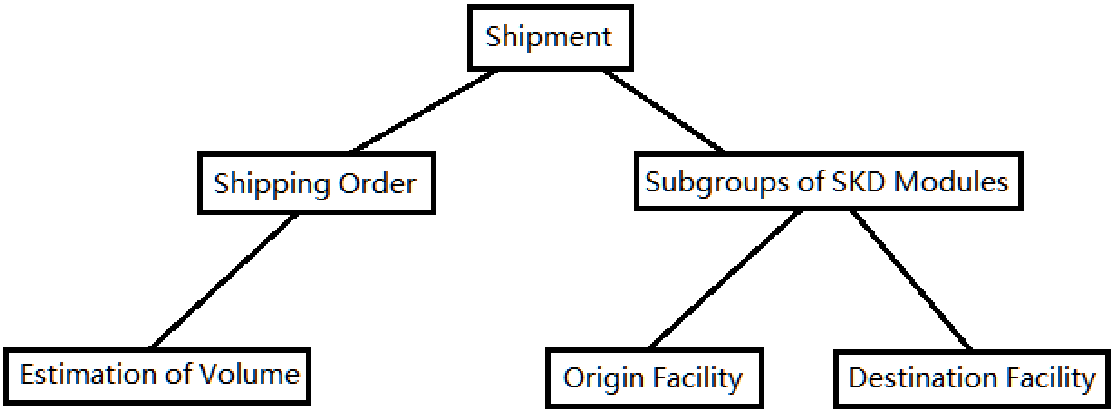


Figure 3.2. Mind map of the constraints related to shipment

Figure 3.3 shows the mind up of constraints coupled with container uncertainties.

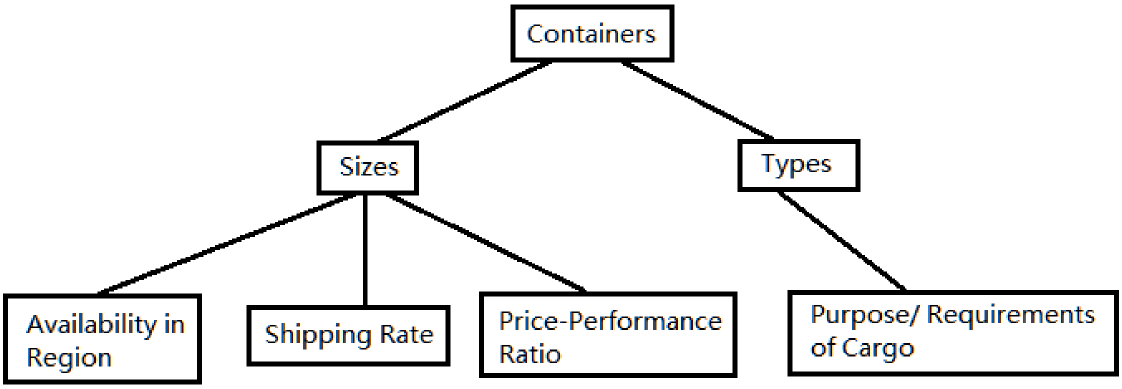


Figure 3.3. Mind map of the constraints related to containers

Figure 3.4 shows the mind up of constraints coupled with space-wise loading plan uncertainties.

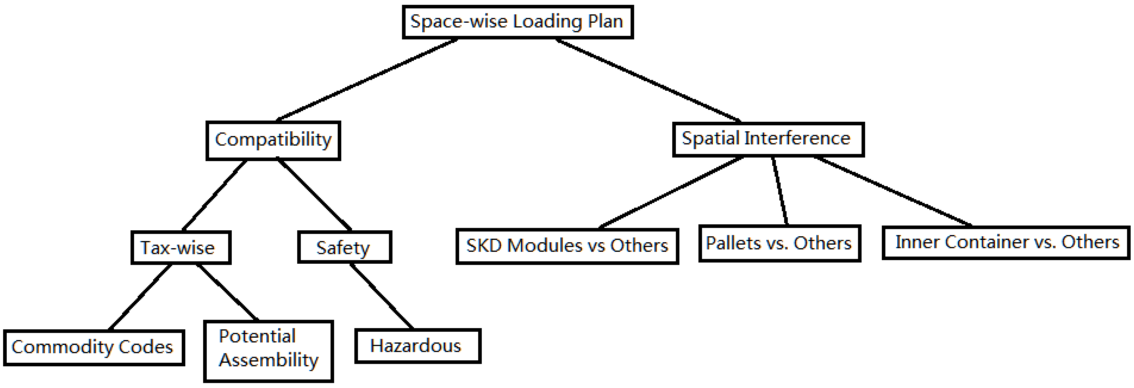


Figure 3.4. Mind map of the constraints related to space-wise loading plan

Figure 3.5 shows the mind up of constraints coupled with container loading sequence uncertainties.

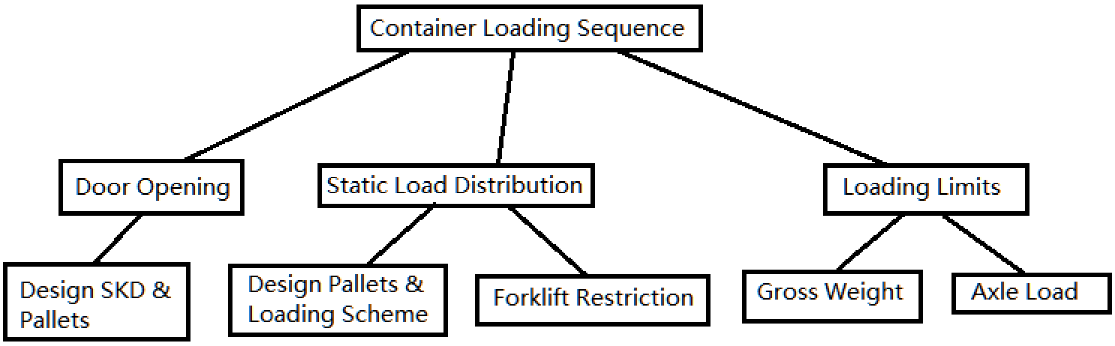


Figure 3.5. Mind map of the constraints related to container loading sequence

Figure 3.6 shows the mind up of constraints coupled with Dunnage and loading sequence uncertainties.

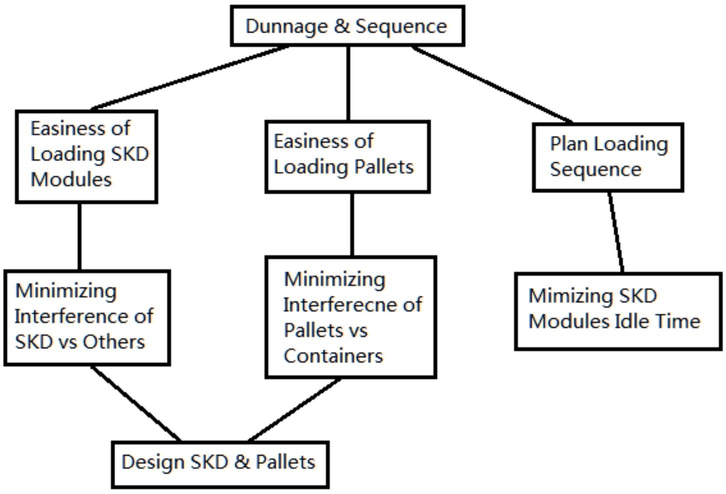


Figure 3.6. Mind map of the constraints related to dunnage and loading sequence

Figure 3.7 shows the mind up of constraints coupled with one-the-way uncertainties.

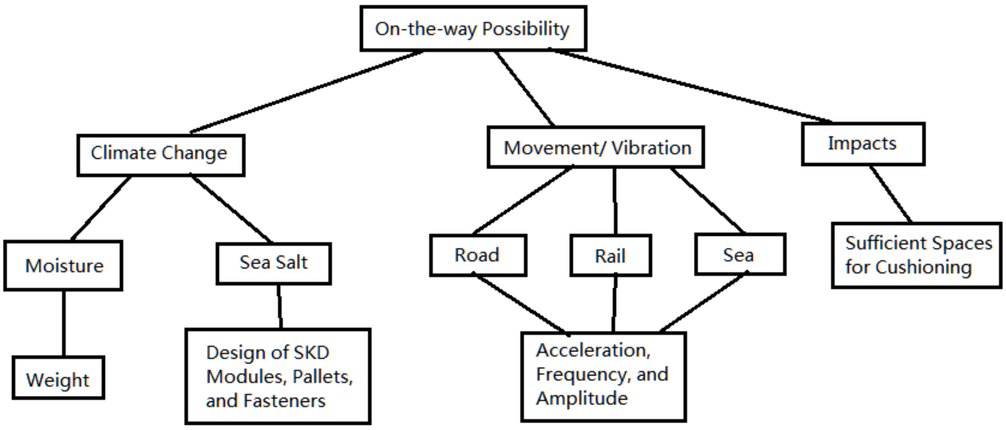


Figure 3.7. Mind map of the constraints related to one-the-way possibility to the shipment

The general understanding of the cost components in the shipping procedure can be summarized in Equation 3.1.

$$\begin{aligned}\text{Shipment Cost } = & \text{ Cost associated with each container } + \\ & \text{ Possible damage of each container } + \\ & \text{ Cost associated each pallet } + \\ & \text{ Disassembling labor cost (each SKD module) } + \\ & \text{ Reassembling labor cost (each SKD module) } + \\ & \text{ Disassembling facility cost (each SKD module) } + \\ & \text{ Reassembling facility cost (each SKD module) } + \\ & \text{ Disassembling overtime cost (each SKD module) } + \\ & \text{ Reassembling overtime cost (each SKD module)}\end{aligned} \tag{3.1}$$

The above shipping cost break-down is used as a guideline for engineers and researchers. The parameters can be modified depending on the needs for different industries. Equation 3.2 shows the costs in detail to illustrate the complexity of controlling cost in shipping configuration. There are several factors that should be considered into the calculation of the total shipping cost, such as insurance, port register, and so on. Since those are not inside the focus of this research, they are only listed in the Equation 3.2 as a place holder for future investigations.

$$\begin{aligned} C_{shipping} = & \sum_{l=1}^{K} C_{rate_l} + \sum_{m=1}^{K} C_{ins_m} + \sum_{n=1}^{K} C_{port_n} + \sum_{p=1}^{K} C_{reg_p} + \sum_{q=1}^{K} \delta_{dam_q} \cdot P_{dam_q} \\ & + \sum_{r=1}^{M} C_{plt_r} + \sum_{s=1}^{N} R_{lbr1} \cdot t_{dis_s} + \sum_{u=1}^{N} R_{lbr2} \cdot t_{reass_u} + \sum_{v=1}^{N} C_{F1} \cdot t_{dis_v} \\ & + \sum_{w=1}^{N} C_{F2} \cdot t_{reass_w} + C_{F1} \cdot t_{extra1} + C_{F2} \cdot t_{extra2} \end{aligned} \tag{3.2}$$

where, l, m, n, p, q are indexes of containers, with total K containers,

r is index of pallets, with total M pallets,

s, u, v, w are indexes of SKD modules, with total N SKD modules,

C_{rate_k} is the rate per container,

C_{ins_k} is the insurance per container,

C_{port_k} is the port authority fee per container,

C_{reg_k} is the regulation violation fin per container,

δ_{damk} is the unit damage for each container,

P_{dam_k} is the possibility of damage for each container,

C_{plt_m} is the cost of each pallet,

R_{lbr1} is the labor rate per unit time at origin, for disassembling

t_{dis_n} is the disassembling and palletization time per SKD module,

R_{lbr2} is the labor rate per unit time at destination, for reassembling,

t_{reass_n} is the unpalletization and reassembling time per SKD modules,

C_{F1} is the facility and storage cost per unit time at origin,

C_{F2} is the facility and storage cost per unit time at destination,

t_{extra1} is the extra time needed at origin, and

t_{extra2} is the extra time needed at destination.

3.2 Simplification of Irregular Shapes

Handling three-dimensional shapes involves meshing over the entire surface of each three-dimensional shape. Bortfeldt and Wäscher (2012) indicated that using triangles for meshing is a common practice in not only three-dimensional CLP, but also other fields such as finite element analysis (FEA). Irregular three-dimensional shapes could need hundreds of thousands triangles to mesh the complicated surface. Computational resources and time could be wasted if the precision of the meshing is over what it is needed. Theoretically, one may want the meshing precision as high as possible to detect the potential interferences between SKD modules, in order to avoid those interferences when planning the loading scheme. However, high precision causes prolonged time in calculations. For example, the computer used in this research needs over 10 minutes to load the engine SKD modules of the John Deere's 9000R tractor, shown in Figure 3.8.

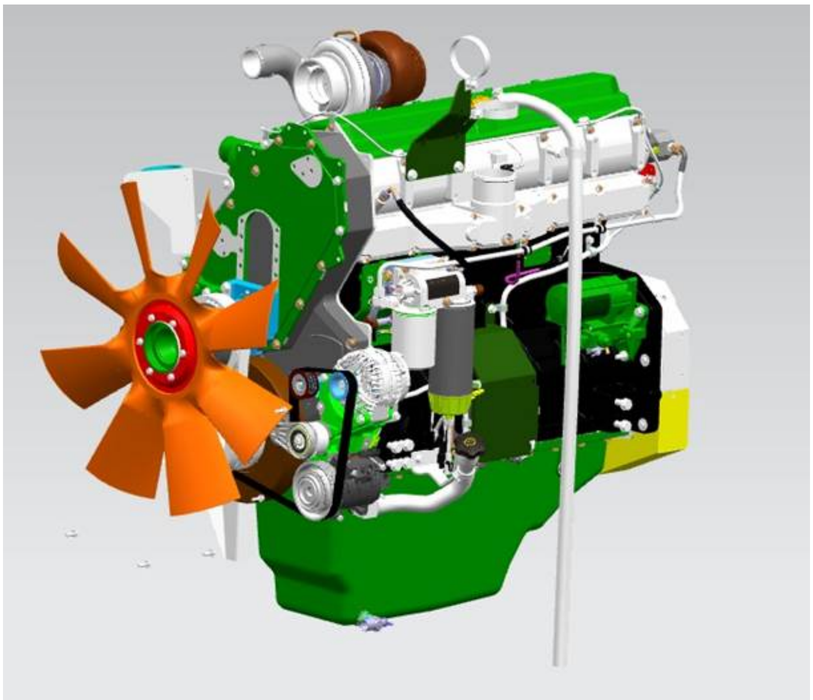


Figure 3.8. Illustration of the engine SKD module in three-dimensional computer-aided designing (CAD) file with permission.

There are more than 140,000 of triangles contained in the meshing of the engine SKD module, with three-dimensional coordinates for all vertex. The number of triangular meshes is counted while importing the three-dimensional computer-aided design (CAD) file into the computer for rendering. Therefore, it is very important to reduce the time consumed for computing meshes. One can use a computer with better performance to tackle this issue. Nevertheless, not all users have the choice to upgrading performance of their computers.

Considering the constraint of eliminating interferences, the author comes up with the idea of applying constraints before placing. Specifically, the constraint of eliminating interferences can be applied to the irregular shapes before actually putting efforts on searching for spot in container without interferences. Imagining wrapping cushions around daily shipments, the shipment will be protected with cushions, with increased overall dimension of the object. Also the surface of the shipment will be smoothed into another shape by the cushions, but still an irregular shape.

Therefore, by simplifying the three-dimensional irregular shapes to a certain extent, the new shape, referred as envelop shape, can tackle two concerns: complicated meshes and constraint of eliminating interferences. The process of creating envelop shapes has three major steps: projection, simplification, and inverse projection.

Projection is actually an action that representing a three-dimensional irregular shape by three two-dimensional irregular shapes, by applying three-way orthogonal projections. Figure 3.9 illustrates the basic idea of orthogonal projections.

Constraints, in the form of image manipulations, will be applied to those 3 two-dimensional orthogonal projections, forming two-dimensional envelop shapes. Raster model discussed in Chapter 2 is one type of image manipulations that could be used for image simplifications. Thereafter, using the same idea of the projection

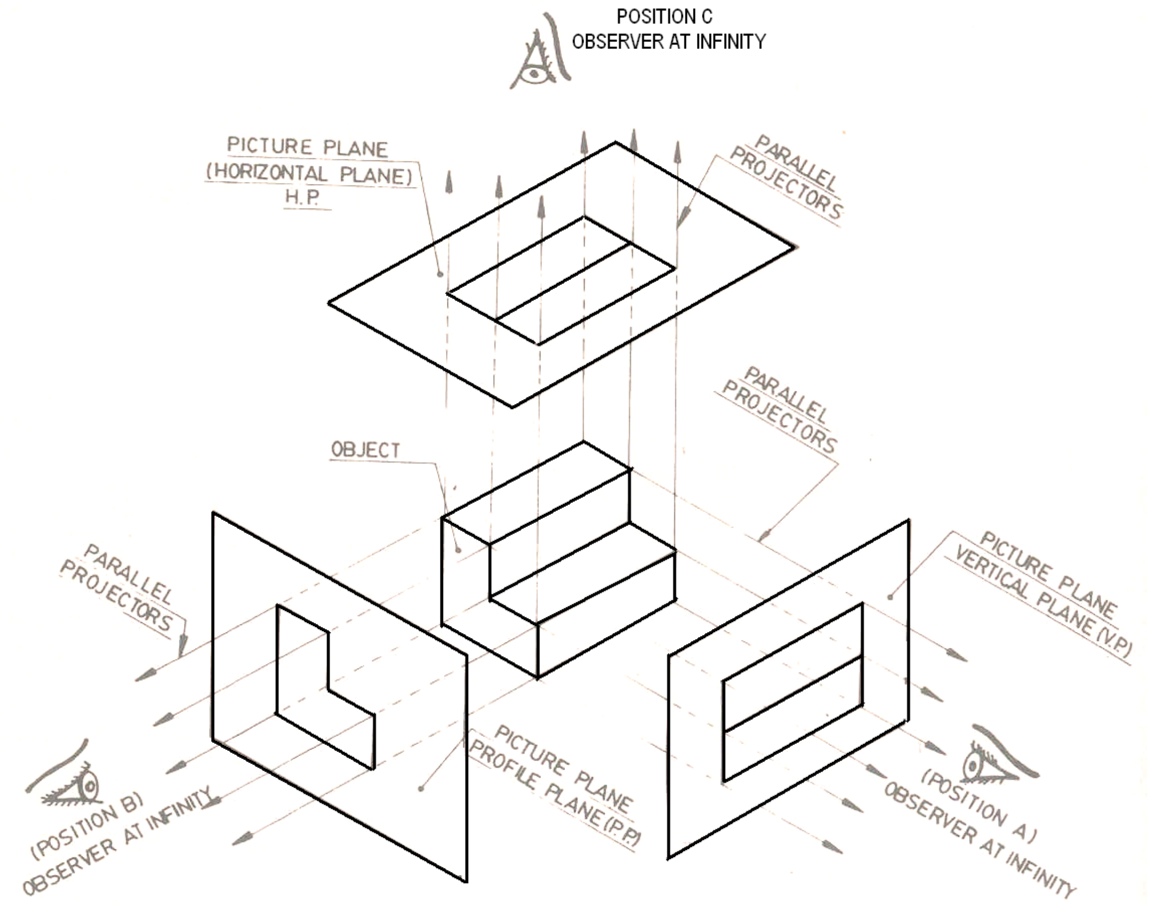


Figure 3.9. Projecting a three-dimensional object into three two-dimensional shapes Miller (2000)

inversely to the two-dimensional envelop shapes, the result is the three-dimensional envelop shape.

Along with the envelop shapes, constraints have to be stored in the database for filtering out improper loading schemes. Each company has their own definitions to the factors that alter the decision making process of the shipping configuration optimization. Properly building and maintaining a constraint database also allows companies to fully understand those constraints and the mechanisms behind them.

3.3 Generating Possible Shipping Configurations

According to the discussion of the intuitive idea in Chapter 1 and the discussion of the current heuristic methods in Chapter 2, the metaheuristic approach in this research uses the following steps.

(a) Select SKD modules with relatively large sizes and heavy weights as core SKD modules.

(b) Place the core SKD modules near the center of the pallet with the area larger than the base area of the core SKD modules.

(c) Place SKD modules with relatively smaller size and lighter around the core SKD modules, on the same pallet, to form the new modules called pallet modules (P-Modules). The small SKD modules are chosen from the pool of SKD modules which satisfy all constraints that required for the shipping.

(d) Regard P-modules irregular shapes and perform the simplification again for envelop shapes.

(e) Place heavier and larger simplified P-Modules into containers near the required CoG.

(f) Fill the container with lighter and smaller simplified P-Modules.

Even though the constraints, eliminating interferences, compatibility, etc., were applied before placing, there still exist a large number of possible shipping configuration layouts (container loading schemes) that satisfy all constraints in the database (LaValle, 2006; Myers, Montgomery, & Anderson-Cook, 2009). Evaluation system needs to be established for finding the optimal shipping configuration (Box & Wilson, 1951; Hesse, 2007).

3.4 Evaluation of Configurations

Key performance evaluation system is constructed in order to rank the suggested shipping layouts by the key performance indicator (KPI). The KPI is calculated based on the quantified criteria that are formulated by the engineers, considering the actually situations in the particular project or case (Arora, 2012; Nguyen & Lo, 2012; Shimada & Yamasaki, 1993; Zhao, 2007). Cutting shipping cost is one of the major goals for manufacturers (World-Trade-Press, 2008), evaluating the shipping configuration layouts by ranking the cost from low to high fits the real world practice in industry. Therefore, cost concerns and other factors are used to be the criteria for constructing the KPI for the container loading problem. For this research, fifteen criteria are selected and listed in Table 3.6 suggested by the shipping experts from John Deere.

Table 3.6: Criteria selected for KPI evaluation.

Indicator	Criterion	Indicator	Criterion
1	Total price from carrier	9	Spatial rank
2	Regulation fine	10	Facility capacity rank
3	Port fee	11	Loading easiness
4	Damage fee	12	Unloading easiness
5	Dis/assembly fee	13	Pallet weight
6	Pallet cost	14	Pallet size
7	Compact ratio	15	Number of pallets
8	Regulation rank		

There is a weight associated with each criteria, distinguishing which on is more important than another. Forced decision matrix (FDM) is applied in order to obtain the relative importance weight for each criterion minimizing the possible human error when distinguishing importance. Define j and k as the index of criteria

$\mathcal{A}$, $j, k \in \{1, 2, \ldots, m\}$. In the case of this research, $m = 15$. Construct an $m \times m$ zero matrix $\mathcal{M}$ for the base of FDM. Forced decision matrix uses two-way comparison to eliminate bias (Belvedere et al., 2013; Bestle & Schiehlen, 1996; Zhao, 2007). That is to say, item $\mathcal{A}_j$ needs to be compared with $\mathcal{A}_k, \forall k \in \{1, 2, \ldots, m\}$. For the case of $j = k$, the criterion is actually comparing with itself, meaning nothing. Therefore, the instance of comparing with the criterion itself is defined as,

$$\mathcal{M}_{j,k} = null, \forall j = k = 1, 2, \ldots, m \tag{3.3}$$

The values for each element in the matrix $\mathcal{M}$ is defined as

$$\mathcal{M}_{j,k} = \begin{cases} 4 & \text{if } j\text{th criterion is much more important than } k\text{th criterion} \\ 3 & \text{if } j\text{th criterion is important than } k\text{th criterion} \\ 2 & \text{if } j\text{th criterion has the same importance } k\text{th criterion} \\ 1 & \text{if } j\text{th criterion is not as important as } k\text{th criterion} \\ 0 & \text{if } j\text{th criterion is much less important than } k\text{th criterion} \end{cases} \tag{3.4}$$

The importance of each criterion is defined as

$$p_j = \sum_{k=1}^{m} \mathcal{M}_{j,k} \mid j = 1, 2, \ldots, m \text{ and } j \neq k \tag{3.5}$$

The relative importance of each criterion is defined as

$$F_j = \frac{p_j}{\sum_{j=1}^{m} p_j} \mid j = 1, 2, \ldots, m \tag{3.6}$$

Each criterion in the KPI has a relevant cost associated with it, that measures how the total cost can be affected if a particular criterion went wrong. Engineers evaluate the cost related to each criterion and denote it as $c_j \mid j = 1, 2, \ldots, m$. Therefore, the relative cost importance of each criterion C_j is

$$C_j = \frac{c_j}{\sum_{j=1}^{m} c_j} \mid j = 1, 2, \ldots, m \tag{3.7}$$

With the relative importance of each criterion in Equation 3.6 and the relative cost importance of each criterion from Equation 3.7, engineer can obtain the value of each criterion V_j, shown in Equation.

$$v_j = \frac{F_j}{C_j} \mid j = 1, 2, \ldots, m \tag{3.8}$$

If the value of a particular criterion is less than 1, it means that the cost associated with the criterion is larger than the importance from the comparison. That is say, that criterion needs to be focused more in order to reduce the total cost of the shipping. If the value of a particular criterion is greater than 1, the criterion has a relatively low efficiency when handling the shipping actions. Therefore, the relative value of each criterion V_j is calculated as

$$V_j = \frac{v_j}{\sum_{j=1}^{m} v_j} \mid j = 1, 2, \ldots, m \tag{3.9}$$

Define $i = \{1, 2, \ldots, z\}$ as the index for the shipping configurations generated, denoted as $\mathcal{H}$, with total number of z of them. After obtaining V_j for each criterion of KPI, the total KPI score K_i for different shipping configurations can be calculated from combing the score of particular shipping configuration ($\mathcal{H}_i$) on jth criterion, denoted as $s_{i,j}$.

To obtain the score on each criterion, evaluation decision method (EDM) is used to generate relatively justified evaluation (Beale, 1959; Khuri & Mukhopadhyay, 2010; Miller, 2000). Let $\sigma_{i,j}$ be the value of parameter that used to evaluate the jth criterion based on ith shipping configuration. Define a linear continuous projective map $f_j : s_{i,j}^{\sigma_{i,j}}$ with rule

$$s_{i,j} = f_j\left(\sigma_{i,j}\right) = \begin{cases} 5 & \text{if } \sigma_{i,j} \text{ has the value of better than ideal} \\ 4 & \text{if } \sigma_{i,j} \text{ has the value of good} \\ 1 & \text{if } \sigma_{i,j} \text{ has the value of worse than passing level} \end{cases} \tag{3.10}$$

To summarize, the final container loading KPI score for ith shipping configuration is expressed as following

$$K_i = \sum_{j=1}^{m} \left(V_j \cdot s_{i,j}\right) \tag{3.11}$$

The scores of the shipping configuration on each criteria will be assessed and registered in each step that involving that particular KPI criteria.

3.5 Summary

Presented in Chapter 3, the major work of this research was discussed in a detailed approach. The detailed composition of the constraints during the entire process of container loading is explained and compiled into mind-maps and programmable equations. Chapter 3 also introduces the concept of envelop shapes for simplifying three-dimensional irregular shapes, especially SKD modules. The three-way orthogonal projection and raster model are discussed along with the possible image manipulations. As one of the core portion of the metaheuristic approach, the placing procedure is discussed, it will be refined along the research in the later chapters. The key performance indicator (KPI) evaluation system, collaborating forced decision matrix (FDM) and evaluation decision method (EDM), is discussed in detail for helping researcher and engineers to evaluate the configurations.

For Chapter 4, the author will introduce the topological representations for shapes, constraints, and container loading problem.

CHAPTER 4. TOPOLOGICAL REPRESENTATION

This chapter will use topology to deals with two issues: representation of shape and representation of container loading problem (CLP). As mentioned in Chapter 1, the definition of the differences between regular shapes and irregular shapes are ambiguous. Also in the same discussion, container loading problem is proposed to be represented in topological words.

4.1 Topological Representation of Shapes

Note in the literature, Egeblad, Garavelli, Lisi, and Pisinger (2010) categorized only rectangular shapes are regular shapes, while Wäscher et al. (2007) thought regular shapes should include rectangles, circles, boxes, cylinders, balls, etc. In Euclidean geometry, regular shapes are actually regular polygon. The regular polygon is defined in two-dimensional space which is equiangular and equilateral (Hauser, Hegen, & Theisel, 2007). Equiangular means all (inner) angles are equal, while equilateral means all sides of the polygon have the same length.

According to the above definition, the regular shapes can be convex or a star-like. Convex shapes are those can be deformed into a ball, or balloon, if it is made of rubber that can be freely stretched without breaking. The aforementioned deformation can be imagined as blowing a balloon. The ability of being blown to a balloon is actually the intuitive understanding of homeomorphic. Homeomorphism is a continuous, one-one, and onto function which has continuous inverse from one space to another (Armstrong, 1983). Homeomorphism can also be defined as a function $f : X \to Y$ from topological space (X, T_X) to another topological space (Y, T_Y), which has the following properties,

- f is continuous,

- f is a bijection (one-to-one and onto), and
- the inverse function f^{-1} is continuous, as well.

Homeomorphism is also called as bicontinuous and the function f is an open mapping. The expression of (X, T_X) means a space X with its own topology T_X defining the measuring rules in that space (J. Wang, 2001).

From the above ambiguous definition, it seems that the irregularity of the shapes presents how difficult for placing and arranging the shapes into a certain space without overlapping. If that is the case, shapes homeomorphic to ball (or plate in two-dimensional) may be irregular, while shape not homeomorphic to ball may be quite easy to handle as regular shapes. Therefore, the author proposes that the irregularity of the shapes should be judged by whether its triangular mesh is equivalent to a tree.

Before discussing the above argument, there are several concepts need to be clarified (Armstrong, 1983; Lamberson Jr., 2011). A connected set of vertexes and edges of P will be called a graph. Tree, in topology, is a graph that does not contain any loops. Therefore, the graph in Figure 4.1(a) is a tree, while the graph in Figure 4.1(b) is not a tree, due to the loop in the graph.

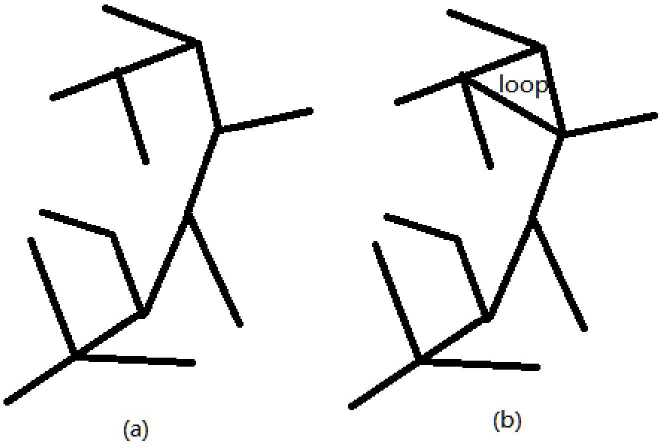


Figure 4.1. Illustrates the differences between tree (a) and graph (b)

Let f, g: $X \rightarrow Y$ be maps. f is homotopic to g if there exists a map $F : X \times I \rightarrow Y$ such that $F(x, 0) = f(0)$ and $F(x, 1) = g(x)$ for all points $x \in X$ (J. Wang, 2001). Figure 4.2 shows that path a, b, c are homotopy, connecting 0 and 1. Path d is not homotopic with path a, b, c due to crossing a hole.

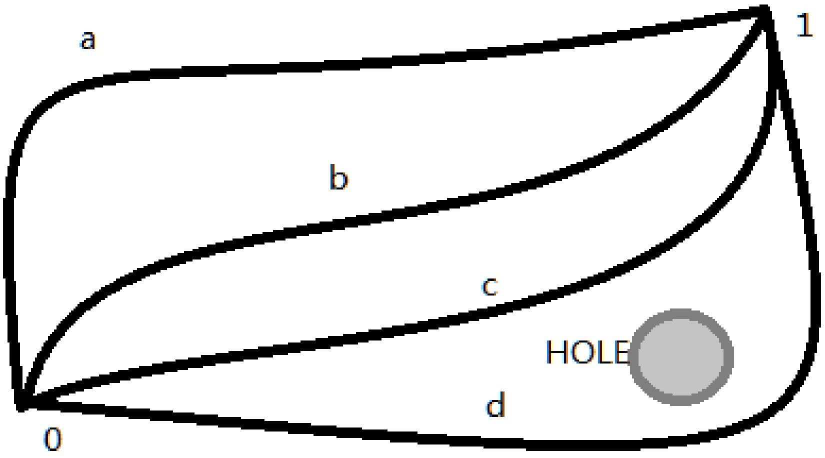


Figure 4.2. Illustrates the homotopic paths a, b, c, and d

Shown in Figure 4.3, the path 1-2-4 is homotopic to path 1-3-4 and path 1-4. Similarly, the path 3-1-2 is also homotopic to path 3-4-2 but not path 3-2. Homotopic equivalence defines the homotopy group can be equivalent as a single path (Armstrong, 1983). That is to the shape in Figure 4.3 can be simplified as path 1-4 by applying homotopic equivalence relationship.

The author proposes that if a triangular meshed shape can be simplified into tree, without any loops, that shape is topological regular. That is to say, the shape shown in Figure 4.3 is topological regular. Shown in Figure 4.4(a)(b)(c), there are three triangular meshed shapes.

After simplifying shapes in Figure 4.4(a)(b)(c), are turned into Figure 4.4(d)(e)(f). Since shape (d) is tree, shape (a) is regular. Shape (e) is same as shape (a), therefore, shape (b) is also topological regular. Shape (f) is not a tree

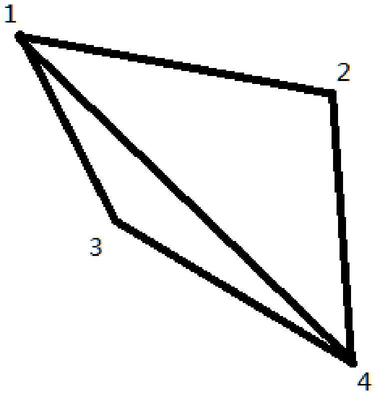


Figure 4.3. Illustrates how homotopic equivalence is identified

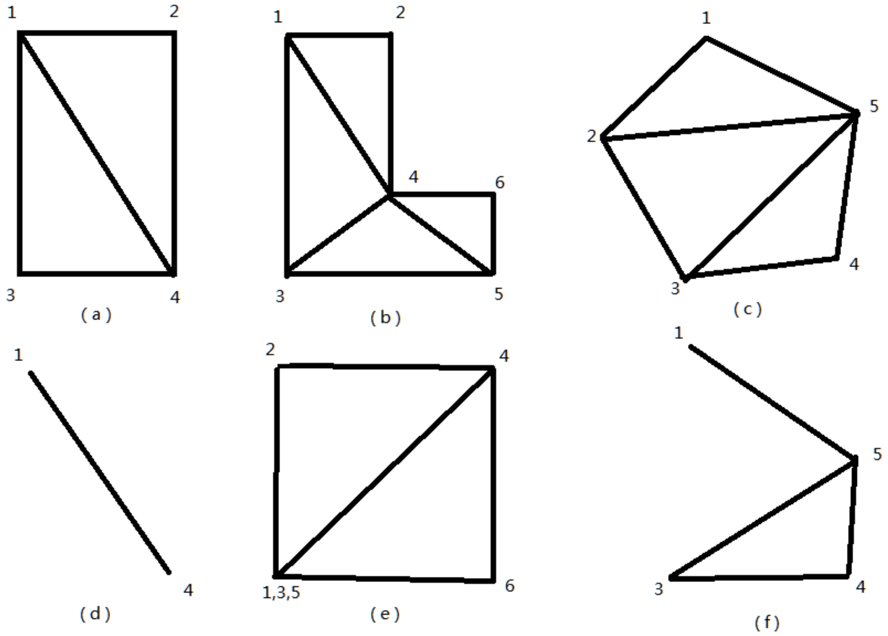


Figure 4.4. Illustrates homotopic equivalence for triangular meshes

and can be further simplified using homotopic equivalence relationship. Thus, shape (c) is topological irregular.

Apart from the above example, Figure 4.5 provides another set of examples comparing pentagon and hexagon in sub-figure (a) and (b). The pentagon and hexagon are simplified to the graphs shown in sub-figure (c) and (d), respectively. According to the definitions, the graph in the sub-figure (c) has a loop, while the graph in sub-figure (d) does not. Therefore, the hexagon can be simplified into a tree graph, but the pentagon can not. Categorizing pentagon as irregular shape and hexagon as regular shape corresponds to the easiness of handling when packing them into a certain space. For example, hexagons can form bee-cone-like packing solution, while pentagons cannot be easily packed in the similar way.

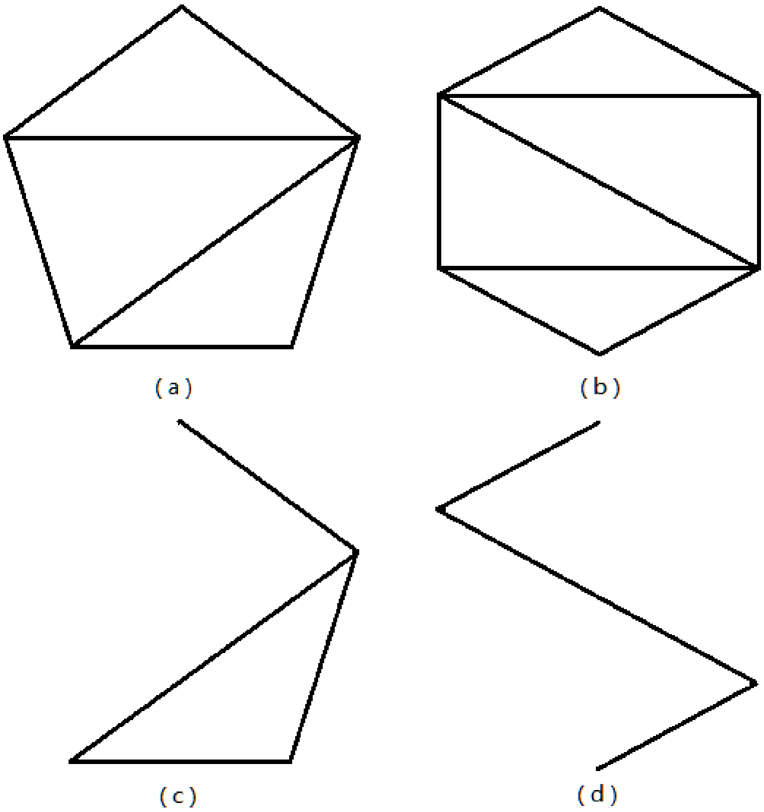


Figure 4.5. Illustrates examples of applying homotopic equivalence to simplify pentagon and hexagon. The new definition demonstrates the ability of differentiating regular and irregular shapes from the topological aspect, as well as from the easiness of CLP handling aspect.

This homotopic equivalence is applicable for three-dimensional triangular mesh as well. The only difference is the homotopic equivalence relationship can only be applied inwards to the three-dimensional object. It is because that homotopy relation cannot cross holes as demonstrated in Figure 4.2. Holes in both two- and tree- dimensional spaces are boundaries and restrictions for homotopic relation as the continuous map cannot be broke for valid homotopy relations.

4.2 Topological Representation for CLP

Container loading problem is actually the action of placing a set of well-defined objects into a set of well-defined space following a set of well-defined constraints. There are two steps for topologically representing container loading problem, expressing spaces and expressing placing process.

4.2.1 Expressing CLP Spaces

The target space, such as the container, is a compact, connected space in the real world application due to $\mathbb{E}^3$. Where compact means that a subset of a space is closed, containing all its limit points and bounded. If a space is not the union of two disjoint non-empty open set, the space is called connected. Denote the given available target spaces as T_i, where i is an index. Let the different type of the items, which need to be places into the containers, be S_j, where $j \in J$, another set of index. Since the items are also defined in $\mathbb{E}^3$, the items are compact and connected spaces. Both the target spaces and item spaces share the same measurement and metric. Similarly, three-dimensionally existing objects share the aforementioned properties, they are — pallets, racks and so on. The assembling process can be considered as pasting one or more pairs of homomorphic subspaces which belong to different items (Parvizian, Düster, & Rank, 2011). Homomorphism stands for a map between two algebraic structures that preserving the structural properties (Armstrong, 1983;

Bendsoe & Sigmund, 2003; Fulton & MacPherson, 1994). This process creates new compact and connected space that is the union of the two items.

The container loading process can be consider as identification of remaining space. This idea can be represented from the following two aspects: quotient space and covering space.

4.2.2 Expressing CLP Process in Quotient Space

Quotient space is considered as pasting all the point with the same properties into one point (Armstrong, 1983). Therefore, after placing an arbitrary item S into the specific space T, the occupied spaced is removed from the remaining space. It is the same as pasting all the points of S into one single point as quotient space $T/mod(S)$. Here, the equivalent relation established among all the points belong to S is that S is the union of all its points.

With this representation, the remaining space Tr_i after placing the ith in the target space is:

$$Tr_i = \frac{Tr_{i-1}}{mod(S_i)} \tag{4.1}$$

where Tr_{i-1} is the quotient space of the remaining space before placing the ith object. S_i is the ith object to place.

4.2.3 Expressing CLP Process in Covering Space

Let $p : E \longrightarrow B$ be a continuous surjective map. The open set U of B is said to be evenly covered by p if the inverse image $p^{-1}(U)$ can be written as the union of disjoint open sets V_α in E such that for each α, the restriction of p to V_α is a homeomorphism of $\{V_\alpha\}$ onto U (Armstrong, 1983; Bendsoe & Sigmund, 2003). If every point b of B has a neighborhood that is evenly covered by p, then p is called a covering map, and E is said to be a covering space of B. Figure 4.6 shows the covering space induced by map p.

Figure 4.7 shows the map p taking multiple covers to the preimage space.

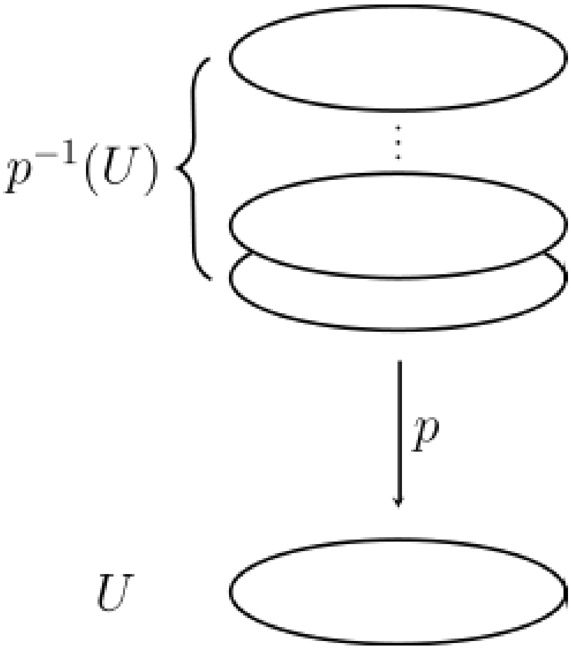


Figure 4.6. Illustration of covering space with function p connecting cover spaces $p^{-1}(U)$ to original space U (Armstrong, 1983)

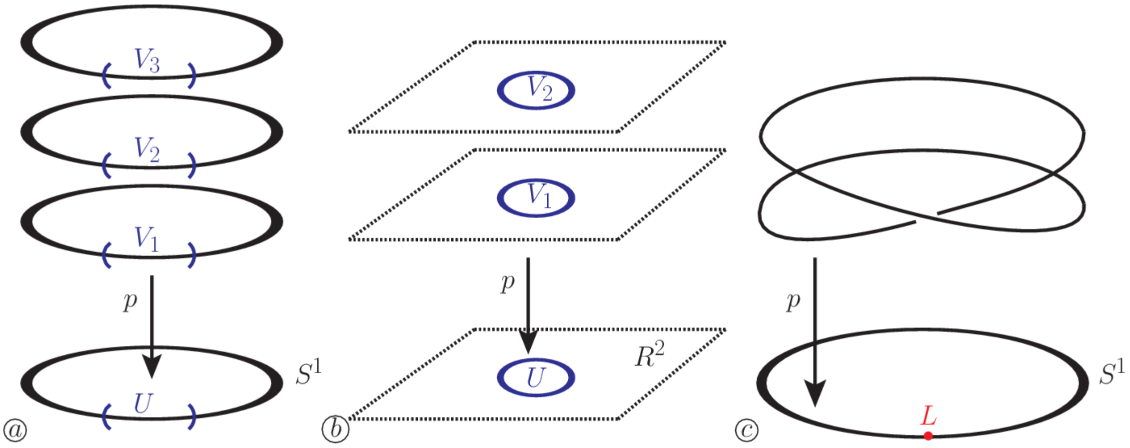


Figure 4.7. Illustration of covering map p connecting V_n to S^1 (Armstrong, 1983)

According to the definition, let space E represent a certain space, and the disjoint V_α are the non-interference objects (SKD modules) placed in it. Map p is a well-defined continuous surjective map that identifies itself as a certain container loading scheme. Position b is a target center of gravity (CoG) in the new container space B. That is to say, container loading scheme p takes all the objects $\{V_\alpha\}$ from a unconstrained space E to a constrained space B, with the images of $\{V_\alpha\}$ in B may not be disjoint (Hauser et al., 2007). Space B can be pallet space if space E is objects space, and space B can be container space if space E is P-Module space. For a single set of items in the space E, there are infinitely many covering map p. Testing the disjointness can be the constraint for eliminating interferences: if the images of $\{V_\alpha\}$ in B are disjoint, we consider this container loading scheme p satisfies the spatial constraint; if not, the loading scheme p is a fail.

The major benefit of using covering map to represent container loading problem is that the shapes in space E and B are homeomorphism. Topological invariants are remained unchanged with homeomorphic transformation. Meanwhile, the constraints attached to the topological invariants are also preserved under covering map (S. Lin, 2004). In other words, global constraints, such as compatibility of commodities, can be transferred to local constraints. Also, local constraints, such as easiness of loading, can be transferred to global constraints. Along with the homomorphism in quotient space, which preserves structural relationships, the KPI evaluation system can be applied to any steps in the entire container loading process.

In this way, simplifying the searching process by applying constraints in different steps, at different time is possible, as well as controlling the searching direction. Moreover, KPI can be also applied for filtering out infeasible search results by evaluating shipping configurations at each search step along the searching path.

Expressing the relationships of irregular shape and regular shape helps clarify the differences between each other, making the researchers and engineers understand the type of shape that they are dealing with, and then choose approaches wisely (Zhang, Dai, & Fang, 2010). Topological representation of the container loading problem opens the door of finding solutions to the container loading problem from other approaches. With topological representation, one may transfer the container loading problem from the current domain to another one preserving the properties, in which the new domain may provide easier way to solve the problem.

4.3 Summary

Chapter 4 introduces topological methods of expressing irregular and regular shapes and made the definitions of both clearer than the existing ambiguous ones. The topological representation of the container loading problem has been approached from two different aspects, quotient space and covering space. In next chapter, pixelation and pallet modules will be introduced as they are derived from the topological concepts mentioned in this chapter.

CHAPTER 5. PIXELATION AND PALLET MODULES

Before the actual placing of the shipments into containers, simplifying the irregular shapes by creating the envelop shape. This chapter will focus on the details of manipulations to the two-dimensional orthogonal projection shapes and applying virtual cushion, pixelation, and overlap detections.

5.1 Virtual Cushion

Virtual cushion is applying cushion around the shipment, like gift-wrapping, to form the envelop shapes for two-dimensional shapes from the orthogonal projection mentioned in Chapter 3. One benefit from creating envelop shape and wrapping the shipment with virtual cushion is simplifying the complex contour of the irregular shape. The other benefit is including the constraint of eliminating interferences before placing process, which is also discussed previously. The actual image manipulations have three components: outlining, validating, and inflation.

5.1.1 Outlining Two-Dimensional Contour

The goal for the image manipulations in the actions of applying virtual cushion is enlarging and smoothing the complicated surface of the irregular shapes. Three-dimensional enlarging involving three-dimensional vectors for every triangles in the mesh of the object. By setting the thickness of the virtual cushion, two triangles from the meshed surface may collide with each other or totally get through each other. These conditions are unwanted and not easy to tackle under two-dimensional image manipulation.

The three-way orthogonal projection provides the possibility of dealing the virtual cushion under two-dimensional space. With the $x - y - z$ three-dimensional coordinate, the irregular shape will be orthogonally projected onto $x - y$ plane, $x - z$ plane, and $y - z$ plane (Lengyel, 2012). Before enlarging the two-dimensional image from the orthogonal projections, the outline contour needs to be identified. This process is started from rendering the three-dimensional image of irregular shapes onto the screen. Distance factor, λ, is used to set up a relationship between the actual dimensional of the irregular shapes and the size rendered on the screen, defined in Equation 5.1.

$$\lambda = \frac{D}{d} = \frac{\text{Distance in real world}}{\text{Distance on-screen measured from real world}} \tag{5.1}$$

The on-screen distance measured from real world varies depending on the size of the screen and the resolution (Angel & Shreiner, 2011; Peters, 2014). Let h and w be the width and height of the resolution, number of pixels, for a particular screen. Let R represents the diagnose size of the screen. Then the on-screen distance per pixel, Λ, can be approximated as shown in Equation 5.2.

$$\Lambda = \frac{R}{\sqrt{h^2 + w^2}} \tag{5.2}$$

The image on the screen is scanned for shape of the object with the coordinates of the points at the shape edge (Angelides & Agius, 2011; Brunelli, 2009). The edge and the interior of the shape are marked differently, which will be used later for inflation. The logical process of outlining the contour can be expressed in pseudocode, shown in Algorithm 5.1.

Algorithm 5.1 Outlining contours of two-dimensional projection shape

```
Initialize Pixel Color ← null;
Obtain object projection shade for certain plane of three orthogonal projections;
foreach row of pixel on-screen do
    foreach pixel in the row do
        if this pixel in object projection shade then
            Pixel Color ← blue;
        else
            Pixel Color ← white;
        end
    end
end
foreach row of pixel on-screen do
    for $i = 2$; $i <$ number of pixels per row; $i++$ do
        Initialize L ← Pixel Color of $(i - 1)$th pixel;
        Initialize C ← Pixel Color of $i$th pixel;
        Initialize N ← Pixel Color of $(i + 1)$th pixel;
        if $L \neq N$ then
            if $L =$ red $| N =$ red then
                Continue;
            else
                C ← red;
            end
        else
            Continue;
        end
    end
end
```

The action of rendering the image onto the screen for identification of contours can be performed off-screen (Eck, 2010). Using off-screen rendering will let the computer graphics process unit (GPU) load the information from the irregular shape, in computer-aided design (CAD) file. Calculations and manipulations toward the information in the GPU can be conducted by GPU or the central processing unit (CPU) or the computer (Farrell, 2009; Hees, 2006).

The two-dimensional orthogonal projection of the irregular shape is now formed with outline contour marked in different color. The distance factor for each irregular shape since the sizes of them are different and they have to be filled into the screen in order to perform the image manipulations. Take the John Deere 9000R tractor as an example, among those SKD modules, the largest is more than 6 meters in length 1.8 meters wide, 2 meters high. The smallest SKD modules is 20 cm long, 10 cm for width and height. However, this method is not limited to the size of the screen. One can split the whole projected shape into sections and use screen to render them, identify contours one by one. Moreover, apart from the distance factor, more information should be carried along the contour identification process, such as the starting and ending corner of the particular section in that whole projection image.

5.1.2 Validation for Contour

The image manipulations are based on the three-dimensional visualization file, which could be the computer-aided design (CAD) file of the SKD modules from the manufacturer. For those instance that unable to obtain the three dimensional CAD file, taking multiple photos and combine them into three-dimensional CAD file is possible through free-ware, such as Google Sketch®. The CAD file only represents the shape of the parts in the same way of how they are assembled, often different from how they are wrapped and shipped. For example, the side mirrors of the John Deere 9000R tractor, which are mounted in the cabin SKD module. In the CAD file of the cabin SKD module, those side mirrors are extended and unfolded.

When actually packing and shipping the cabin SKD module, those mirrors are folded and wrapped with bubble wrap.

Therefore, it is important to observe or familiar with how the shipments are actually being packed. From the observations and on-site investigations, validations need to be conducted to those two-dimensional orthogonal projections. Comparing with the actual packing methods and the projection image, one can correct the projection image according to the observations and use the modified one for later image manipulation.

5.1.3 Inflation of Contour

When the corrected contours of the two-dimensional orthogonal projection images are available, inflation will enlarge the outline contour with a certain amount, called inflation rate, denoted as Q. The inflation rate is defined as the distance from the surface of three-dimensional shape, or from the outline of the two-dimensional image. The distance is predefined by the shipping engineers according to the minimum clearance that the manufacturer would like to set between SKD modules or other objects. As discussed above, there is a distance factor that relates the actual irregular shape dimensional and the size on screen as an image. Therefore, the inflation rate can be a real life length, with the distance factor implementing the conversion between inflation rate and on-screen distances. That is to say, if the inflation rate is 10 cm, the result of inflation may be visualized as being wrapped for the thickness of 10 cm.

The logical process for the inflation is shown in Algorithm 5.2. As the outline contour and the interior of the two-dimensional orthogonal projection image are color coded differently, the newly generated inflated region can be colored to the same as the interior. Construct a circle centered on the outline contour with the radius set to the on-screen distance of the inflation rate. The region inside the circle will be color coded as the same color as the interior color. Performing this action for all outline points will have the outline inflated.

Algorithm 5.2 Inflation to the two-dimensional projection shape

```
Data: Inflation distance $d$ (in pixels)
foreach row of pixels on-screen do
    foreach pixel in that row do
        Initialize $C \leftarrow$ Pixel Color of current pixel;
        if $C = red$ then
            Mark pixels around current pixel with radius $d$ to blue;
        end
    end
end
```

One may argue that not all portion of the shipment need the same thickness of wrapping, and using same amount of inflation rate may induce the following situation: over-protecting will waste of space, while under-protecting will place the shipment in risk of interference. Possible solutions for this concerns include introducing non-uniform inflation by adding one more command to the Algorithm 5.2 for checking the thickness of the object underneath the surface. Generally speaking, the thinner of the underneath object, the thicker of the wrapping for protection. Then maximum, minimum, and the incremental rate can be set by the engineers to control how the inflation will be added onto the surface of the outline contours. Since this involves company regulations and preferences, the customization of this concept is left for future research.

Figure 5.1 illustrates the processes of the identifying the outline contours, correction of the outlines, and inflation to the irregular shaped image. The engine SKD modules of John Deere 9000R tractor is used as an example. The blue line is the outline contour identified, while the red ling is the inflation result with 10 cm inflation.

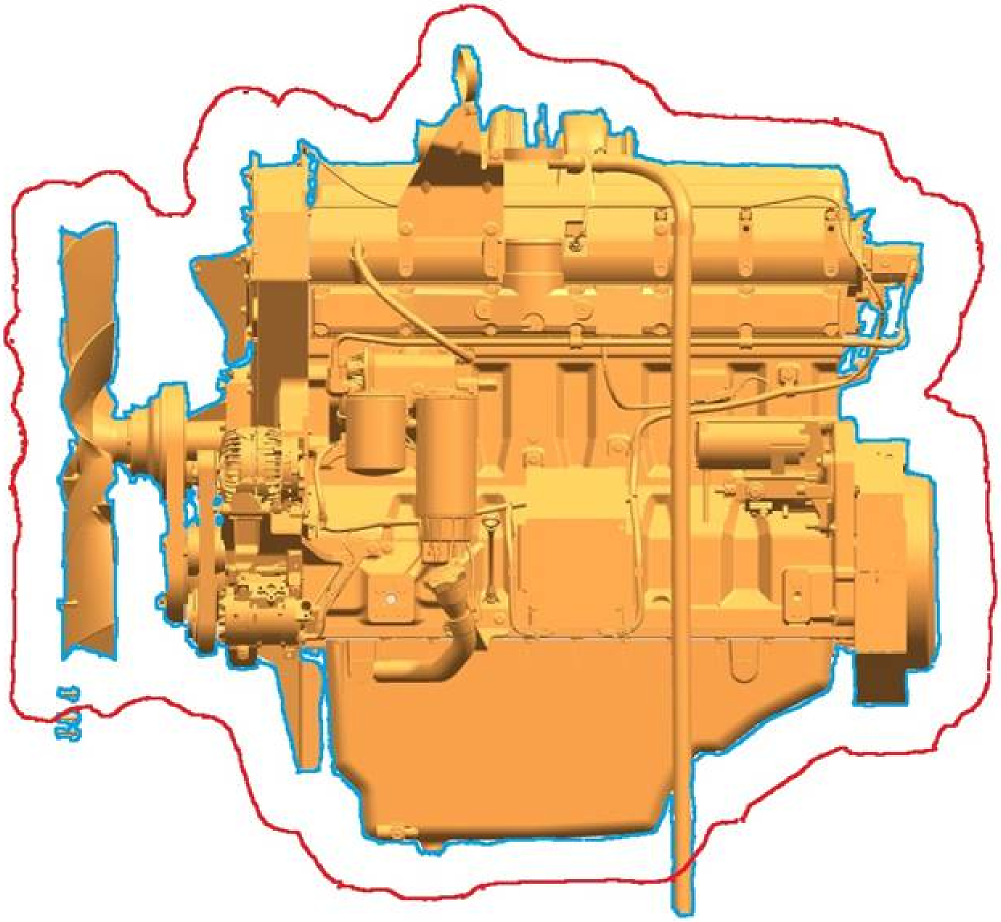


Figure 5.1. Cushioning process performed on the virtual target — side orthogonal projection of the John Deere 9000R tractor engine SKD module.

In Figure 5.1 above, the part that sticking out the red cushion outline located near the bottom of engine SKD turns out to be a rubber pipe. According to the observation to the physical engine SKD, that rubber pipe is gently wrapped and fastened on the engine by workers. Hence, that particular part is ignored for the cushioning process. Meanwhile, on the left-hand-side of the image under the fan blades, several screws are misplaced due the CAD model error. Those screws are also removed from the outline contour since they supposed to be the fasteners for the fan blade at the location near the rotating axis of the fan.

If the gap, outside the irregular shape, is too small compare to the inflation rate, the gap will be filled as the interior. For example, in the engine SKD module shown in Figure 5.1, the gap between the fan blades and the engine main body is smaller than the 10 cm inflation rate. The result from inflation is filling those gaps and consider as interior.

5.2 Pixelation

The cushioning process adds a certain level of protection to the irregular shaped shipments. However, in order to ensure there is zero interference and zero potential interferences under possible extreme dynamic conditions, there is another “layer” of protection virtually coated onto the irregular shaped shipments with the process of pixelation. Pixelation places the two-dimensional shape onto a virtual chessboard when rendering on-screen or off-screen. The cells of the chessboard, referred as pixels, are used to set up the resolution of the envelop simplification. The size of the pixels is defined by the engineers, similar to the inflation rate, as real world length. The length of inflation rate and pixel size can be in any units that measuring length, as long as using the same to measure the irregular shapes, due to the same distance factor.

Therefore, when coving the two-dimensional shape onto the virtual chessboard, a certain number of pixels will be fully occupied, while a certain number of pixel may be partially occupied. Partially occupied pixels are considered as fully occupied ones if the occupation percentage higher than a predetermined value, cut-off rate, denoted as α. If the occupation percentage is less than the cut-off rate, that particular pixel is considered as unoccupied. The pixel shown in Figure 5.2 should be treated as occupied if $a_i/A_i > \alpha$, where a_i is the shaded area covered by the image and A_i is the entire area of the pixel.

Figure 5.3 demonstrated pixelation on the same outlines from the engine SKD module and marked occupied pixels as red.

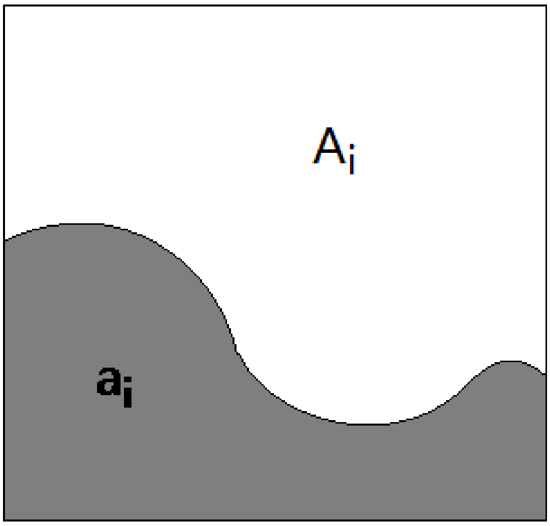


Figure 5.2. The cut-off ratio regulates the boarder of treating the pixel as occupied or unoccupied.

Pixelation is modified from the raster model, widely used in the industries for topological optimization, as well as machine vision (Bendsoe & Sigmund, 2003; X. Huang & Xie, 2010). Raster model equivalent to the pixelation if set $\alpha = 0\%$, meaning that cells will be considered as occupied as long as being covered for any portion of that cell. However, pixelation is more flexible with engineers' predefined cut-off ratio. To make sure all portions of the SKD modules are fully protect but not over protected, the pixelation cutoff ratio and inflation rate value should be and are jointly determined by shipping configuration experts. One more factor that measuring the size of the pixel is defined with the distance in real world, named round-up size, denoted as ζ. For example, 10 cm round-up level stands for a pixel in actual size as $10cm \times 10cm \times 10cm$ cube. With the relationships shown in Equation 5.1 and Equation 5.2, the round-up size can be converted to on-screen distance. Shown in Figure 5.4, an improper using the combination of cut-off ratio and round-up size leads a portion of the inflated irregular shape sticking outside the two-dimensional envelop shape. If the inflation rate is not large enough, the actual

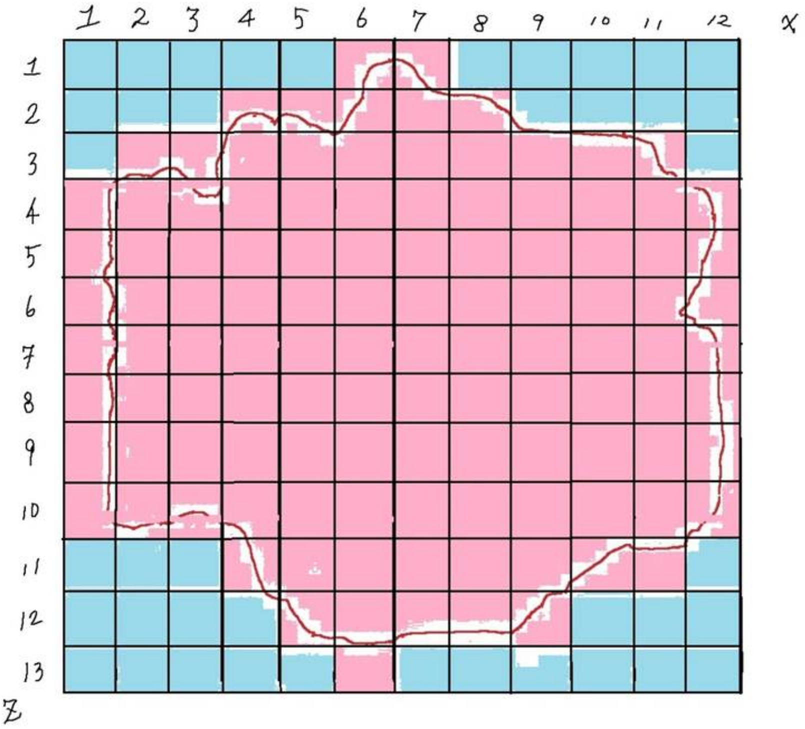


Figure 5.3. Pixelation on the side orthogonal projection image of John Deere 9000R tractor engine SKD module

portion of the irregular shape may be exposed outside the protection from both inflation and pixelation.

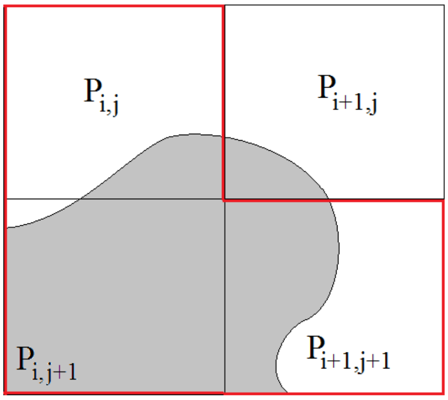


Figure 5.4. Demonstration of the result possible result of inappropriate round-up size and pixelation cut-off ratio combination ($\alpha = 10\%$). The pixels inside the red lines are recognized as occupied pixels. That is to say that the pixel $P_{i+1,j}$ is categorized as unoccupied. Therefore, the part (shaded area) has a certain segment excluded from the simplified shape, which introduce potential damage when fitting other part into that pixel.

When planning for the worst case, Equation 5.3 shows the limit for combining the values of inflation rate, round-up size, and cut-off ratio.

$$Q > \zeta \cdot \alpha \tag{5.3}$$

Under this limit, the actual portion of the irregular shape will not be outside the envelop shape as the inflation cushion is thick enough to overcome the under recognition of the pixelation.

5.3 Reassembling Simplified Irregular Shapes

The three two-dimensional orthogonal projection images are pixelated into envelop shapes. Similar to the projection mentioned before, the inverse action can take those three images back to one three-dimensional shape (Govil-pai, 2004; Kaufmann & Wagner, 2001; Kumar, 1995). The steps for the inverse projection are illustrated in Algorithm 5.3.

Algorithm 5.3 Inverse projection for two-dimensional envelop shape reassembling.

```
Obtain pixel dimension from $x - y$ plane, $x$ and $y$;
Obtain pixel dimension from $y - z$ plane, $z$;
Construct three-dimensional zero matrix $\mathcal{M}$ with size $x \times y \times z$;
for each plane do
    Construct two-dimensional matrix with plane dimension;
    Let elements represent the occupied cells to be 1;
end
foreach layer of the matrix along $z$ do
    Add values of $x - y$ matrix to elements of $\mathcal{M}_z$;
end
foreach layer of the matrix along $y$ do
    Add values of $x - z$ matrix to elements of $\mathcal{M}_y$;
end
foreach layer of the matrix along $x$ do
    Add values of $y - z$ matrix to elements of $\mathcal{M}_x$;
end
Assemble elements with value 3 and their coordinates to three dimensional envelop shape;
```

From the left-hand side portion of Figure 5.5, the new object is much simpler than the original engine SKD modules (showed as the right-hand side portion of the same figure for comparison). These simplified SKD modules are used to perform the formation for Pallet Modules, which is discussed in the following section.

Form the Figure 5.5, the complicated shape of the original engine SKD module has simplified to the envelop shape, which is irregular shape but simply

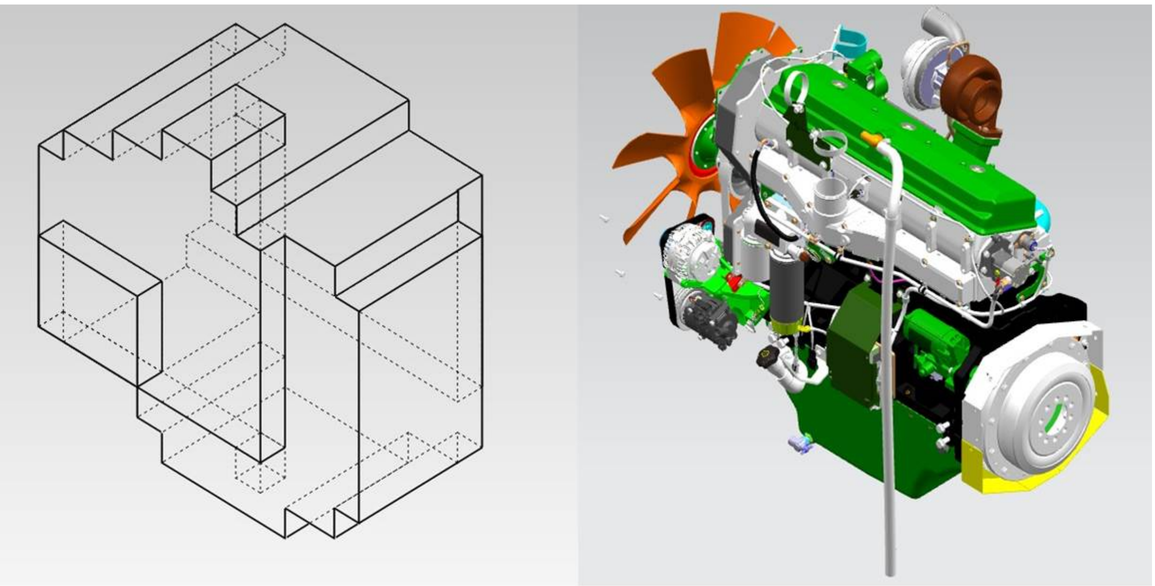


Figure 5.5. Three-dimensional simplified shape (left) compared with original three-dimensional John Deere 9000R tractor engine SKD module (right). Inflation rate $Q = 10$ cm, round-up size $\zeta = 10$ cm, and cut-off ratio $\gamma = 50\%$

enough. The envelop shape still keeps a blurred shape of the original irregular shape, very similar to wrapping the object with cushion.

5.4 Placing SKD Modules into Pallet Modules

Irregular shaped shipments need to be placed on a certain form of pallet or into a certain form of boxes due to the irregular shape. According to the previous discussion, the envelop shapes from the irregular shaped SKD modules are placed on the pallets, which are considered as regular shapes. More specifically, the pallet are recognized as an empty cuboid with the dimension of the pallets. For the conditions that the pallets have not yet been designed, one can use the certain dummy dimension as a starting point for refining the design. Finding the dummy dimension will be discussed later in this section.

5.4.1 Identify Core Objects

The physical properties of the irregular shaped shipments usually vary a lot in terms of weight, size, orientation, and so on. However, the key factors of placing objects onto pallets or other forms of containers are very limited: volume, stability, and weight. These are also topological invariants in the Euclidean space. For example, the topological space that contains only the irregular shape object includes information of the irregular shape will not change when placing the irregular shape in the topological space of pallets or boxes (Saleem, Khan, & Ch, 2012; Shi, Yao, & Ma, 2005). The volume that the irregular envelop shape occupied and the weight of it will remain the same on pallet or in container. The irregular shape's stability of the particular pose, or orientation, will be same no matter in the space of the pallet or the space of containers. Other attached to the invariants include compatibility, hazardous conditions, easiness of loading and so on.

Since this properties are identical before and after loading onto pallets or containers, one can tackle the constraints discussed earlier in the relatively simple space environment (Spelta & Araújo, 2012). That is to say, the topological space created by a pallet is simpler than a large container space, because of smaller size and less other constraints, such as axle load.

To address the space, stability, and weight in the pallet space, the shipment objects need to be categorized for determining the priorities. Weight and Volume are two factors that used for categorizing the objects. If the weight of a particular object is higher than the average weight of the set of shipments, that object is categorized as *heavy*. If lower than the average weight, that object is categorized as *light*. If the volume of a certain object is larger than the average volume of the set of shipments, that object is categorized as *core*. If smaller than average volume, that object is categorized as *minor*. Table 5.1 listed the criteria and categories of the shipment object.

Table 5.1: Categorizing the shipment objects into group depending on the size and weight.

Volume	Heavy in Weight	Light in Weight
Large	Heavy Core (HC)	Light Core (LC)
Small	Heavy Minor (HM)	Light Minor (LM)

5.4.2 General Searching Sequence for Pallets

Higher stability can be achieved by locating the center of gravity (CoG) as low as possible and near the center of the container or pallet. Since heavy object affects the CoG more than light objects, the heavy SKD modules should be placed close to the center of the pallets and as low as possible. On the other hand, locating the light core (LC) near the center of the pallets and placing heavy minor (HM) on the same pallet also work maintaining the stability. Therefore, general loading sequence of the SKD modules onto pallet should be placing the heavy ones near the center of the pallet and other light weighted ones around, described in Algorithm 5.4.

Algorithm 5.4 General searching sequence of SKD modules onto pallets

```
Obtain list of HC, LC, HM, LM objects and rank from heavy to light;
foreach set or subset of shipment do
    Initialize List Empty ← 0;
    while List Empty $\neq$ 1 do
        Function: Search Placing (HC Object List);
    end
    List Empty ← 0;
    while List Empty $\neq$ 1 do
        Function: Search Placing (LC Object List);
    end
    List Empty ← 0;
    while List Empty $\neq$ 1 do
        Function: Search Placing (HM Object List);
    end
    List Empty ← 0;
    while List Empty $\neq$ 1 do
        Function: Search Placing (LM Object List);
    end
end
Function: Search Placing (object list)
if object list empty then
    List Empty ← 1;
else
    Choose the heavies unsettled HC from the list;
    Locate it at the center of the pallet;
    if outside the pallet then
        Move the selected object to fit the pallet;
    else
        Continue;
    end
    Estimate remaining space;
    Update the lists with those larger than the estimated space being filtered out;
end
End Function
```

If the pallets have not been designed yet, the initial trial value may be set to a certain value more of the shade area of the core objects for that pallet. The extra amount of the area on the pallet may be determined depending on the size of the core compared with the size/ door opening of the container.

5.4.3 Constrained Searching Sequence for Pallet

Compatibility of the SKD modules in the container is very important for reducing the possible tax and other unwanted boarder control troubles. Intuitively, among the total number of possible shipping configuration layouts regarding to the defined shipments and containers, there should be many layouts that conflict with the compatibility requirements. However, filter those invalid shipping configuration out from the result can be tedious due to much more searching and evaluations actions on those huge number of possible shipping configurations. By using the SKD modules, that capable for the constraints, to search for possible placement, three dimensional searching can be replaced by text searching. The above idea can be implemented by adding compatibility search before placing, shown in Algorithm 5.5

Algorithm 5.5 Total weight checking added to the search function

Function: Search Placing (object list)

```
if object list empty then
    List Empty ← 1;
else
    Choose the heavies unsettled HC from the list;
    if the SKD module(s) currently on pallet is compatible with the one just selected
    then
        Continue;
    else
        Break;
        Update the list by removing the selected one;
    end
    Locate it at the center of the pallet;
    if outside the pallet then
        Move the selected object to fit the pallet;
    else
        Continue;
    end
    Estimate remaining space;
    Update the lists with those larger than the estimated space being filtered out;
end
End Function
```

The weight limit of the pallet can be controlled by adding command of checking weight limit to the searching function in Algorithm 5.4, which is shown in Algorithm 5.6.

Algorithm 5.6 Total weight checking added to the search function

```
Function: Search Placing (object list)
if object list empty then
    List Empty ← 1;
else
    Choose the heavies unsettled HC from the list;
    if the remain weight less than the selected then
        Continue;
    else
        Break;
        Update the list by removing the selected one;
    end
    if the SKD module(s) currently on pallet is compatible with the one just selected
    then
        Continue;
    else
        Break;
        Update the list by removing the selected one;
    end
    Locate it at the center of the pallet;
    if outside the pallet then
        Move the selected object to fit the pallet;
    else
        Continue;
    end
    Estimate remaining space;
    Update the lists with those larger than the estimated space being filtered out;
end
End Function
```

5.4.4 Searching Possible Location

Searching for possible locations for SKD modules on pallets has several steps: estimating, aligning, applying bounding box, and fixing the location. Estimating means the remaining volume for placing has to be estimated and compared with the next possible object on the list. If fitting the estimated volume, one can placing the object in the way that align the longest dimension of the envelop shapes with the longest dimension of the empty space. Then, checking the overlap between the bounding boxes of the objects. Shown in Figure 5.6, a bounding box of the particular object is the smallest cuboid box that containing all parts of the object inside the box (Lafore, 2002; Rayasam, 2007).

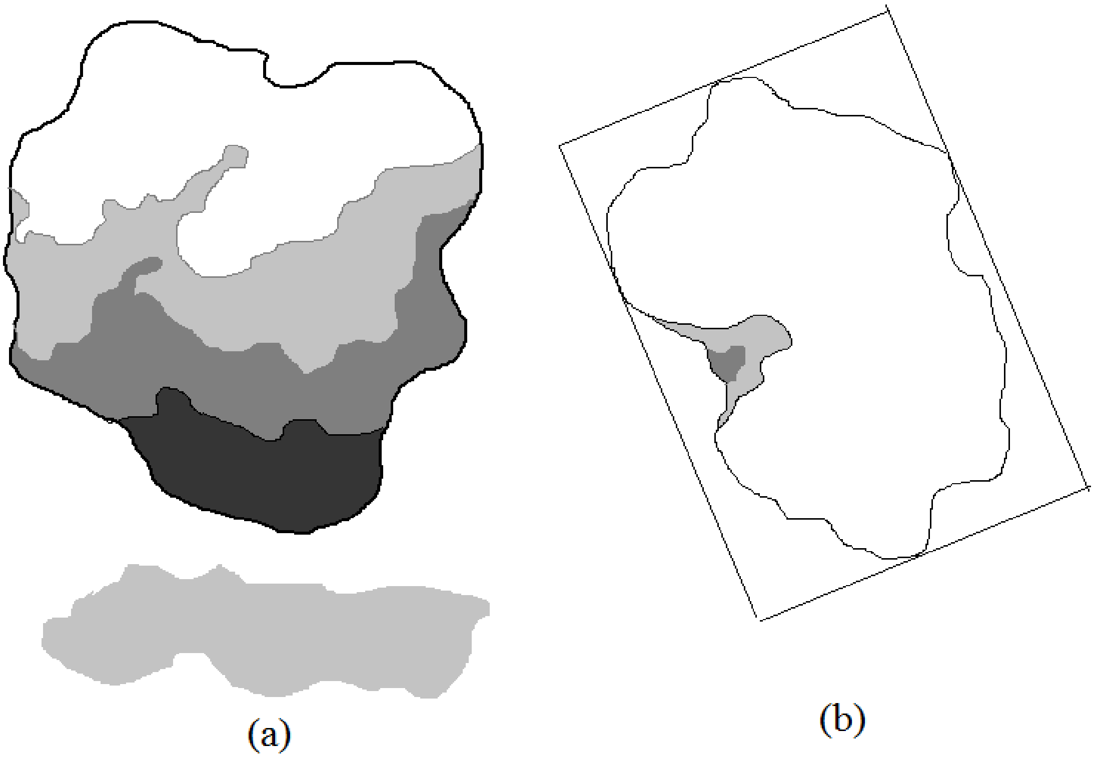


Figure 5.6. The bounding box example for an arbitrary irregular shape

If there is no overlap when checking the bounding box, the location of the SKD modules can be fixed. However, if there is overlap between bounding boxes, one has to check overlap surface by surface, even for the envelop shapes (Rozvany, Olhoff, & North Atlantic Treaty Organization. Scientific Affairs Division., 2000). When having overlap for bounding box, it might turn out to be false alarm since the bounding box is larger than the shape inside the bounding box. If there is no overlap detected after checking surface by surface, the location of the object placement can be fixed. If there indeed exists overlap, one has to move the object according the occurrence location of the overlaps.

When fully loaded with compatible SKD modules, for volume-wise and weight-wise, the pallet is referred as a Pallet Module (P-Module), which will preserve topological properties when loading into the container. Therefore, all pallet modules can be considered as irregular shaped shipments and perform the pixelation, compatibility, and son on again, similar to those conducted for irregular shapes. Moreover, the pallet modules can be placed into containers using the constrained searching sequence mentioned above for searching valid spots in containers.

5.5 Summary

For Chapter 5, the metaheuristic algorithm for constructing envelop shapes for three-dimensional irregular shapes is developed with on-screen modified raster model simplification. The categorization of SKD modules is formed with comparing the volume and weight among the whole set of shipment. The metaheuristic algorithm for searching sequence is discussed regarding to the concept of applying constraints before placing and using topological invariants to transfer unchanged properties between spaces. Next Chapter will focus on reducing the search pattern by using constraints orientated guided local search.

CHAPTER 6. STATIC SEARCH AND DYNAMIC GUIDED LOCAL SEARCH

Chapter 6 explains the modifications to the current guided local search (GLS) method, as well as identifying the different situations for orientating the irregular shaped shipments. The modifications include static search and dynamic guided local search. Static search uses single level nested approach, while the dynamic guided local search uses multiple level tree type search pattern.

6.1 Loading Pallets

As discussed in last chapter, the three-dimensional irregular shape is orthogonal projected to three two-dimensional shapes. Outlining contours, inflation, pixelation are performed to the image of the two-dimensional projection shapes, forming two-dimensional envelop shapes. The projection shapes are reassembled into the three-dimensional envelop shapes after those image manipulations. Pallet module (P-Modules) represents the whole placing arrangement as an irregular shaped module.

Therefore, the image manipulations that worked with irregular shipments can be performed to the P-Modules, creating envelop shapes for pallets with SKD modules loaded. The process of placing loaded pallets into containers can be treated with the similar way of loading SKD modules onto pallets.

6.2 Orientation of Shipments

For shipments that both of regular or irregular shapes, the orientation of the shipment on the pallets or inside the container matters the space utilization of the packing action. Poses of the shipment, especially those of irregular shapes, are also crucial to the stability, potential interferences, and easiness of loading. There are three levels of freedom regarding to the orientation: fixed, limited, and free.

6.2.1 Fixed Orientation

Depending on the special requirements that restricted by the constraints, a particular shipment may have only one oriented regarding to the placing on pallet or into the container. There are a number of situations that restrict the orientation of the shipment to only one.

- Space related:
  The combination of the shipment and container dimensions may restrict the object orientations inside container. For example, the chassis SKD module from John Deere 9000R tractor measures approximated 7 meters and the interior length of a 40' container is approximated 12 meters. Under this condition, the chassis SKD module can only align its longest axis with the length-wise of the 40' container.

- Center of gravity related:
  The shipment may not be of even density as a part or a product, even it is of regular shape. To lower the center of gravity, the heavier end is preferred be pointing downwards.

- Support and fasteners related:
  Depending on the way the irregular shaped shipment is designed to be fixed on pallets, there may exist only one set of fastener location on the shipment, which limits the possible orientation of the shipment. For example, the engine SKD module from John Deere 9000R tractor has only 8 screw holes for attaching the stand/ rack for loading on pallets. Those 8 screw holes are also used to hold the engine SKD module on the tractor when in operation.

- Floor load related:
  Due to the strength of the container floor, several heavy P-Modules may need to be placed with certain distance to avoid overloading. Also, the strength of the pallets restricts the distance of placing heavy ends of the SKD modules.

- Loading process related:
  The combined center of gravity of the pallets and the equipment used for loading may limit the orientation of the shipment in container and on in-plant. For example, the axle SKD module was observed being carried by the forklift with the long axle aligned with the lateral direction of the forklift, in order to locate the combined center of gravity closer to the forklift. Moreover, due to the maneuverability of the loading equipment, the potential orientation may be invalid because of the spatial restraint between the loading equipment and the container.

- Overall stability related:
  The overall stability also involved moment of inertia (MoI) from the whole container stand point. Regarding to the limitations from controlling the MoI, certain orientation of the shipment may be restricted.

- Easiness of disassembling and reassembling related:
  Altering the original orientation significantly, such as flipping upside down, is impractical for large size and heavy weight of shipments. Therefore, container loading orientations are restricted by the original pose.

6.2.2 Limited Variation of Orientations

The constraints that mentioned above limit the possible orientations of the objects to some extend that there are still certain orientations. Limited variation of orientations specifically means the possible orientations are only axis-aligned rotations with integral times of right angles. Shown in Figure 6.1, one of the cuboid surface is limited to facing downward, shaded as gray color. There are only four possible axis-aligned orientations for this cuboid. That is to say, a cuboid shape object has up to 24 limited orientations if there is no limitations for restricting surface to the floor.

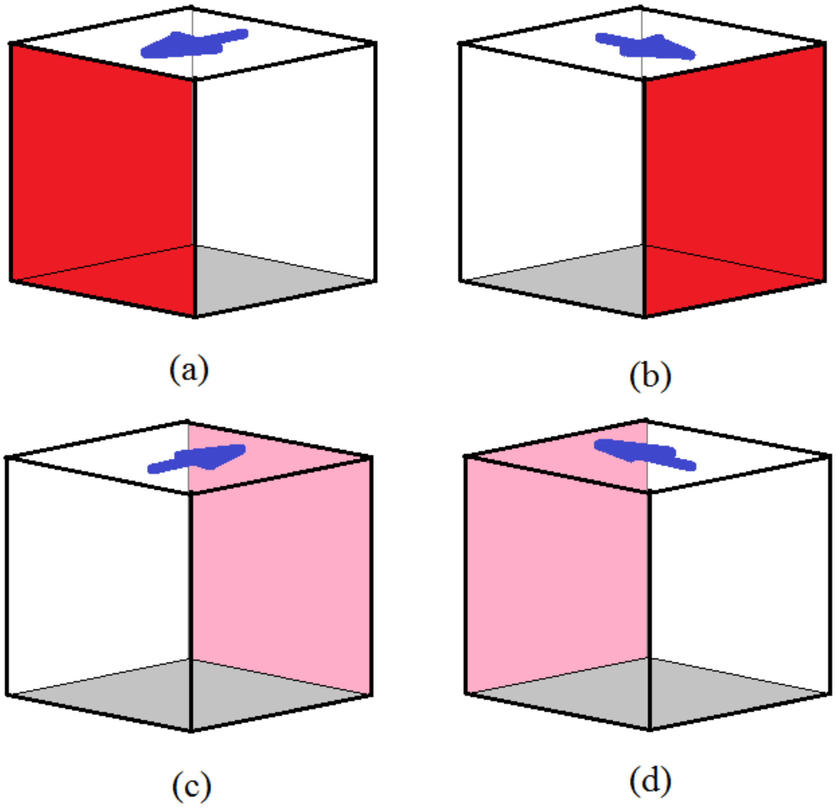


Figure 6.1. Illustration of the four possible limited variation of orientations restricting the gray color surface downward. The red surfaces and the blue arrows shown on top of the cuboid helps to distinguish the differences of orientations.

6.2.3 Free Orientation

Shipments with no spatial, weight, or other forms of constraints can be placed as all possible orientations, called free orientation. The shipment actually has infinite number of possible orientations. Even when placing the shipment into a certain restrained space, such as pallet and container, the object may still remain unconstrained. Therefore, searching for optimal placing for these objects is said to be simple because it can be placed in constrained space with any orientation, the suitable locations and poses will be easy to find. However, searching optimal placing for free orientation object is complicated because the infinite number of possible orientations increase the evaluation process for finding an actual optima among the orientations. That is to say, computer has to take a lot of efforts to figure out which is the best.

Therefore, guided local search (GLS) is used for searching the best with a guide, instead of searching the whole constrained space or all possible solutions randomly. However, there are more factors, controls, and programming, needed for guided local search. The developed metaheuristic approach has two different searches, static search and types of modifications to the current guided local search: static and dynamic.

6.3 Static Search

Calling this modification as static is because that the searching is bounded in a certain area and targeted limited orientations shapes. For loading the pallets with SKD modules, placing heavy core or light core shipments near the center of the pallets, which are constrained spaces. The static search of the metaheuristic approach takes the pallet volume as the empty space for searching. The pallet volume is defined by the area of the pallet and the allowed height on the pallet not interfere with the ceiling of the containers. By applying three-way orthogonal projection and pixelation to the pallet volume, the available pallet space is divided into pixels. The three-dimensional pixelation is very similar to the envelop shapes of the shipments. Therefore, static search can be implemented as searching pixels. Algorithm 6.1 illustrates the logical implementation of static searching.

Algorithm 6.1 Static search for pallet volume

```
Obtain pallet volume size in terms of number of pixels in x, y, z coordinate as $a$, $b$, $c$;
Denote the index of pixels in the x, y, z coordinates as $i$, $j$, $k$;
foreach placing of object do
    Obtain the current available space in pallet volume;
    Obtain and record occupied pixels in x, y, z coordinates;
    Initialize array x-bound, y-bound, z-bound ← 1;
    foreach corner pixel do
        Update the coordinate as this corner is the one with $i = j = k = 1$;
        while $i \leqslant a$ && x-bound(last value) $\neq 1$ do
            while $j \leqslant b$ && y-bound(last value) $\neq 1$ do
                while $k \leqslant c$ && z-bound(last value) $\neq 1$ do
                    if $Pixel_{(i,j,k)}$ occupied then
                        z-bound append k;
                        y-bound append j;
                        x-bound append i;
                        Break;
                    else
                        k++;
                    end
                end
                j++;
            end
            i++;
        end
    end
    Function: StaticPlacing (x-bound, y-bound, z-bound);
end
```

The Algorithm 6.1 is used to find the remaining space for the next placement. The function mentioned with name *StaticPlacing* is defined in Algorithm 6.2.

Algorithm 6.2 Defining the function StaticPlacing

```
Function: StaticPlacing (x-bound, y-bound, z-bound);
Initialize array SizeLimit ← [x-bound, y-bound, z-bound];
Sort elements of SizeLimit from large to small;
foreach largest Compatible object from unplaced list do
    Sort element of object dimension from large to small, an array with 3 elements;
    if first dimension leqslant SizeLimit(0) then
        if second dimension leqslant SizeLimit(1) then
            if third dimension leqslant SizeLimit(2) then
                Place selected object with longest axis align with longest axis of SizeLimit, and similar for other axis alignment;
            else
                Break;
                Next highest volume object from unplaced list;
            end
        else
            Break;
            Next highest volume object from unplaced list;
        end
    else
        Break;
        Next highest volume object object from unplaced list;
    end
end
End Function
```

The static search involves several iterations of searching for the suitable object to place. Those iterations are belongs to a single non-branched search.

Non-branched searches are straight forward and require limited tree type decision making.

6.4 Dynamic Guided Local Search

The dynamic guided local search targets free orientation shapes and more constraint driven search pattern. The original guided local search (GLS) is a series of nested decisions, also called tree type decision making. Theoretically, to obtain the best result, one needs to use infinite number of branches for the guided local search. Also, the guided local search was originally used for searching feasible spot with fixed orientations when placing object into constrained space. However, the present metaheuristic approach extends the application range to searching optimal orientation for placing irregular shape with free orientation.

6.4.1 Sextuple-Tree for Free Orientation Objects

Sextuplet-tree means a tree structure has six branches at each node (Lalonde, Vandapel, & Hebert, 2005). Decision making process with series yes-no questions is and example of binary tree, which means tree with two branches at each node. Similarly, sextuple-tree in decision making means a series questions with six possible answers of each question. The reason for using six branches instead of other numbers is that this setting fits the nature of searching in three-dimensional Euclidean space. More explicitly speaking, the objects and containers are in three-dimensional Euclidean space, which has three bases with two directions of each bases.

The best way of search optimal pose for free orientation objects is evaluating every possible posed under three-dimensional space with three degree-of-freedom rotations. However, the proposed metaheuristic approach initializes the optimal pose searching with sextuple-tree and then uses coupled-sextuple-tree search for the rest of possibilities. Coupled-sextuple-tree means there are two or more branches are coupled with each other. Hence, there exists a node with two upper level root nodes. The illustration in Figure 6.2 and the logical process shown in Algorithm 6.3 demonstrate the working principle of the sextuple-tree searching for free orientation objects.

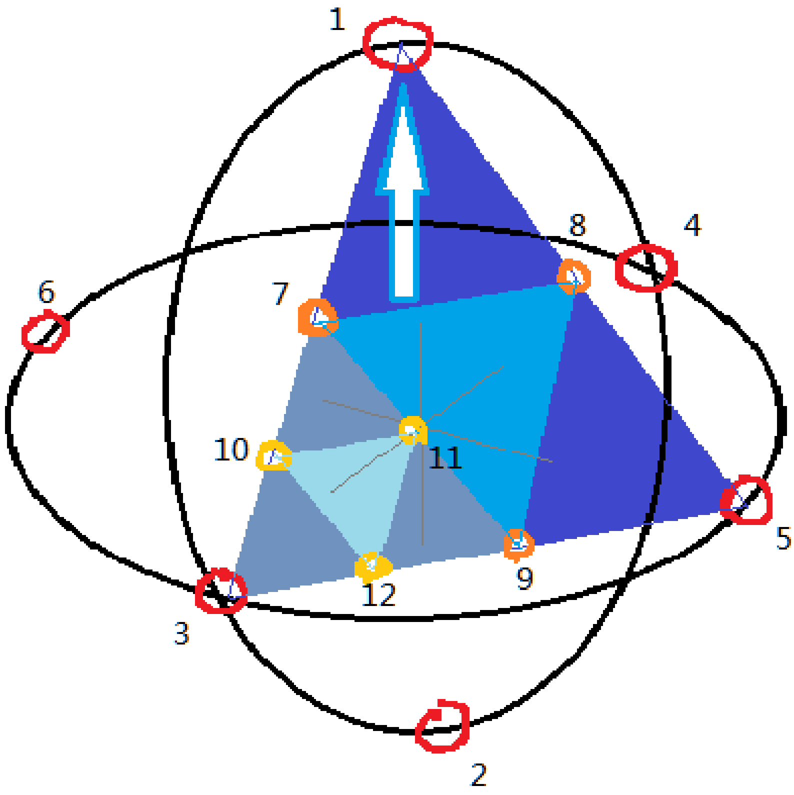


Figure 6.2. Illustration of sextuple-tree search pattern for optimal poses of free orientation objects.

The iteration can go to as many as predefined value by the engineers, depending on both the precision required and the performance of the computer. The direction numbers used in the iterations in the Algorithm 6.3 are examples, the actual numbering in each iteration should follow the patterns shown in the algorithm. Moreover, when looking for the mid-point of line connecting two directions, one can use the shortest spherical distance instead of straight line for better accuracy.

Algorithm 6.3 Logical process of sextuple-tree search pattern. Points numbers are referred to the illustration in Figure 6.2

```
Randomly select an positive direction of axes from the x, y, z directions of the object as target, denoted as $T$;
Identify x, y, z directions for the container;
Mark the positive and negative direction of the x, y, z directions of the container as number 1 to 6;
comment: shown in the designated figure.
foreach directions from 1 to 6 do
    Set $T$ heading to the direction;
    Evaluate this pose, such as KPI score;
    Validation;
    Record evaluation result corresponding to this direction;
end
Select three nearby directions with highest sum of evaluation score;
comment: Sum up evaluation scores from every three nearby directions. For example, the sum of evaluation scores from direction 1, 3, 5 is the highest.
repeat
    Identify three directions corresponding to the midpoints of lines connecting directions 1, 3, 5;
    foreach directions of 1, 3, 5, 7, 8, 9 do
        Set $T$ heading to the direction;
        Evaluate this pose, such as KPI score;
        Validation;
        Record evaluation result corresponding to this direction;
    end
    Select three nearby directions (among directions 1, 3, 5, 7, 8, 9) with highest sum of evaluation score;
    comment: For example, the sum from direction 3, 7, 9 is the highest;
until certain predifined iterations | no better evaluation score can be obtained;
Record the direction of highest evaluation score from the last iteration;
```

6.4.2 Sextuple-Tree for Guided Local Search

In comparison to the sextuple-tree model for searching the optimal pose for free orientation objects, the sextuple-tree guided local search for placing objects on pallets (or placing pallets in containers) uses the same concept but different approaches. The free-orientation sextuple-tree focuses more on changing the poses and searching for the optimal pose in the domain of three-rotational degrees of freedom. The guided local search sextuple-tree model targeting locations in the container domain and searching for suitable places for different objects. Both these two usages of the sextuple-tree model in the container loading problem should be applied, for searching for empty spots and optimal poses after obtaining empty spots.

The sextuple-tree for guided local search can be applied at two levels. The first level is the one that initiates the search. Industrial constraint oriented search enables using a constraint for setting the initial search condition. For example, target location of center of gravity (CoG) can be used to place the first heavy core (HC) or light core (LC) object. The second level is determine the searching focus for placing the next object. Placing sequence is determined as the categorization of the objects, with weight and volume as the criteria. Therefore, the sextuple-tree at this level helps to place the next heavies object near the objects that have been placed, for controlling the CoG and moment of inertia (MoI). Figure 6.3, Algorithm 6.4, and Algorithm 6.5 explain the sextuple-tree used in initiation of the search and in placing search, respectively.

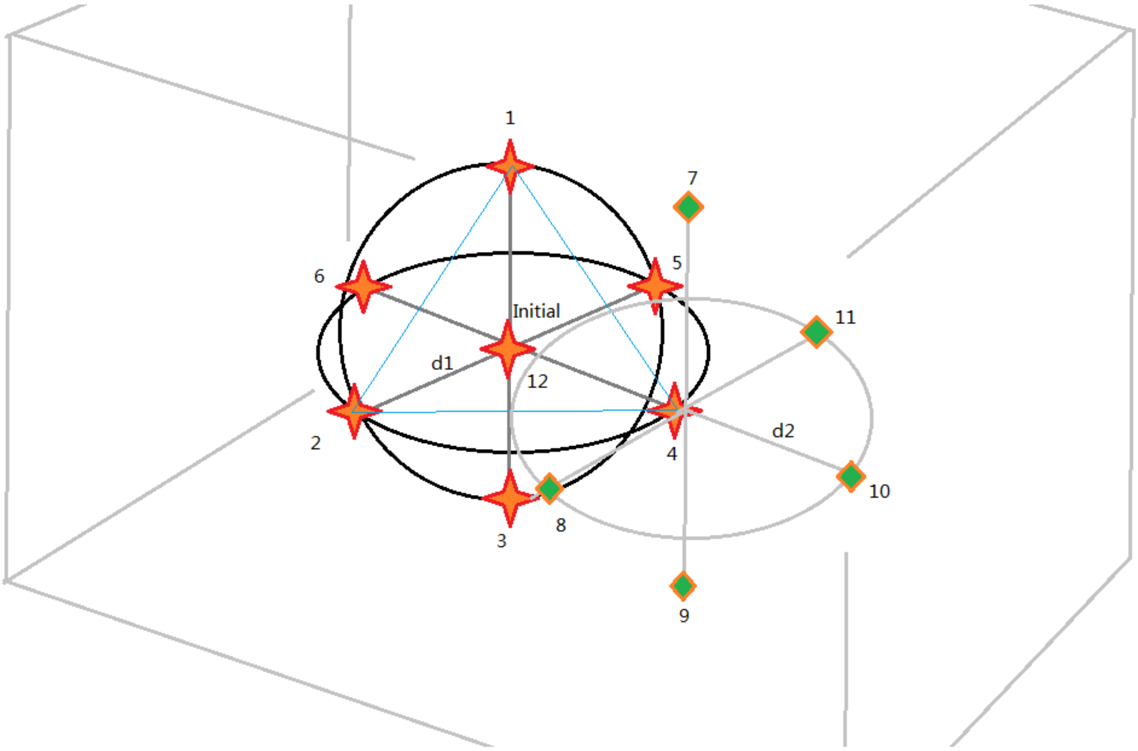


Figure 6.3. Illustration of sextuple-tree used for guide local search

Noticeable, the distance of each sextuple-tree, marked as d_1 and d_2 for example, can be different, depending on the needs. One can link the distance with size of the last placed object, since searching for empty spots inside the size of the object is meaningless. For instance, the distance should be set to greater than sum of the bounding sphere radius of the last placed object and the bounding sphere radius of the next object in the list.

Algorithm 6.4 logical process of implementing sextuple-tree at the level of initiation of the guided local search. Numbers in this logical process referred to Figure 6.3. Location of CoG is used for industrial constraints oriented search initialization.

```
Obtain target location of CoG;
Set initial at the target CoG Select the first object in the valid placing sequence;
Place the first selected object at initial;
Perform user defined customized searching patterns;
Evaluate the placing configuration, in terms of KPI score;
Set the score associated with initial as reference;
Set location 1 to 6 as search locations;
comment: distance between search locations and reference location is predetermined by engineers;
repeat
    foreach search locations do
        Place the first selected object at initial;
        Perform user defined customized searching patterns;
        Evaluate the placing configuration, in terms of KPI score;
        Compare the score with reference;
    end
    Choose the location with highest evaluation score and set to reference location for next iteration;
until no better score location can achieved;
```

The basic idea of using sextuple-tree at placing object level of guided local search is maximizing the possibility of finding better placing spot, while minimizing unnecessary searching efforts. The Algorithm 6.5 can be considered as same as the one shown in Algorithm 6.4 due to the high similarity between them. As a matter of fact, these two have the same basic logical process that applying sextuple-tree for guided local search. The two algorithms can occur in the same approach for multiple constraints. However, one should be careful of inter-locking the search when using multiple constraints for initializing the search, where inter-locking means the situation of over-constrained.

Algorithm 6.5 logical process of implementing sextuple-tree at the level of placing search. Numbers in this logical process referred to Figure 6.3.

```
Place the first object at the location of initial;
Identify six locations along the direction of the principle axes around the initial position;
repeat
    foreach search locations do
        Place the next valid object from the placing sequence list at search locations;
        Evaluate the placing, such as KPI scores;
        Compare the scores among the search locations;
    end
    Choose the location with highest evaluation score and set to initial location for next iteration;
until no better score achieved | all valid objects from placing sequence list are placed;
```

6.5 General Logical Process for Topology-Based GLS

Several detailed operation-wise search patterns were discussed above, while the general logical flow of the topology-based guide local search is not clarified. The reason of calling the modified guided local search as topology-based is that topological basic and optimization concepts were involved in the guided local search, in forms of guiding the local search. Figure 6.4 briefly explains the general logical flow of the topology-based guided local search.

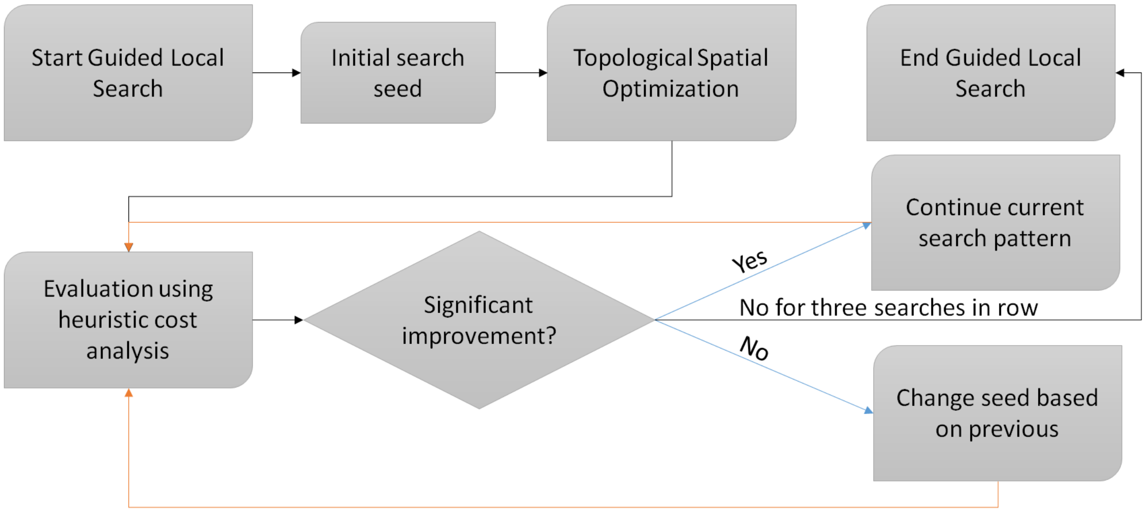


Figure 6.4. Flow chart of the logical process that controlling the topology-based guided local search

There are several operators in the Figure 6.4 need to be explained with a few more words. The initial search seed is the initial predetermined starting point for searching. Function-wise, the initial search seed is very similar to the initial value given for finding the numerical solution for the differential equations. Topological spatial optimization stands for the topology-based placing search patterns, such as static search for envelop shapes and the sextuple-tree search at placing object level. The heuristic cost analysis includes: the relationships between constraints and shipping configurations; and the KPI evaluation system. Changing seed action includes performing sextuple-tree search at the level of initializing another local search pattern.

6.6 Summary

Chapter 6 explained the relationship between placing configuration and the different types of orientations of the object, such as fixed, limited variation, and free orientation. The topology-based static search was also discuss focusing on placing object with limit variation of orientations onto the pallets. Sextuple-tree decision making was introduced with two different circumstances of utilizations in the guided local search: GLS for free orientation objects and GLS for placing in constrained spaces. Tackling the process of finding optimal poses of the objects with free orientations with sextuple-tree topological spatial optimization simplifies the number of search iterations needed. Topology-based guided local search uses sextuple-tree at two different levels: initiate search pattern and optimization within the search pattern. Finally, the general logical process for topology-based guided local search was clarified and open for modifications depending on the specific usage for engineers.

Starting from next chapter, two real world industrial cases will be introduced for better visualization of the container loading problem with irregular shaped shipments and the usage of the proposed metaheuristic approach.

CHAPTER 7. CASE I: JOHN DEERE 9000R TRACTOR SKD SHIPPING CONFIGURATION OPTIMIZATION

This industrial case is the motivation for researching on the present research. Through Center for Technology Development (CTD) in College of Technology (COT), industrial leading companies provide numbers of real world cases proposed for potential solutions. Generalization and commercialization of the solutions to those case are expected when communicating with industry experts from the manufacturers.

7.1 Understanding Industrial Needs

The John Deere 9000R tractor is the case that selected as the starting point of this research. This 9000 series of tractor are the largest and most powerful tractor in the John Deere agricultural equipment family. The “R” means designed for Russian fields, which are at low temperature, slippery land, and so on. Therefore, the weight of the tractor is increased by adding by adding extension and several other weights on chassis. Table 7.1 shows a brief list of the SKD modules and their weights from John Deere 9000R tractor.

The SKD modules have great differences between their weights, ranging from 1 kg to 5722 kg. The bright side of wide range of weight distribution is easier for distinguishing heavy and light objects. With the average weight as 403.30 kg, SKD modules with weight higher than average are categorized as heavy, such as Chassis, Cabin, Front/rear, and Engine SKD modules. Similarly, judging by the volume, Chassis, Cabin, Fuel RH (tank), Fuel LH (tank) are categorized as core objects. Therefore, HC and LC object are identified as the ones should be placed near the center of the pallets, as well as in the container.

Table 7.1: List of the SKD modules with corresponding weights from John Deere 9000R tractor.

Item Name	Weight (kg)	Item Name	Weight (kg)
Chassis	5722	LH Step	2
CAT 4 Draw Bar	99	Rear Fender	24
CAT 5 Draw Bar	181	Intake Elbow	1
Cabin	987	Crossover Fuel Tank	3
Fuel RH w/ air filter	242	Crossover Fuel Tank Support	15
Front Fender	26	Intake	11
Fuel LH	293	Engine	1375
Cooler Pipe	6	Crossover Fuel Hose	2
CAC Pipe	5	Intake Pipe	10
Exhaust Assembly	75.5	Turbo Elbow	3
Front/Rear Axle	1447	Intake Hose	2
Hub	78.5	Light Bar Kit	125
Hub Extension	172.8	Draft Link LH/RH	57
Quick Coupler	231	Wheel	96.5

During the intensive site visits to John Deere's shipping center in Waterloo, IA, the entire disassembling process of 9000R tractor is observed and analyzed. Combined with the discussion with shipping experts, the shipping procedure and the packaging concept from John Deere were identified. For example, wooden pallets are the major shipping dunnage John Deere uses for overseas shipping due to light weight and low cost compared with metal fixtures or reconfigurable dunnage. More importantly, many underlying constraints and mechanisms are revealed during the discussion, including those mentioned in Chapter 3, such as compatibility and commodity codes.

With the understanding of the shipping factors and the contributions from the shipping experts, the forced decision matrix (FDM) is constructed, shown in Figure 7.1.

Evaluation Components	Container Cost	Regulation Fine	Port Fee	Damage Fee	Dis/assembly Fee	Pallet Cost	Compact Ratio	Configuration Time	Regulation Rank	Spatial Rank	Facility Capacity Rank	Stability Rank	Loading Easiness	Unloading Easiness	Pallet Weight	Pallet Size	No. of Pallets	P_i	$f_i = \frac{P_i}{\sum P_i}$
Container Cost		3	2	3	3	3	2	3	4	2	3	3	4	4	3	2	2	46	0.0846
Regulation Fine	1		2	2	1	2	2	1	0	3	3	1	2	2	1	2	1	26	0.0478
Port Fee	2	2		3	3	3	2	2	0	2	1	2	3	3	1	2	2	33	0.0607
Damage Fee	1	2	1		2	3	3	4	3	3	2	0	2	2	2	3	2	35	0.0643
Dis/assembly Fee	1	3	1	2		3	1	1	2	1	3	0	1	1	2	3	3	28	0.0515
Pallet Cost	1	2	1	1	1		3	2	2	1	2	1	2	2	3	2	1	27	0.0496
Compact Ratio	2	2	2	1	3	1		2	1	2	3	1	1	1	2	3	3	30	0.0551
Configuration Time	1	3	2	0	3	2	2		3	2	3	3	3	3	2	3	2	37	0.0680
Regulation Rank	0	4	4	1	2	2	3	1		1	2	3	2	2	3	3	3	36	0.0662
Spatial Rank	2	1	2	1	3	3	2	2	3		3	4	4	4	2	3	2	41	0.0754
Facility Capacity Rank	1	1	3	2	1	2	1	1	2	1		2	2	3	2	3	3	30	0.0551
Stability Rank	1	3	2	4	4	3	3	1	1	0	2		2	2	3	2	3	36	0.0662
Loading Easiness	0	2	1	2	3	2	3	1	2	0	2	2		2	3	3	2	30	0.0551
Unloading Easiness	0	2	1	2	3	2	3	1	2	0	1	2	2		3	3	2	29	0.0533
Pallet Weight	1	3	3	2	2	1	2	2	1	2	2	1	1	1		1	1	26	0.0478
Pallet Size	2	2	2	1	1	2	1	1	1	1	1	2	1	1	3		2	24	0.0441
No. of Pallets	2	3	2	2	1	3	1	2	1	2	1	1	2	2	3	2		30	0.0551
																	Total	544	1.0000

Key:
Much more important: 4 ~ 0
Important: 3 ~ 1
Same Importance: 2 ~ 2
Not as important as: 1 ~ 3
Much less important: 0 ~ 4

Figure 7.1. Illustration of the forced decision matrix according to John Deere's shipping experts' preference

The forced decision matrix is initially constructed for understanding the importance of each constraint and factor. Combined with the key performance indicator (KPI), the forced decision matrix is applied as the evaluation system for filtering out invalid configurations.

7.2 Approaches for Shipping Configuration Optimization

According to the typology summarized by Bortfeldt and Wäscher (2012), the John Deere tractor shipping case (with only 40' containers) is Multiple Bin-Size Bin Packing Problem (MBSBPP), packing a strongly heterogeneous set of cargo into a weakly heterogeneous assortment of containers such that the value of the used containers is minimized. If this shipping optimization case includes multiple sizes of containers, the case can be categorized under Residual Bin Packing Problem (RBPP), packing a strongly heterogeneous set of cargo into a strongly heterogeneous assortment of containers such that the value of the used containers is minimized.

Along the road of searching for methods to tackle the problems that haven't been tackled, the uniqueness of this case is that most SKD modules (shipments) are limited variation of orientation, compared to other cases researched by other. For example, no SKD modules over 100 kg have their orientation significantly altered from the original orientation on the tractor. Those SKD modules have the bottom surface towards the bottom all the time, only rotations around the vertical axis.

Front and rear axles have the shape at the boundary between regular and irregular, shown in Figure 7.2. The concept of principle axis is also introduced to represent the poses in a more visualized way, also prepare for placing with limited variation of orientations.

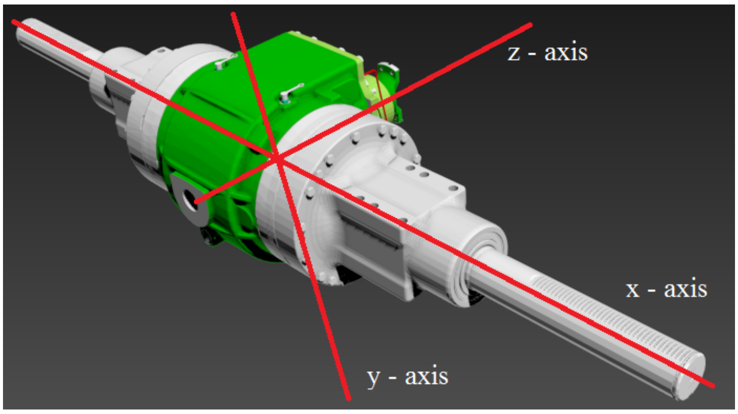


Figure 7.2. The axle SKD module from John Deere 9000R tractor with principle axes highlighted (permission obtained)

Obtaining bounding box of the object is similar to identification of the principle axes. There are two types of bounding box, oriented bounding box (OBB) and axis-aligned bounding box (AABB). Oriented bounding box means that the construction of the bounding box follows predefined principle axes, while axis-aligned bounding box stands for bounding box without predefined axes. Identifying the principle axes for regular shapes is similar to OBB, while for irregular shapes is closer to the AABB approach. The general method of identifying the principle axes for irregular shape is shown in the Algorithm 7.1.

Algorithm 7.1 Logical process of identifying the principle axes for irregular shape

```
Obtain the three-dimensional shape;
Place the shape on a reference platform as the original designed way;
Plane $x - y$ is set to be parallel to the reference platform and through the CoG of the object;
Identify the longest straight line $L$ connecting two arbitrary surface point of the object;
such that $L$ is through the CoG of the object and $L$ is parallel to the reference platform;
Line $L$ is the x-axis of the object's principle axis;
Identify line $M$ through the CoG of the object;
such that $M$ perpendicular to $L$ and $M$ parallel to reference platform;
Identify line $N$ through the CoG of the object;
such that $N$ perpendicular to reference platform;
Line $L$, $M$, $N$ are x-, y-, z-axis of the object, as the principle axes;
Follow Cartesian right-hand-rule to identify positive directions of the principle axes;
```

For regular shapes, the $x - y$ plane is assumed to be the reference platform that the object should sit on. The rest of the steps are same as the Algorithm 7.1 shown for irregular shape. Figure 7.3 demonstrate the principle axes of a shipping container.

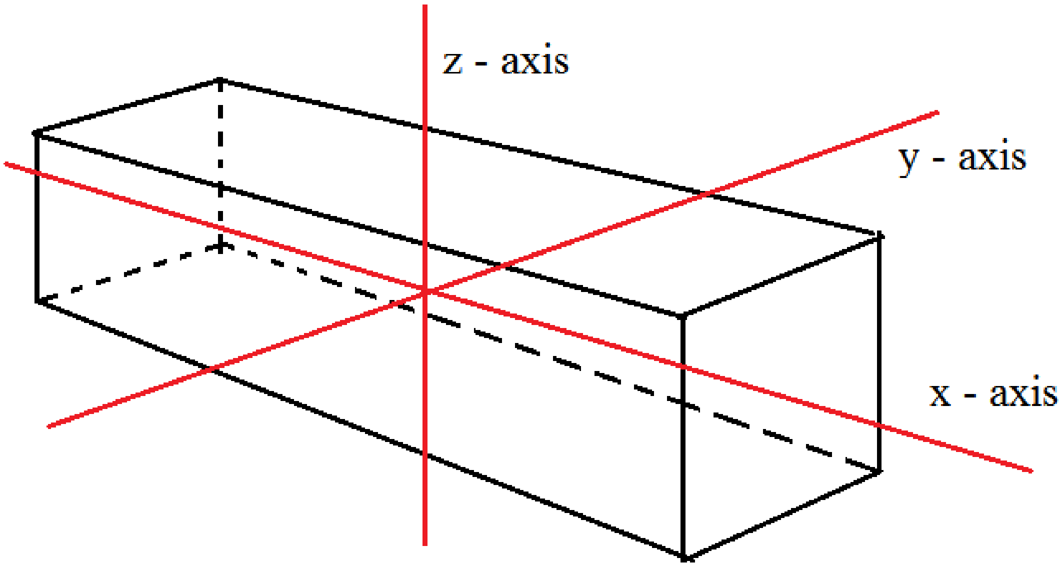


Figure 7.3. Principle axes for sea container as a regular shape

The orientations discussed in the earlier chapters are from the perspective of the object itself. When from the container point of view, the orientation involves more constraints, such as the stability of the container and the possible fixture device in container. Figure 7.4 shows several possible orientations of the axle SKD module loading in the container.

Notice there are several orientation patterns that not from the limited variation of orientation as discussed before. The limited variation of orientation requires only right angle turns along the principle axis that perpendicular to the reference platform. However, from the perspective of the whole container, as a constrained space, the limited variation of orientation includes all possible orientations shown in Figure 7.4. With the enhanced flexibility, the limited variation of orientation can actually provide more possible optimal configurations.

If the approach of the elevated flexibility applies to the limited variation of orientation under the perspective of single object, there may also be more possibility of finding the optimal configuration. Illustrated in Figure 7.5, the axle SKD module

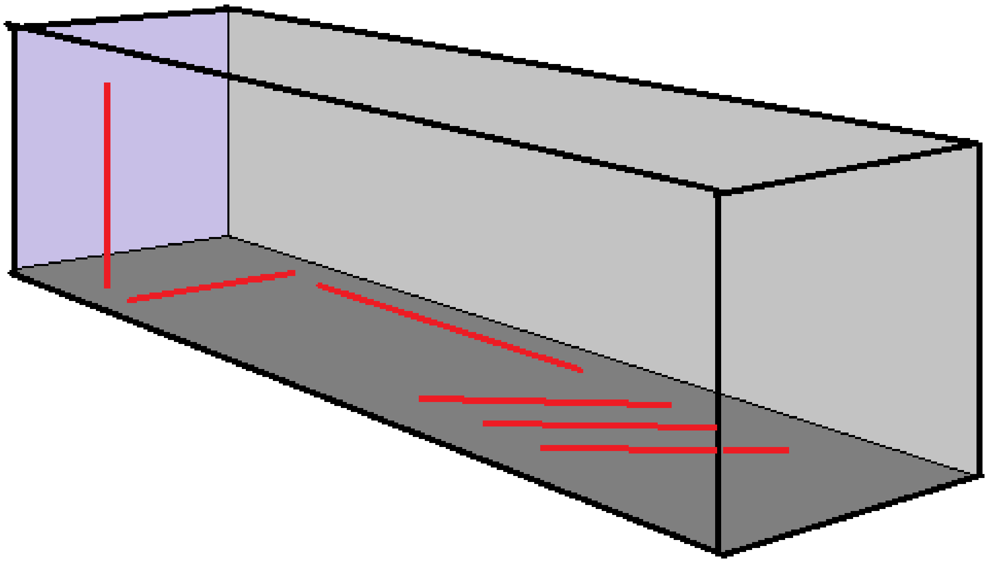


Figure 7.4. Possible orientations for placing axle SKD modules in the container with more options than limited variation of orientations

from the John Deere 9000R tractor is viewed from the x-axis and placed together with a non-right-angle turn along the x-axis. This particular configuration expends range of the potential optimal configuration with more flexible limited variation of orientation and from higher level of view when placing objects.

Therefore, by removing the right-angle turn restriction from the definition of limited variation of orientation and apply free rotation to one or two principle axes, a new orientation type forms with enhanced flexibility compared with limited variation of orientation. Implementing this new orientation type requires more programming and constraint design for the engineers, also more resources consumed by calculations.

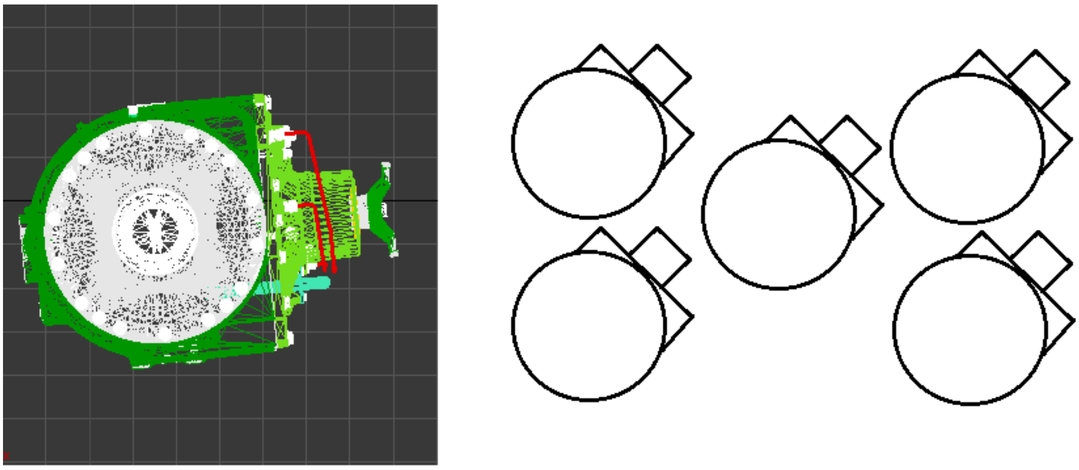


Figure 7.5. Possible group placing of axle SKD modules with more flexibility of limited variation of orientation

7.3 Improvements

Placing minor SKD modules around the core ones on the same pallet with the static search pattern is implemented by the proposed metaheuristic approach, shown in Figure 7.6. The engine SKD modules are placed on the pallet with other minor SKD modules around it. Moreover, the selected minor SKD modules are those located near the engine, considering the easiness of loading and unloading when disassembling or reassembling engine SKD modules. Those minor SKD modules includes engine intake pipe, coolant pipes, and so on.

One may argue that the minor SKD modules mentioned above contain those can be assembled on to the engine SKD module, a violation of compatibility constraint. However, as it was discussed in Chapter 3, the compatibility of SKD modules are defined by the constraint database. In this case, those minor SKD modules and engine SKD module are under the same commodity code. Therefore, those SKD modules are compatible with each other in the same container.

Figure 7.7 to Figure 7.15 illustrate the P-Modules for Deere's 9000R tractor, with core SKD modules near the center of the pallets and several minor SKD modules placed on the same pallet. These layouts were used for pallet design

Figure 7.6. Example of placing minor SKD modules around the core SKD module(s) one the same pallet, forming pallet module (P-Module)

assignments for senior capstone design course offered by department of Mechanical Engineering Technology, Purdue University. Figure 7.7 shows the P-Module for 9000R tractor as the right tank SKD module being the core object, with several other minor SKD modules on the same pallet, such as the draw bar, crossover fuel tank, and so on.

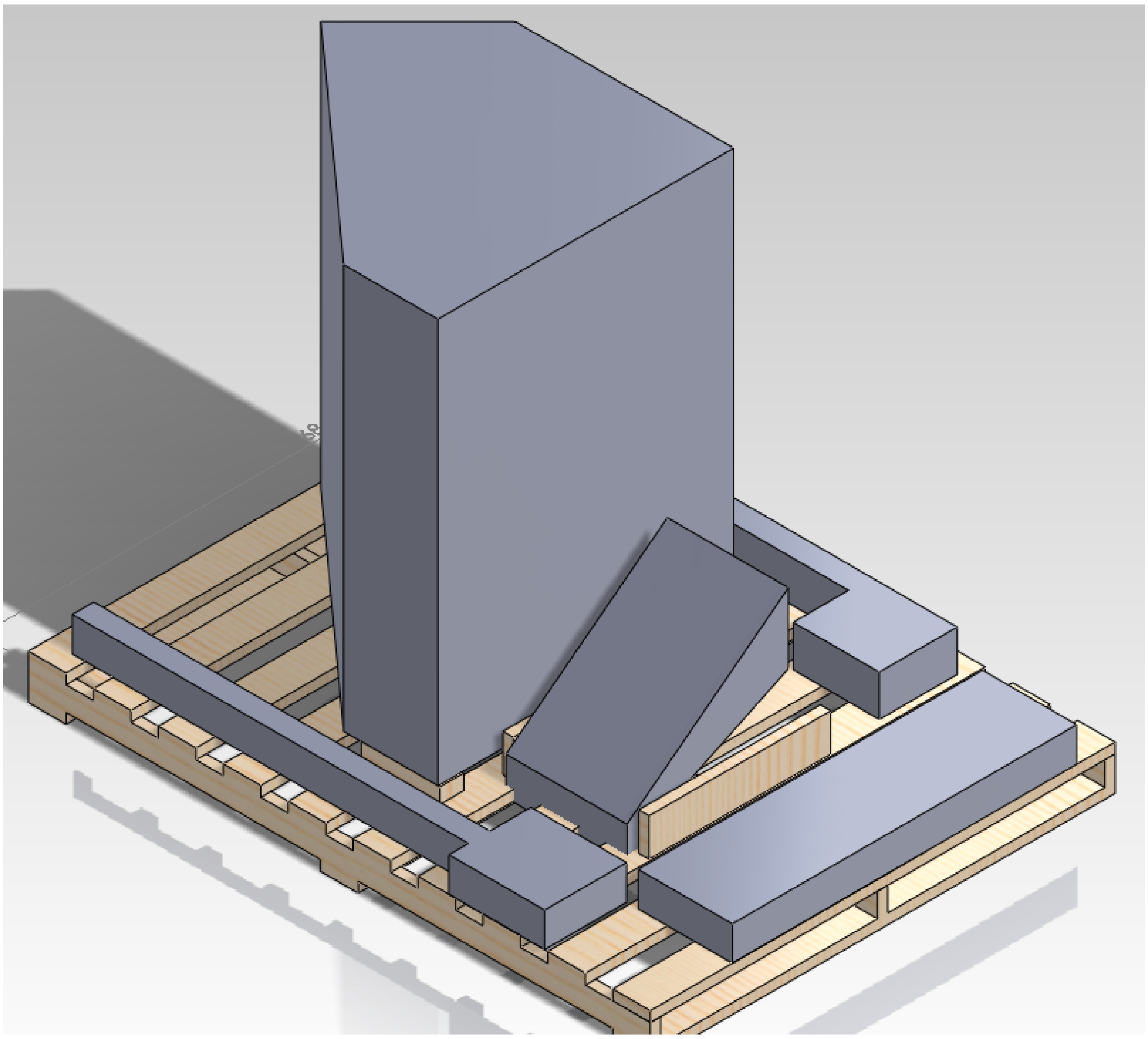


Figure 7.7. Right tank P-Module with minor objects placed on the same pallet

Figure 7.8 shows the P-Module as the left tank SKD module being the core object and the draw bar, intake pipe, and CAC pipe on the pallet.

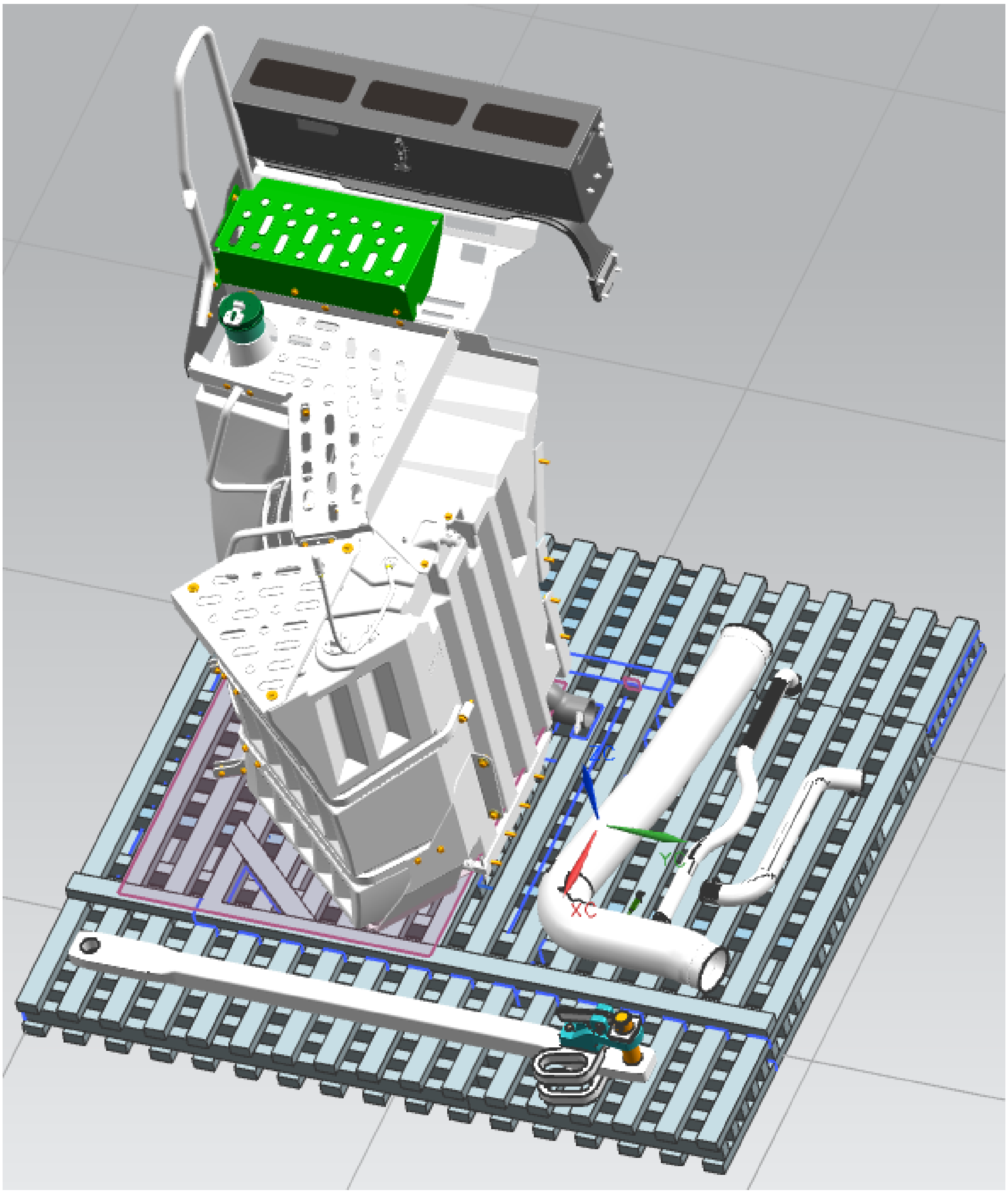


Figure 7.8. Left tank P-Module with minor objects placed on the same pallet

Figure 7.9 shows the P-Module as the rear axle SKD module being the core object and the CAT 4 draw bar, CAT 5 draw bar, and two quick couplers on the pallet.

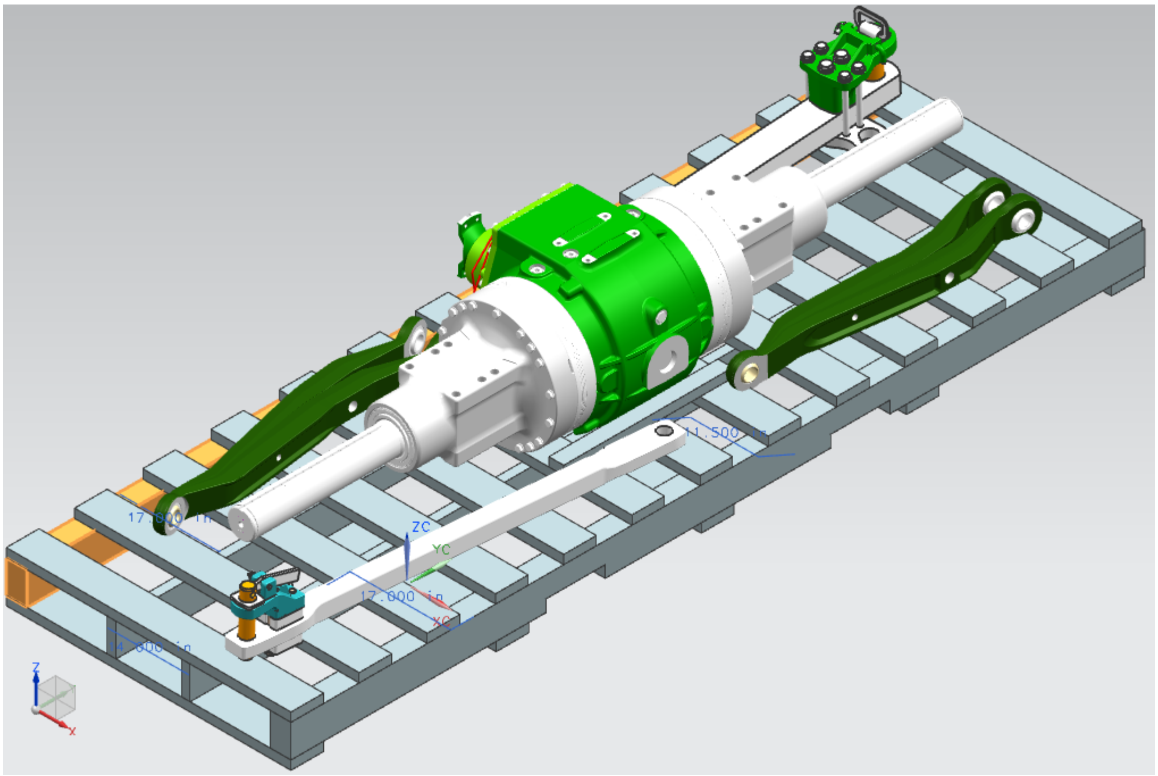


Figure 7.9. Rear axle P-Module with minor objects placed on the same pallet

Figure 7.10 shows the P-Module as the left tank SKD module being the core object and the turbo elbow, exhaust pipe, and Intake hose on the pallet

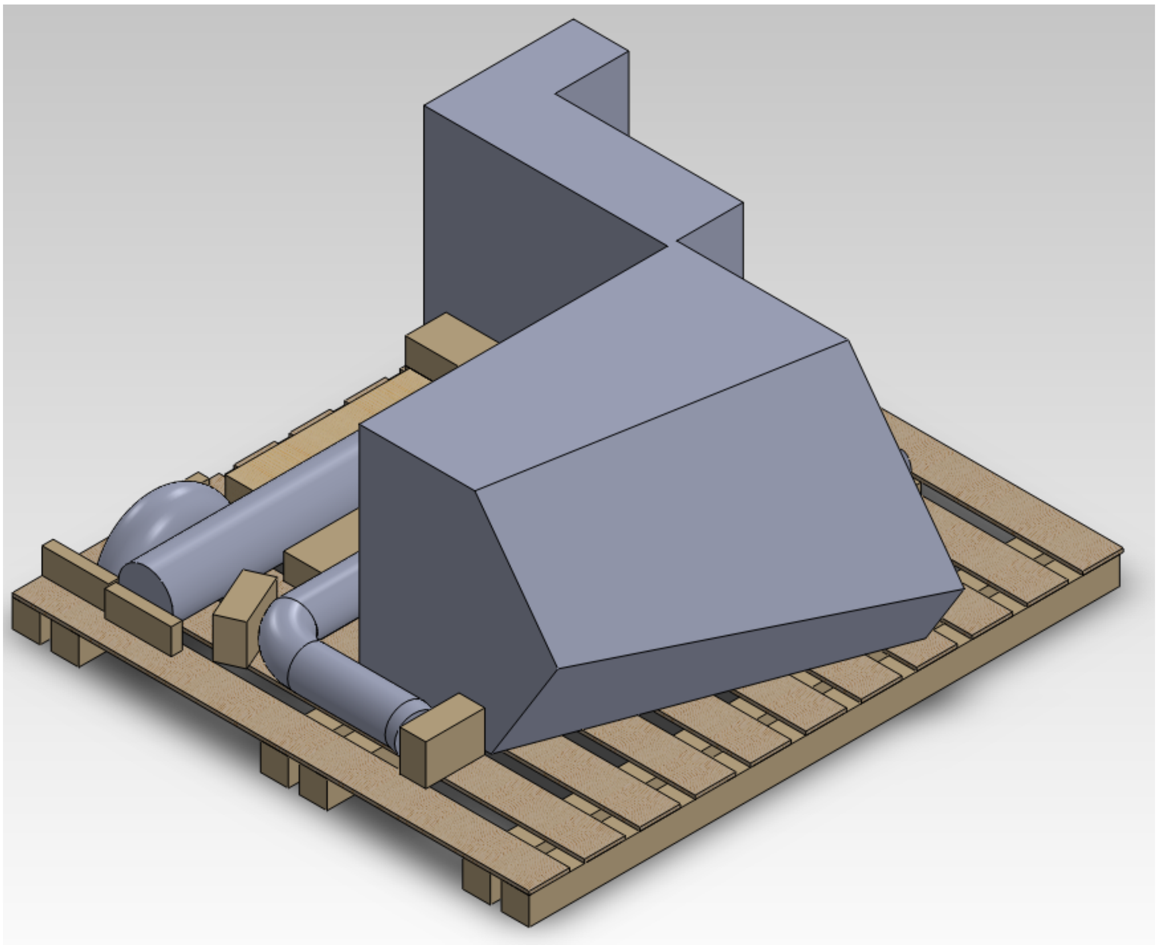


Figure 7.10. Left tank P-Module with minor objects placed on the same pallet

Figure 7.11 shows the P-Module as the engine SKD module being the core object and the LH ladder, Extension Hub, and LH fender on the pallet.

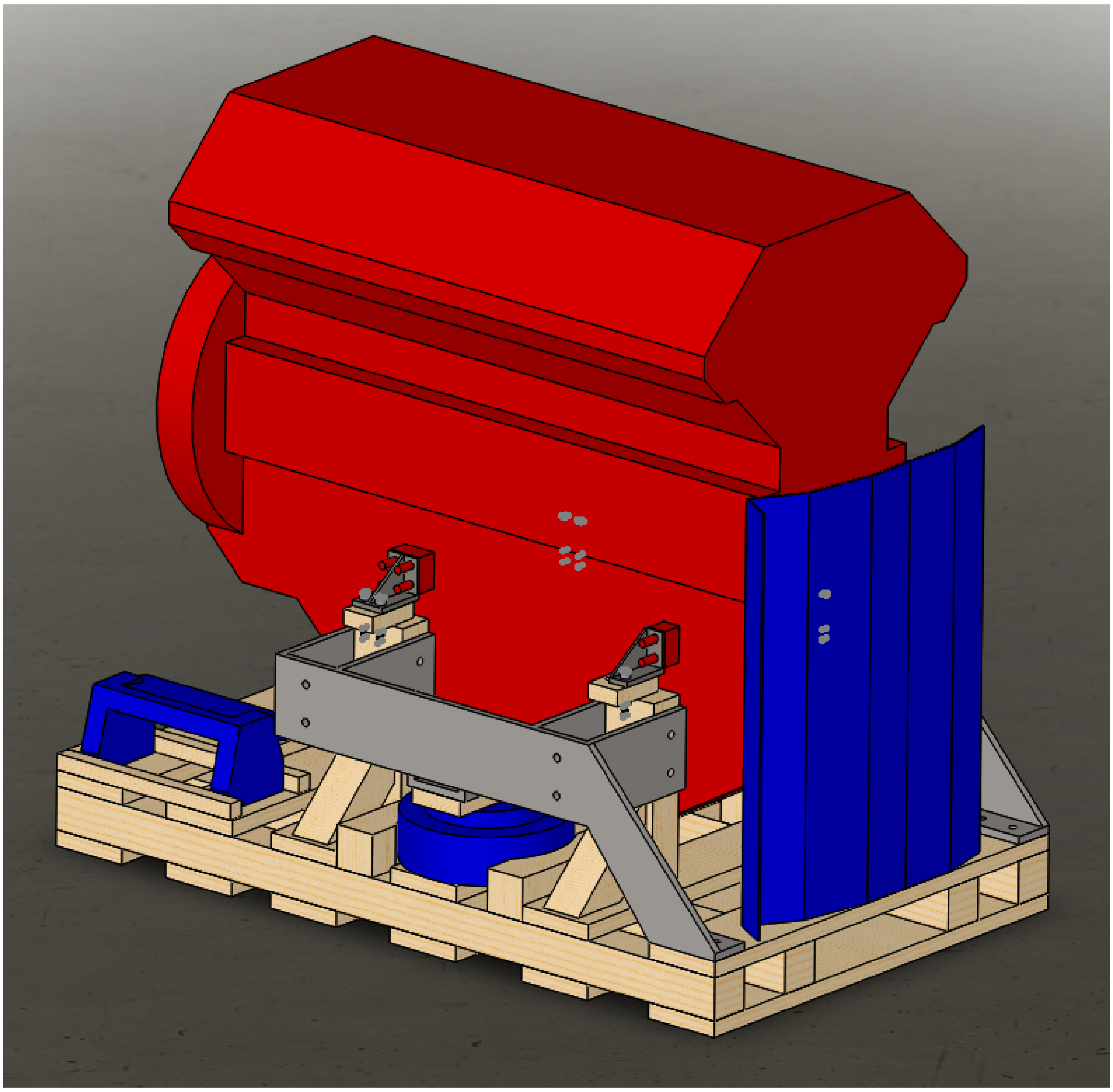


Figure 7.11. Engine P-Module with minor objects placed on the same pallet

Figure 7.12 shows the P-Module as the engine SKD module being the core object and the exhaust assembly, wheel extension hub, and LH fender on the pallet.

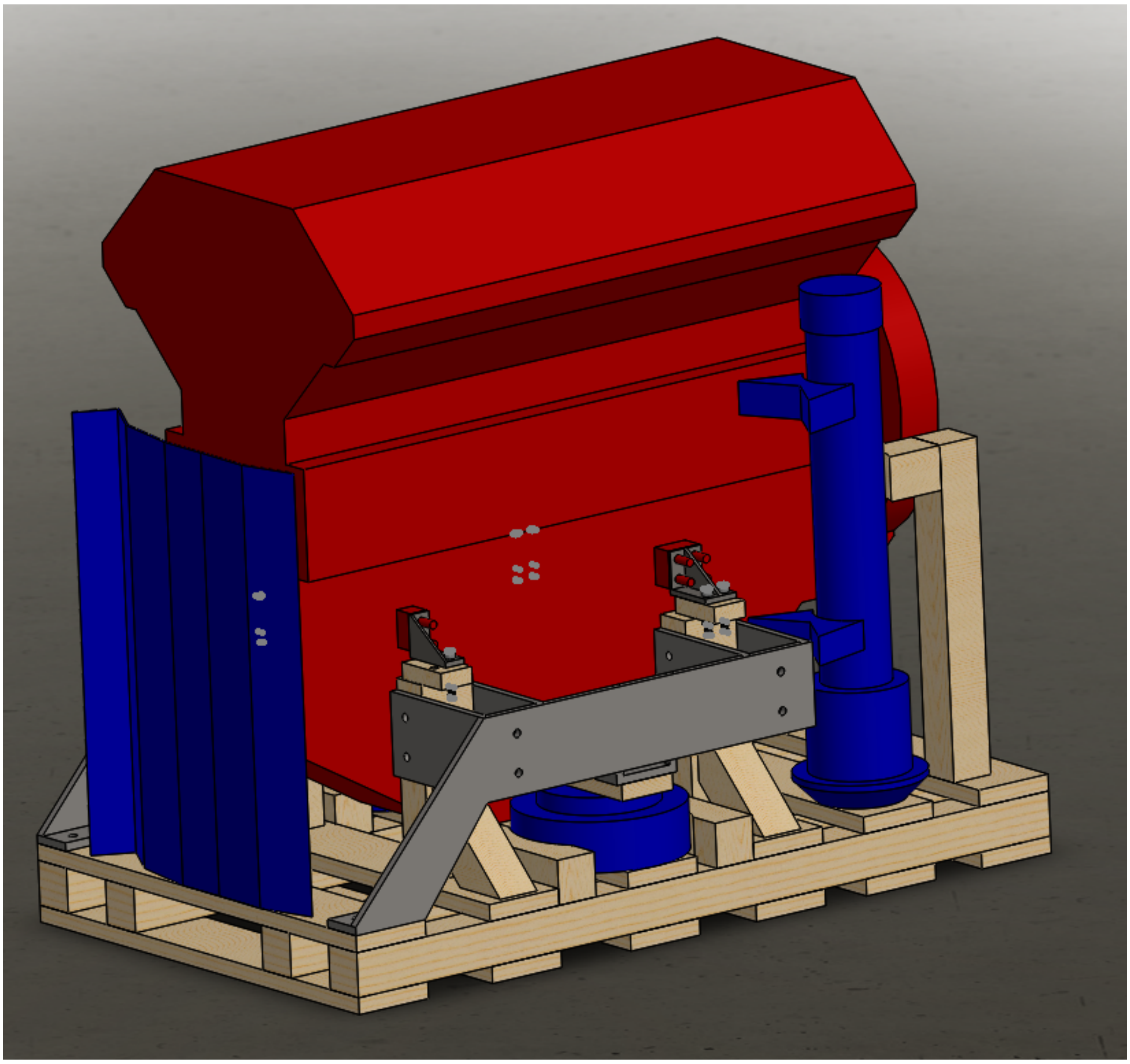


Figure 7.12. Engine P-Module with minor objects placed on the same pallet

Figure 7.13 shows the P-Module as the right tank SKD module being the core object and the crossover fuel tank, exhaust pipe, and exhaust assembly on the pallet.

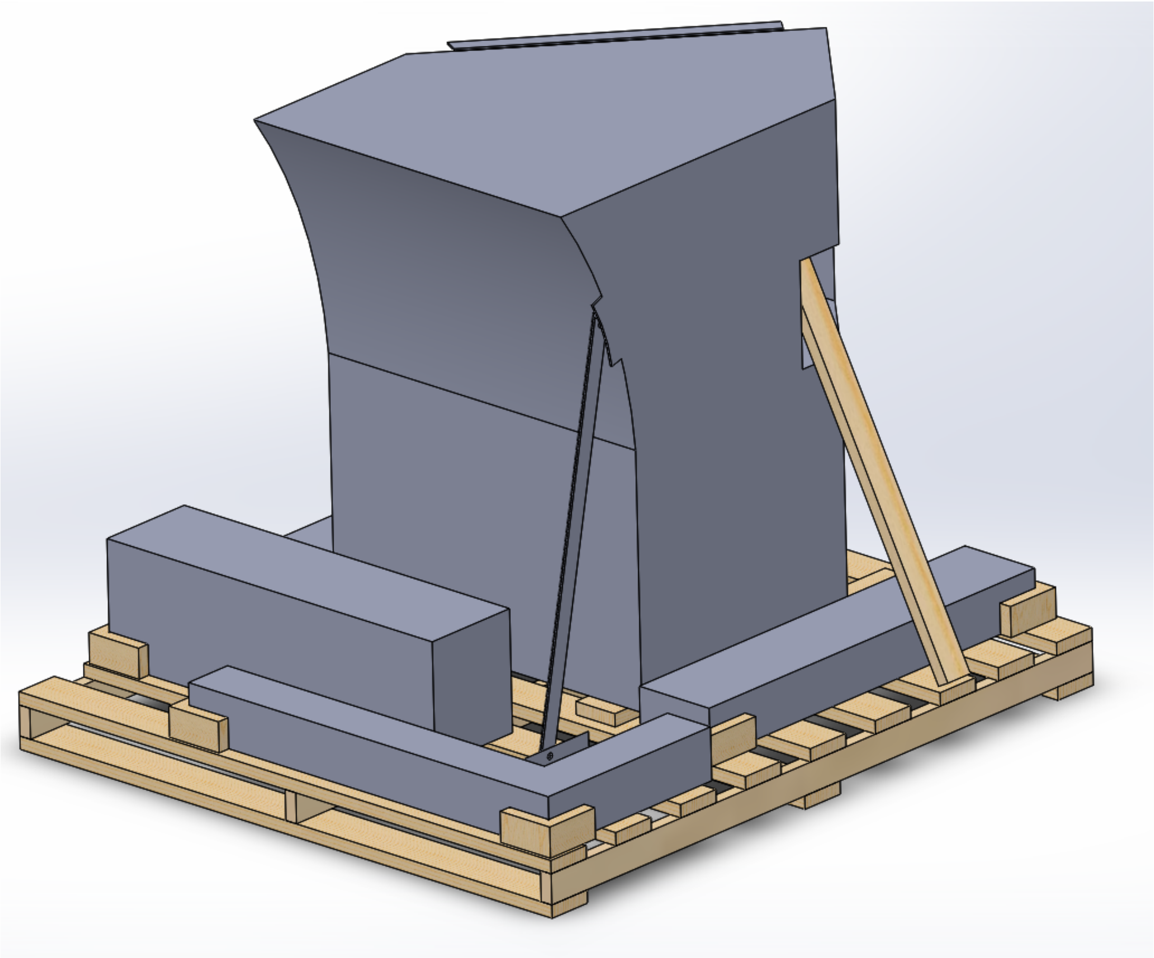


Figure 7.13. Right tank P-Module with minor objects placed on the same pallet

Figure 7.14 shows the P-Module as the right tank SKD module being the core object and the intake pipe, coolant pipe, tool box, exhaust assembly, and two turbo elbow on the pallet.

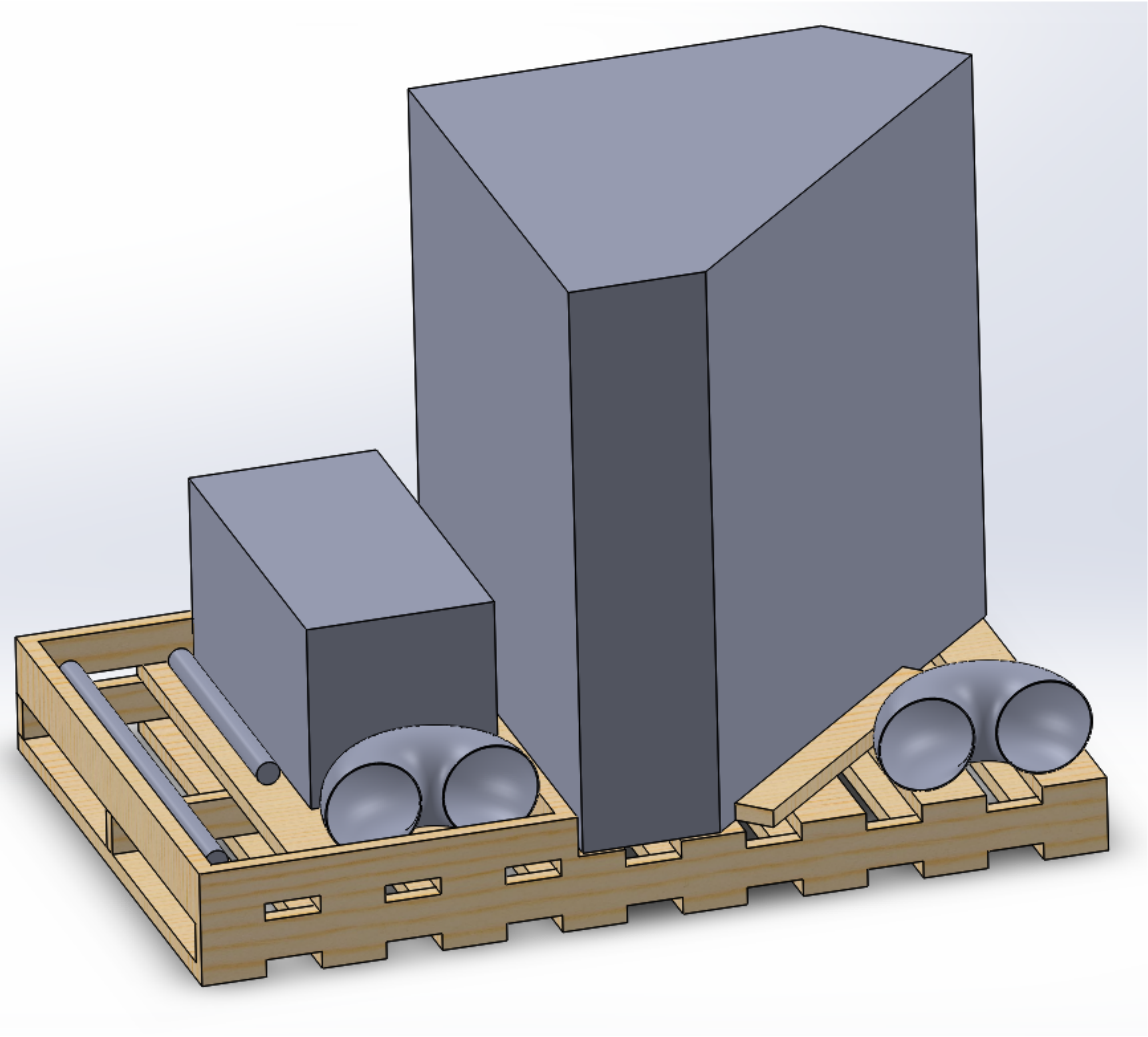


Figure 7.14. Right P-Module with minor objects placed on the same pallet

Figure 7.15 shows the P-Module as the axle SKD module being the core object and two CAT 5 draw bar and four axle extension hubs on the pallet.

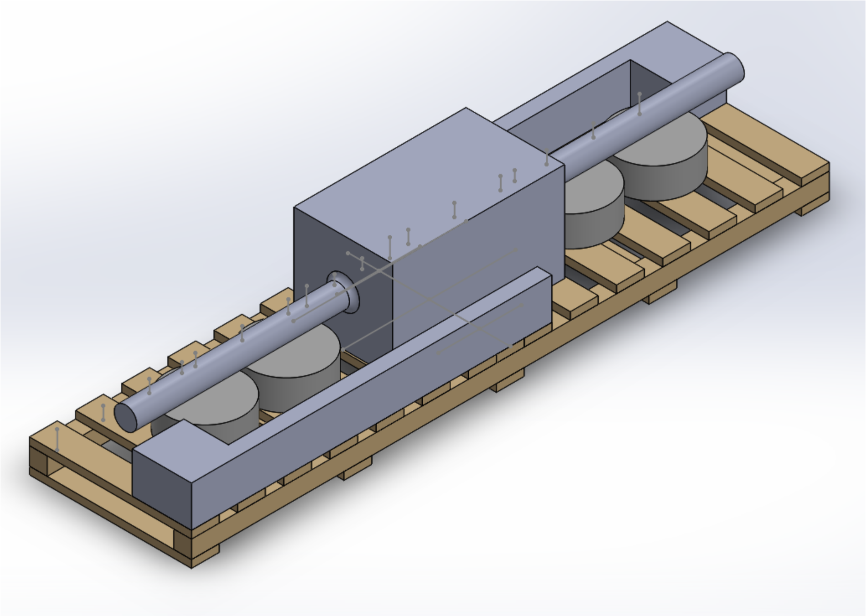


Figure 7.15. Axle P-Module with minor objects placed on the same pallet

After applying the metaheuristic approach of handling irregular shipments with multiple constraints, the comparison between the existing old configuration and the newly generated configuration is shown in Table 7.2. The comparison is set up with the scenario that placing a group of four 9000R tractors into 40' containers.

Table 7.2: Comparison between space utilization of original and new shipping configuration improved by the metaheuristic approach

Comparison factors	Old Configuration	New Configuration
No. of Containers	8 × 40'	7 × 40'
Total Container Floor Occupied (m^2)	225.224	188.692
Improvement	null	16.22%

7.4 Summary

For Chapter 7, the John Deere 9000R tractor case was introduced in detail to illustrate the complexity of the container loading problem involved in this case. The logical process of the identifying principle axes of an object was demonstrated. The limited variation of orientation was expanded to allowing free rotation to one or two principle axis directions, forming new type of orientation, named enhanced limited variation of orientation.

Next chapter will share the research case of American Axle Manufacturing (AAM) warehouse optimization will be introduced and discussed.

CHAPTER 8. CASE II: AAM WAREHOUSE OPTIMIZATION

The American Axle Manufacturing (AAM) warehouse optimization is the phase two research case, generalizing the metaheuristic approach from John Deere's shipping configuration optimization research case. Scenario of this research case is optimizing a warehouse with more than 200 different types of parts, with over 10 thousands parts in total held in a designated area in the facility.

8.1 Understanding the Case

The warehouse area is called material market due to the intense material flow occurs in that warehouse. For example, there is a group of operators grabbing parts needed for production line every hour. The same group of operators moves the parts stored in long-haul packages to the grabbing racks for easy obtaining when needed.

Several pieces of motor-powered equipment are used inside the designated area to moving the parts around. The equipment includes forklifts, bending forklifts, material tugging trailers. However, the operational minimum width of each type of equipment is different. Moreover, there are poles, fire extinguisher, and other obstacles inside the designated area. Not only the material holding racks need to give ways to those obstacles, but also the equipment driving path should not be blocked by the obstacles. The following list illustrates the detailed constraints that coupled with this scenario.

1. Regulatory/ Safety constraints:

    - 42" distance from all electrical panels, extinguishers, fire hoses
    - 48" gap from all trusses and poles
    - 5' separation when equipment and human in same aisle

2. Ergonomic constraints:
    - Hand clearance for manually handled totes must have 4” gap from top edge of the tote to the bottom edge of the level above
    - Hand clearance of 2” side to side
    - 20 pounds weight limit for hand-held totes
    - Reach height for hand-held totes only from 36” to 55” from floor
3. Operational constraints:
    - min. 7’ aisle with material tugger and trailer
    - min. 8’ aisle with conventional forklift
    - min. 6’ aisle with bending forklift
4. Material management constraints:
    - First-In-First-Out (FIFO) should be ensured
    - Thermoformed trays (a type of container) stack 2 level high at maximum
    - All palletized material to be stacked 1 level high on corners for visual management
    - Maintain 24” clearance between bulk storage lanes for inventory management

In the above list, the ergonomic constraint limits the height for placing FIFO totes, due to regulations for proper management actions for keeping operators from possible injury when bending to low and reading to high while carrying weight. There is specific type of racks allowed in this scenario for ensuing FIFO — the flow rack. The flow rack is a inclined the level of rack with rollers between the rack and the toes. As the flow rack spans the depth of the rack, parts loaded from the beck of the flow rack will be able to be rolled front by gravity, if the most front one being taken away. Figure 8.1 illustrated the ergonomic constraints compared with the human height and the rack. The ergonomic constraints from 36" to 55" basically range from ones waist to shoulder.

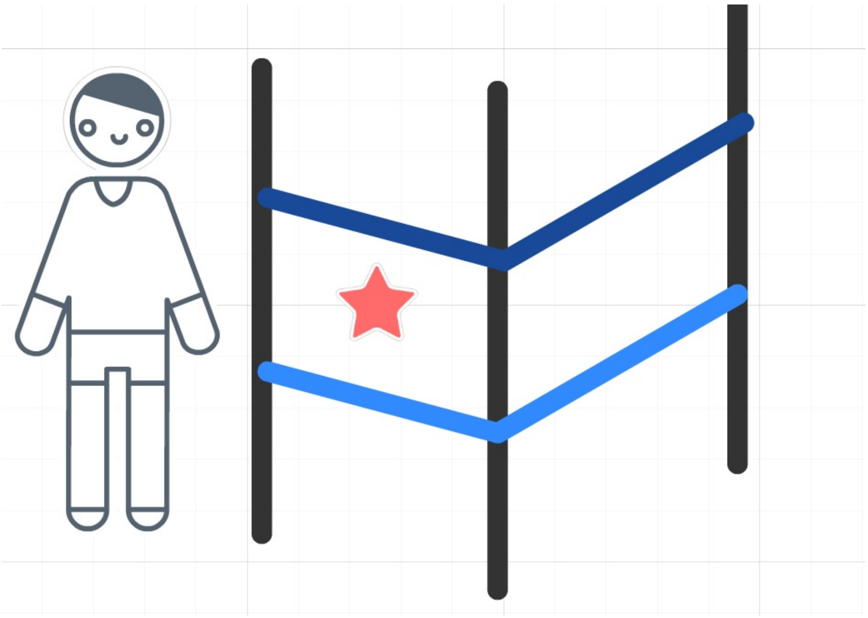


Figure 8.1. Comparison of ergonomic constraint with human height and rack

Operators with different heights have different ergonomic zones, as different heights of waist and shoulder. Therefore, the ergonomic constraints in the regulation have a smaller range to ensure majority of the operators can be protected by the regulation.

Moreover, the constraints includes avoiding obstacles in the given area when planning the racks. There are several different types of obstacles, such as fire extinguisher, poles, electrical box, and so on. The area information can be imported into the metaheuristic approach with being compiled into comma-separated values format. Figure 8.2 shows the current area constraints and floor planning considering only the four poles. However, for this industrial project, fire extinguishers are included.

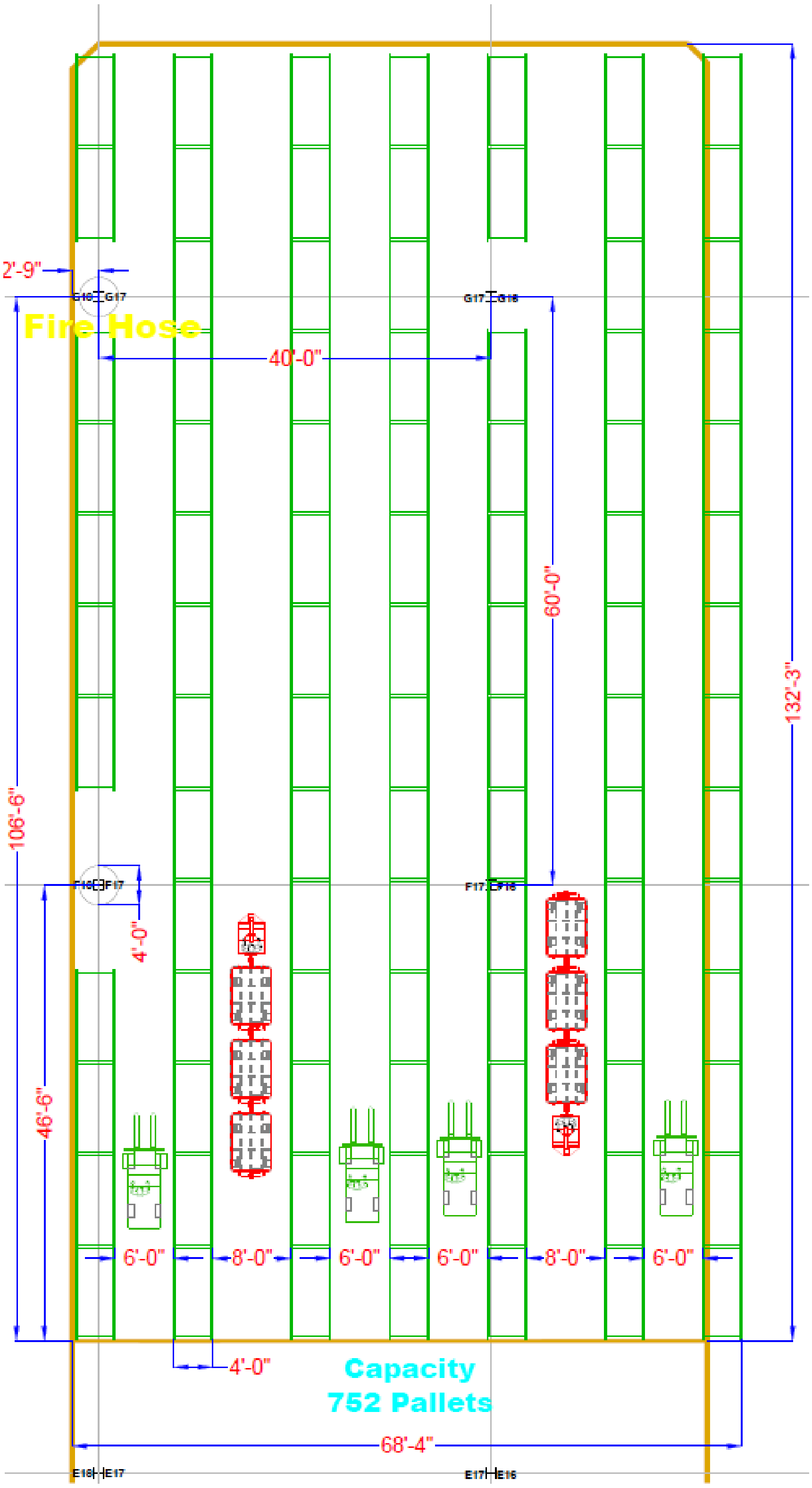
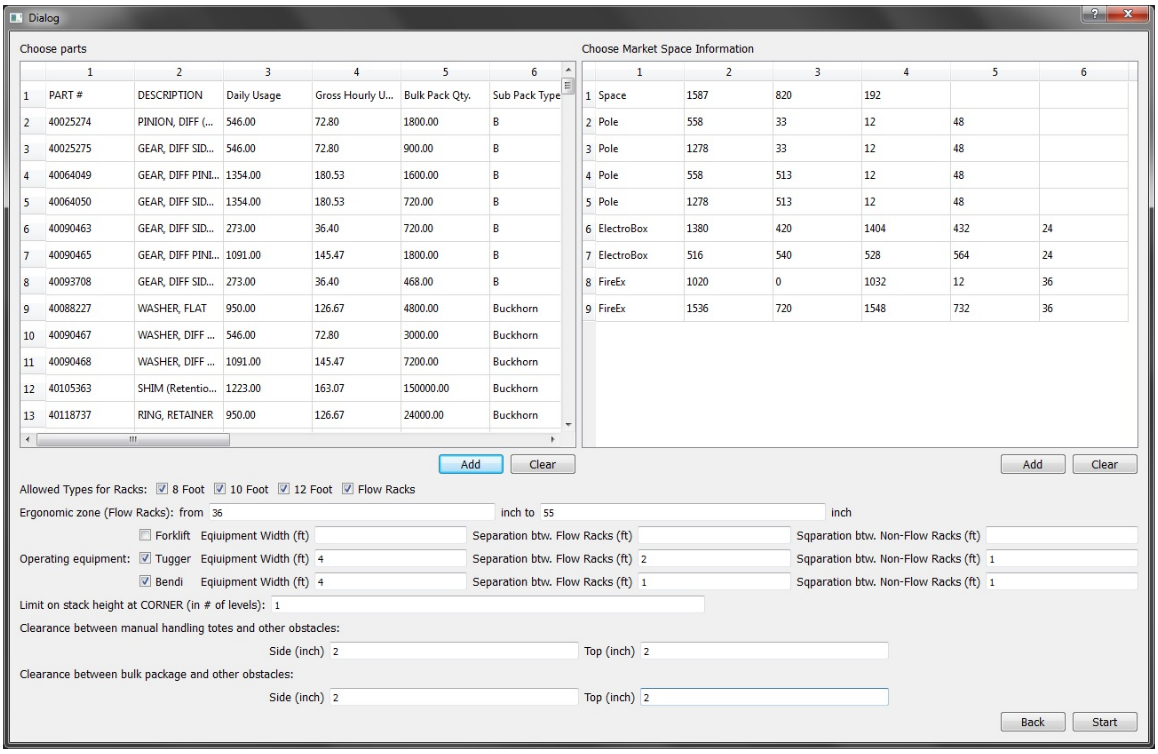


Figure 8.2. Current facility floor planning and constraints information are shown

8.2 Approaches for Warehouse Optimization

Based on the typology of container loading problem (Bortfeldt & Wäscher, 2012), with limited designated area, this warehouse optimization case can be categorized as Single Large Object Placement Problem (SLOPP), loading a single container with a selection from a weakly heterogeneous set of cargo such that the value of the loaded. As mentioned above, there are number of constraints with different types that involved in this case. Figure 8.3 shows a screen shot of the software used to implement the metaheuristic approach for AAM case, as taking constraints into program.



Choose parts

	1	2	3	4	5	6
1	PART #	DESCRIPTION	Daily Usage	Gross Hourly U...	Bulk Pack Qty.	Sub Pack Type
2	40025274	PINION, DIFF (...	546.00	72.80	1800.00	B
3	40025275	GEAR, DIFF SID...	546.00	72.80	900.00	B
4	40064049	GEAR, DIFF PINI...	1354.00	180.53	1600.00	B
5	40064050	GEAR, DIFF SID...	1354.00	180.53	720.00	B
6	40090463	GEAR, DIFF SID...	273.00	36.40	720.00	B
7	40090465	GEAR, DIFF PINI...	1091.00	145.47	1800.00	B
8	40093708	GEAR, DIFF SID...	273.00	36.40	468.00	B
9	40088227	WASHER, FLAT	950.00	126.67	4800.00	Buckhorn
10	40090467	WASHER, DIFF ...	546.00	72.80	3000.00	Buckhorn
11	40090468	WASHER, DIFF ...	1091.00	145.47	7200.00	Buckhorn
12	40105363	SHIM (Retentio...	1223.00	163.07	150000.00	Buckhorn
13	40118737	RING, RETAINER	950.00	126.67	24000.00	Buckhorn

Choose Market Space Information

	1	2	3	4	5	6
1	Space	1587	820	192		
2	Pole	558	33	12	48	
3	Pole	1278	33	12	48	
4	Pole	558	513	12	48	
5	Pole	1278	513	12	48	
6	ElectroBox	1380	420	1404	432	24
7	ElectroBox	516	540	528	564	24
8	FireEx	1020	0	1032	12	36
9	FireEx	1536	720	1548	732	36

Allowed Types for Racks: ☑ 8 Foot ☑ 10 Foot ☑ 12 Foot ☑ Flow Racks

Ergonomic zone (Flow Racks): from 36 inch to 55 inch

Operating equipment:
☐ Forklift Eqiuipment Width (ft) Separation btw. Flow Racks (ft) Sqparation btw. Non-Flow Racks (ft)
☑ Tugger Eqiuipment Width (ft) 4 Separation btw. Flow Racks (ft) 2 Sqparation btw. Non-Flow Racks (ft) 1
☑ Bendi Eqiuipment Width (ft) 4 Separation btw. Flow Racks (ft) 1 Sqparation btw. Non-Flow Racks (ft) 1

Limit on stack height at CORNER (in # of levels): 1

Clearance between manual handling totes and other obstacles:
Side (inch) 2 Top (inch) 2

Clearance between bulk package and other obstacles:
Side (inch) 2 Top (inch) 2

Figure 8.3. Illustration of constraints information entering for the metaheuristic approach program

In Figure 8.3 above, the compiled material information is shown on the left hand side of the dialog, while the compiled area and obstacles information is imported and shown on the right hand side of the dialog. Other constraints, such as available equipment, FIFO, ergonomic zone, and hand clearance are entered at the bottom of the dialog.

Another portion of the constraints is the minimum and maximum number of each material held in the warehouse area. The minimum number of each material is used to prevent the situation that running out of materials or parts, which causing serious delay of production. The maximum number of each material is used to limit the inventory size and reduce cost for parts sitting on shelves for a prolonged time.

Two dimensional floor layout is generated according to the area constraints, material constraints, and other constraints. Shown in Figure 8.4, the optimal configuration of the facility plan has be generated satisfying all constraints. The red frame represents the given area, while the blue, green, and dark green represent 12', 10', and 8' rack respectively. Black dots are poles and small red rectangles are fire extinguishers. Areas shaded as gray are the restriction regions associated with the obstacles.

To test the capability of finding the optimal floor layout under tougher situations, one of the fire extinguishers is set to an abnormally large value. The optimal configuration of the facility plan has be generated satisfying all constraints again, shown in Figure 8.5. The red frame represents the given area, while the pink, dark red, and blue represent 12', 10', and 8' rack respectively. Black dots are poles and small red rectangles are fire extinguishers. Areas shaded as gray are the restriction regions associated with the obstacles.

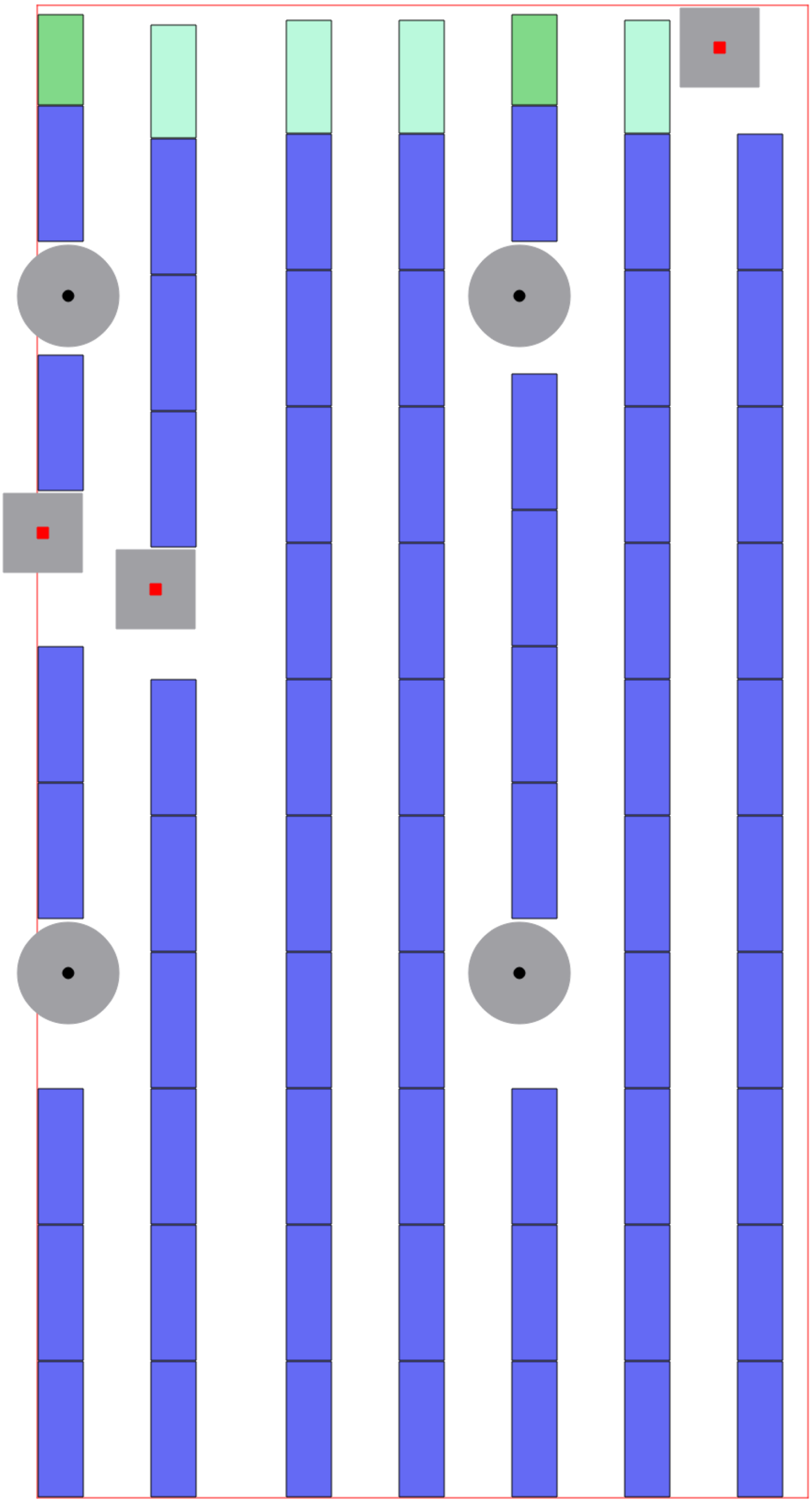


Figure 8.4. Final configuration layout generated by the program enabled with the metaheuristic approach

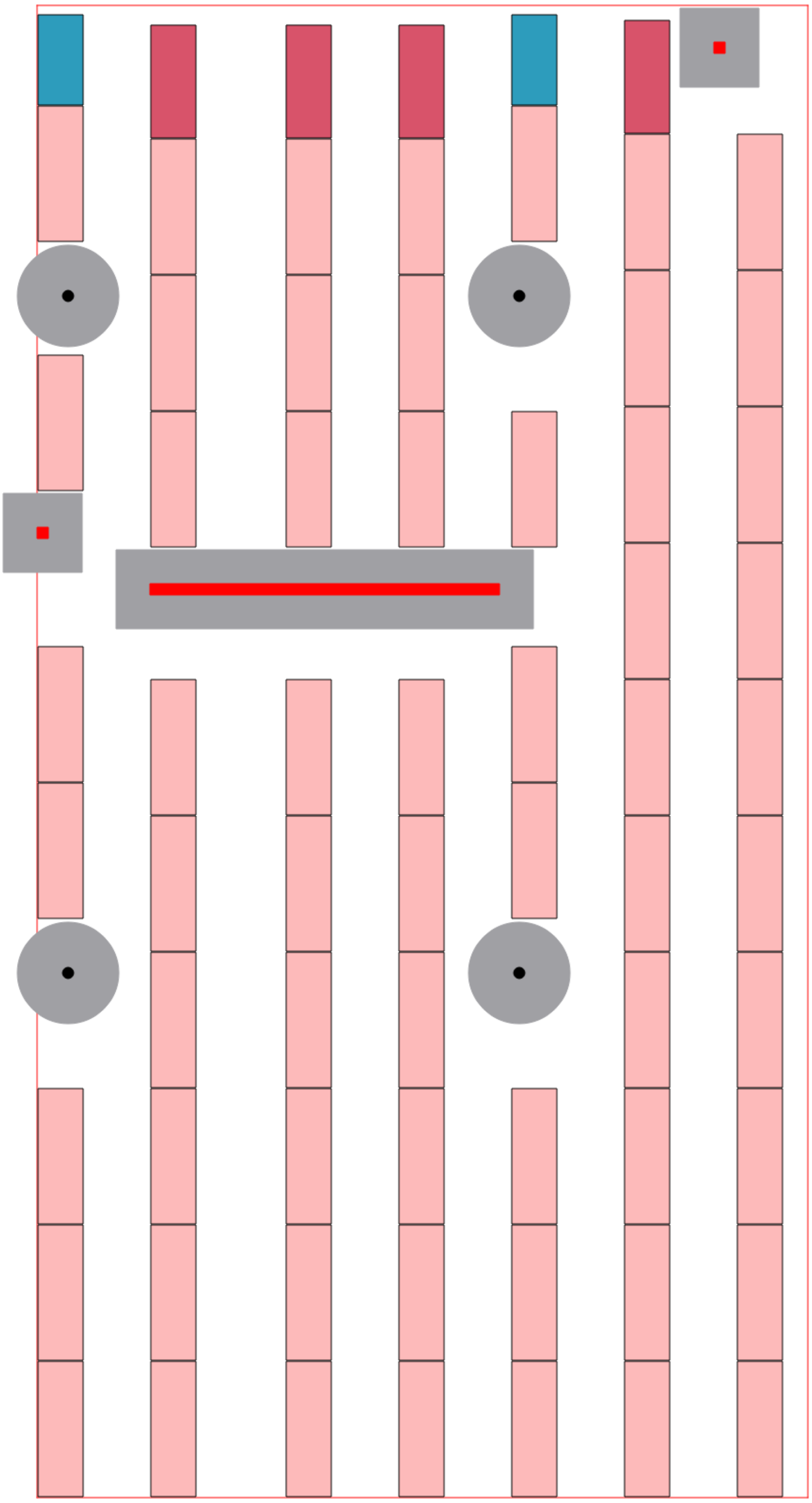


Figure 8.5. Final configuration layout generated by the program enabled with the metaheuristic approach

The ergonomic zone is selected as the constraint oriented guided local search seeding. The reason for using ergonomic zone as the seeding constraints is that the totes (small, sub-package of the materials) are the only object that can be places on the flow rack for ergonomic regulation. Also, the total number of ergonomic enabled flow rack determines the FIFO assurance and minimum inventory constraint for each material. Figure 8.6 shows the final configuration layout generated by the program designed for implementing the metaheuristic approach.

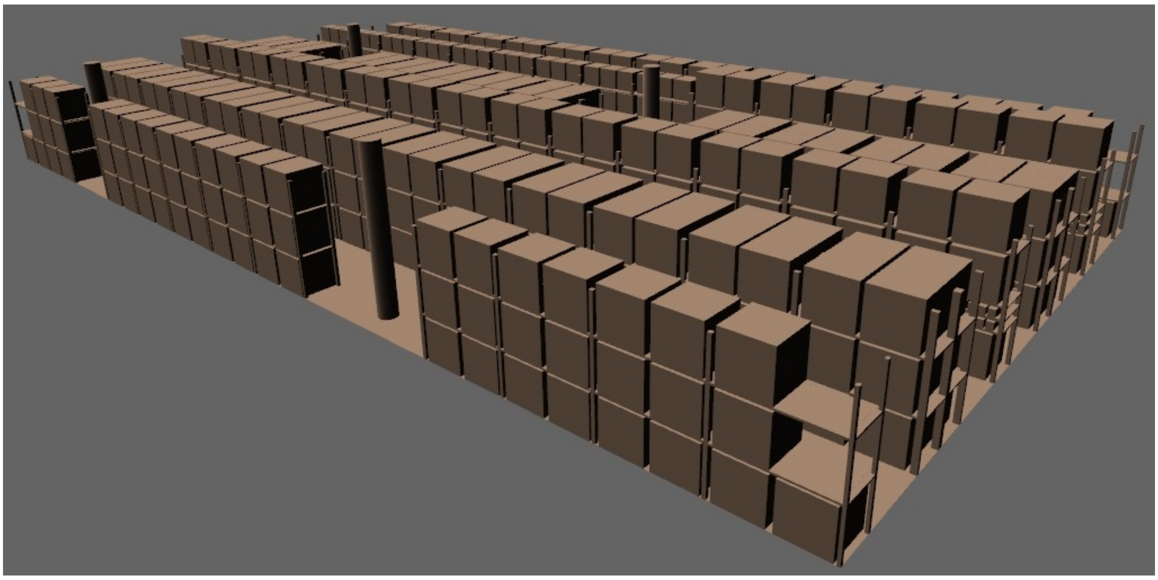


Figure 8.6. Final configuration layout generated by the program enabled with the metaheuristic approach

The poles and other obstacles are successfully avoided by the overlap detection and guided local search of the metaheuristic approach. Moreover, the corners stacks of the designated area are limited to 1 level stacking, implemented with the approach as well. Figure 8.7 shows a close view of the ergonomic zone layout inside the whole configuration layout.

Notice the flow racks in the ergonomic zone are filled with totes for FIFO and hand-held operations, instead of palletized packages. That is to say, the metaheuristic approach with the ergonomic zone as seeding constraint treats the

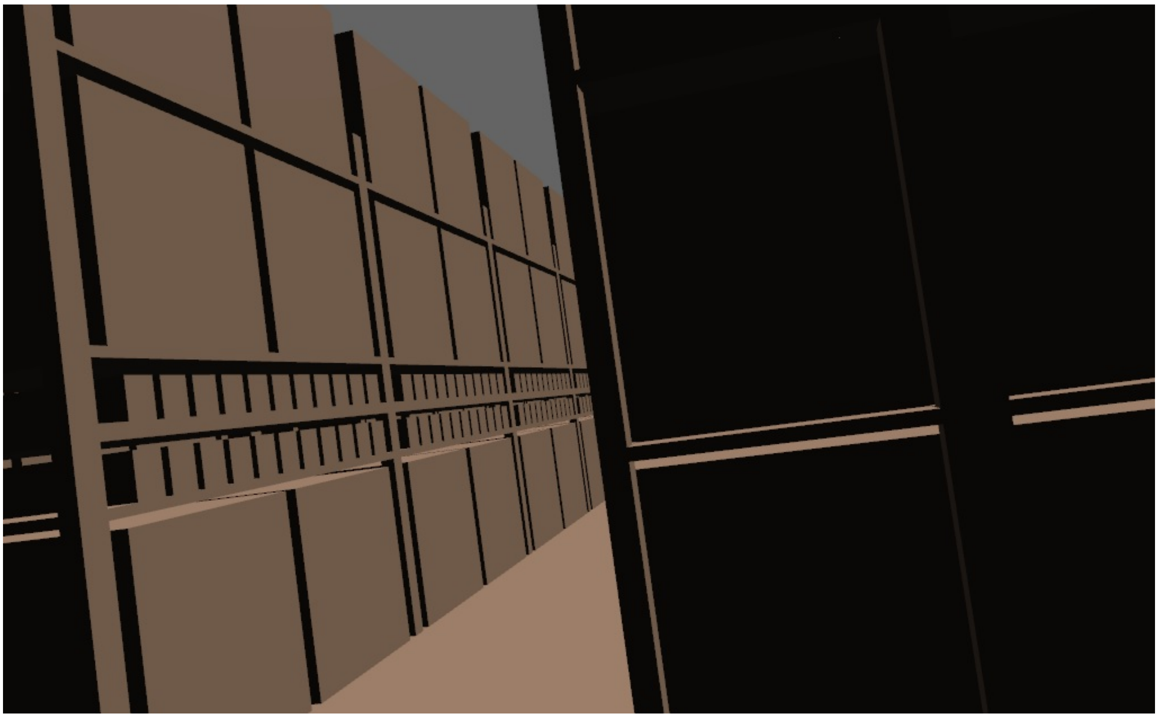


Figure 8.7. Close view of the ergonomic zone with flow racks

ergonomic zone as the highest priority when determining the other placing actions. Figure 8.8 shows colorizing the placing to distinguish the palletized package and totes of different types of the material.

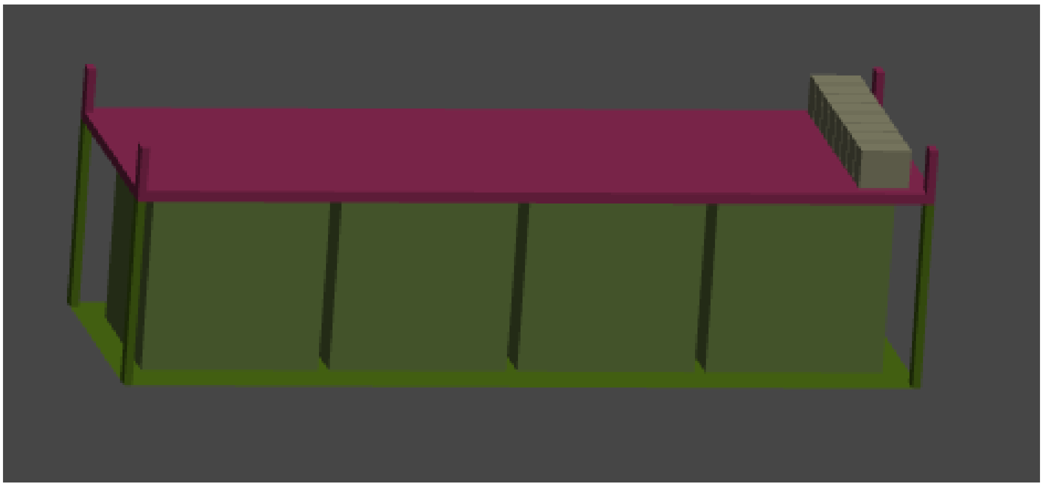


Figure 8.8. Colorization of the pallets and totes for distinguishing different materials

In the area of 68’4” by 132’3”, the current warehouse optimization fits 752 pallets of materials, converting materials in the totes to pallets. The new configuration generated by the metaheuristic approach successfully places 856 pallets of materials and obeyed all constraints, with 13.83% more pallets in the same designated area.

8.3 Summary

Chapter 8 introduced the warehouse optimization case from AAM small part material market. Regarding to the typology of container loading problem, this case is significantly different from the shipping configuration optimization case discussed in last chapter. Moreover, the constraints for this case are much more detailed in scale and formed in different forms, such as ergonomic constraint. However, by selecting the ergonomic constraint as the seeding constraint for guided local search, the metaheuristic approach successfully satisfies the requirements and placed 13.83% more pallets of material in the same area. Therefore, the generalizability of the metaheuristic approach for handling different types of container loading problem can be validated at list for the researched types.

CHAPTER 9. CONCLUSION

This chapter summarizes the research efforts made by the author as conclusions of this Ph.D. work. Prospective research directions based from this research will be illuminated for future work.

9.1 Original Contributions

The original contributions of this research can be categorized to two major types: improvement and exploration. Contributions belong to the improvement are not limited to review and summarize previous research, but include finding the research gap, and formulating novel approaches to attack the irregular shaped container loading problem in research & industrial needs.

9.1.1 Contributions in Aspect of Improvement

The following short list briefly restates the improvement.

- Review literature for container loading problem and introduce new methodology into the research of irregular shaped container loading problem. (Chapter2)

  When reviewing the literature one the container loading problem, the lack of attention and research effort for handling irregular shaped shipments is observed. Only 3% of contain loading problem papers gave general discussions on irregular shaped shipment without technical details. Only 1.8% of CLP papers actually took irregular shaped object into consideration in their heuristic methods. However, there are about 10 CLP papers focusing on regular shaped shipment with heuristic methods or algorithms that may be extended to irregular shaped shipment handling, by modifying minor issues, such as suitable domains, over-complicated search patterns, and so on.

- Reveal shipping procedures and constraints, and formulate the relationship between the irregular shaped container loading problem and their constraints using mind map approach. (Chapter 3)
  The detailed shipping procedure for SKD modules in oversea shipment has been reviewed in the literature. The discussion with the shipping experts from the industry brings up several crucial factors that are unknown for the field of container loading problem, such as the compatibility between different commodity codes, easiness of loading and unloading, coupling the idle time and the loading sequence, and so on. These constraints make the scenario of container loading problem more realistic and more beneficial to the development of industrial shipping. Moreover, the coupled constraints demonstrate the complexity of the real world container loading problems and help to find the optimal solution to the container loading problem.

9.1.2 Contributions in Aspect of Explorations

Exploration type of contributions include applying new concepts or ideas and refining the field irregular shaped container loading problem with exploratory approach. The following list briefly restates the exploration type contributions.

- Introduce key performance indicator and forced decision matrix for evaluation of the shipping configurations. (Chapter 3)
  The key performance indicator (KPI) is applied onto an evaluation system in searching optimal shipping configuration. The forced decision matrix (FDM) is employed to construct a set of criteria with less biased weight that can be utilized in the KPI evaluation system. With this evaluation system, the performance of a configuration can be obtained and controlled from each step of the searching actions.

- Apply topology to define the differences between regular and irregular shapes. (Chapter 4)
  The current definition of regular and irregular shapes are ambiguous, such as a ball can be both regular and irregular shape at the same time. To differentiate between regular and irregular shaped object, the concept of tree from topology is introduced to define both regular and irregular shapes. Even though the improvement and refinement are still needed in this original work, the door of using topology to define the regular and irregular shapes has been opened.

- Apply topology to define the container loading problem for possible simplification in algebraic expressions of Euclidean space. (Chapter 4)
  Similar to defining regular and irregular shapes with topology representations, the container loading process is also represented in topology from two different approaches. The container loading problem are handled in the way of spatial optimization in the current days. However, topology representation of the container loading problem may enable the future of dealing spatial optimization in the algebraic field.

- Apply topological invariant concept to simplify the placing process by dealing with constraints before placing. (Chapter 5)
  The concept of topological invariant stands for the properties preserved by transforming from one topological space to another. By setting industrial constraints as the topological invariants, the preservation relationship of both pallet and container spaces remains in constrained space. Therefore, constraint can be tackled well before it kicked into the container loading problem, which reduce the unnecessary search efforts.

- Introduce envelop shape for two- and three-dimensional objects to combine the shape simplification and interference elimination. (Chapter 5)
  The envelop shape of the two- and three-dimensional objects saves the computer resources by reducing the complexity of the irregular shapes and

adds extra virtual cushion to the object that reducing the potential interferences.

- Introduce topology-based sextuple-tree guided local search with industrial constraint seeding. (Chapter 6)
  Sextuple-tree guided local search utilizes the sextuple-tree model for representation of the remaining space in container for particular condition. The industrial constraint seeding enables using one industrial constraint to initiate the guided local search with setting the particular constraint as highest priority among the constraints.

- Apply metaheuristic approach to different types of container loading problems. (Chapter 7 and Chapter 8)
  The potential value of the metaheuristic method is demonstrated by dealing with multiple types of container loading problem. Concept of using topology-based guided local search is also been validated as a possible approach for future development.

9.2 Conclusion

This Ph.D. dissertation is derived observing and investigating the real world shipping dilemma. The mismatch is found between the industry needs and the market supplies in terms of effectively handling irregular shaped shipments. The ambiguous of defining regular and irregular shape is pointed out and set as one the research problem. Also, the idea of simplifying the container loading problem when dealing with irregular shape by using topological concepts is raised for exploration. The literature review provides in depth analysis into the current research condition regarding on container loading problem with irregular shaped shipments. Previous research involving irregular shaped shipment are reviewed carefully reviewed and evaluated to understand the ability of the algorithm and methodology from those works. Methods or algorithm from container loading problem with regular shaped shipment and from other industrial fields are also evaluated and mutated for potential approaches that may inspire new algorithms.

The procedure of shipping SKD modules oversea is observed and analyzed. More comprehensive list of constraints in container loading problem is investigated, such as easiness of loading and unloading SKD modules onto pallets and compatibility between SKD modules. Meanwhile, the relationship between import tax and commodity code with the ability of assembling SKD modules is created. The evaluation system combined with key performance indicator and force decision matrix is applied to the search pattern for optimal shipping configuration. One of the features of this evaluation system is that the configurations can be evaluated at each step during the process of searching optimal, instead of evaluating all configuration at the end of searching. Invalid shipping configurations is filtered out at each step, which truncates invalid configuration branches.

Topological representations to irregular shapes and container loading problem are proposed as exploratory research for applying the concepts from topology to optimization problems. Representing with topological concepts helps the metaheuristic approach to perform actions such as envelop shape for three-dimensional shapes, dealing with constraints before placing, construction of pallet modules, and sextuple-tree model for guided local search, as well as constraint oriented seeding search.

The topology-based guided local search, generated valid shipping configurations and warehouse optimization layouts that are not able to obtained with existing methods with the large number of constraints to fulfill. The significant savings by using proposed metaheuristic approach to multiple types of container loading problems make one believe that simplification of container loading problem by adopting topological concepts is feasible and worth of future developments.

9.3 Prospective Research Directions

Upon the research questions raised at the beginning of this dissertation were researched and treated with the proposed metaheuristic approach, there are still several questions laid outside of the research scope. Therefore, the following list illuminates the future research direction based on this research with the idea of encouraging future research actions.

- Focusing more on the development of handling irregular shaped shipments in container loading problem,
- Refining the definitions of regular and irregular shapes in two- and three-dimensional shapes,
- Improving the topological representations to container loading problems for simplifying CLP under algebraic domain,
- Exploring on the potential ability of modeling other scenarios other than remaining space in container loading problem, and
- More in depth research on guided local search for other types of container loading problem.

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VITA

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Personal Profile

I am a self-motivated and well-organized graduate student with excellent communication skills. With a strong mechanical engineering and technology background, I am willing to observe, learn, think, and solve both theoretical and hands-on problems. My interest focuses on the specific areas of engineering such as manufacturing and product design, precision machine design, industry and organization related human factor and behavior issues, effective management and evaluation, optimization, as well as technology education. Ambitious to solve problems and never hesitate to perform dirty and tired works.

Education:

Purdue University, West Lafayette, IN

Doctor of Philosophy in Mechanical Engineering Technology,
Engineering/ Industrial Management Program Expected: May 2015

Michigan Technological University (MTU), Houghton, MI

Master of Science in Mechanical Engineering Awarded: Dec 2010

the Hong Kong University of Science & Technology (HKUST), Hong Kong

Bachelor of Engineering in Mechanical Engineering Awarded: Jun 2009

Languages:

Native in Mandarin and proficient in both English and Cantonese

Awards and Achievements:

Student Association Service Reward, MTU Awarded: Aug 2010

Awarded for excellent and valuable service (2009 - 2010)

President, Chinese Student and Scholars Association (CSSA)

University Scholarship, HKUST Awarded: Jun 2006

Academic Excellence

Department of Mechanical Engineering Scholarship, HKUST

Academic Excellence Awarded: Jun 2006

National Competition of Chemistry for High School Students, PRC

First prize and listed as the candidate of the Chinese National Team for the 2005 International Olympics Chemistry Competition Awarded: Mar 2005

Working Experiences:

School of Engineering Technology, College of Technology, Purdue University

Teaching Assistant, MET143 Material Processing Oct 2014 - present

This course serves as an introduction to materials and material processing to the mechanical engineering technology major students. I gained a lot of communication experiences and techniques of conveying concepts and ideas when exchanging information with people with difference backgrounds.

Center for Technology Development, Purdue University

Research Assistant Jan 2012 - present

Shipping Configuration Optimization (SCO) and Warehouse Facility Optimization (WFO)

(Joint project with Deere & Company, American Axle Manufacturing, Eaton, and Faurecia)

This project is to develop a new generation of meta-heuristic method that can utilize the space in the shipping containers by handling the shipment items as irregular shaped objects, instead of cubes. The unique feature of this method is taking the highway and custom regulations, cushioning, and easiness of loading and unloading into consideration. Topological spatial optimization is used in the heuristic method to simplify the irregular shapes. With the simplified shapes, topology-based guided local search and topological grouping method are applied to simplify the solution generation process. The meta-heuristic method for non-stacking semi-knockdown modulus was refined and verified with on-site pilot test in the Phase I of this project (2012 - 2013). The Phase II (2013 - 2015) focuses on developing improved meta-heuristic method that allows stacking and free-rotation of the placement when processing the overlap detection and elimination, as well as dealing with the augmented constraints. This meta-heuristic method is also applied to the warehouse optimization scenario, which computerizes the materials and parts arrangement for better floor utilization.

Multidisciplinary Design Lab, School of Engineering Technology, College of Technology, Purdue University

Research Assistant Jan 2011 - present

Conducted research on topology embedded systems for better spatial utilizations of the mechanisms. Performed daily practices that include the designs and constructions of the mechanical portions of the experiment platforms, maintenance of the laboratory equipment, and safety guidance.

Dining Service, MTU

Leading Catering Staff Aug - Dec 2010

Coordinated catering staffs in terms of preparing the venue, serving dishes, cleaning up for the next event, responding to special requests from our guests, and dealing with unexpected situations

Undergraduate Research Opportunity Program, HKUST

Research Assistant Jun - Aug 2008

Designed and tested a novel method of filter-free vacuum cleaner by collecting the tiny dirt by static electronic force and larger dirt by passing through a series of aerodynamic vortexes.

Manufacturing Department, Zhongxing Telecommunication Equipment (ZTE), PRC

Assistant Efficiency Investigator, Summer Internship Jun - Aug 2008

Investigated and analyzed the material flows, factory layouts and management from the aspects of lean manufacturing. The investigation results with a proposal containing the suggestions for improving the efficiency and the accuracy of manufacturing was submitted and granted for execution.

Academic and Enrichment Activities

CoT Latex Dissertation Template Rework Project, College of Technology, Purdue University

Contributor, report to Prof. Mohler, Assoc. Dean for Academic Affairs & Diversity
Aug 2014 - present

Reworking the current College of Technology Latex template for thesis and dissertation to provide the most updated, accurate, and professional resources to students in the college. The project includes tackling and eliminating huge number of errors and adding brief guidance with typical entry-level examples for authors new to Latex. After that, a guidance with more detailed examples covering much more typesetting situations that students might encounter will be constructed, which is specifically designed for both graduate and undergraduate CoT major students by enabling the adaptability to general course projects and Senior Design Project. The first part is designated to TECH646 students for quick access to the template for practice in class. The second part will take up to two semesters of part time work, but will greatly enhance the capabilities of the template with wide range of document types.

3D Printer Project, Multidisciplinary Design Lab, Purdue University

Research Assistant, Laboratory Contribution Project Oct 2011 - Feb 2012

Modified both the existing structural designs and control modules, and constructed a fused deposition modeling (FDM) type 3D printer using acrylonitrile butadiene styrene (ABS) as extrusion filament. It was built for not only rapid prototyping, but also providing possible future research opportunities, such as thermal control of the heating bed, motion control of the nozzle adapting to the structural deformation, and so on. This 3D printer has the precision up to 0.03 mm for overall linear error, which is close to ten times better than the original version.

Chinese Students and Scholars Association (CSSA), MTU

President Apr - Dec 2010

Improved traditional student's activities, for example, mid-autumn singing competition, badminton competition, Chinese Folk Culture Exhibition, and enhancement of their work and study experience. Introduced new activities that follows the cutting-edge technologies, such as video game competition, winter driving skills class and competition, individual makeup skills class. Communicated with National Education Department of PRC and Chinese Associations of other universities in North America for joint activities.

Chinese Students and Scholars Association (CSSA), MTU

Chief of Entertainment Department Aug 2009 - Apr 2010

Organizing and coordinating all student activities and corresponding promotions held by CSSA. Presented a number of annual and trial activities. Among those activities, the largest event is the annual Chinese Night Dinner and Performance, which welcomed more than two thousands guests to enjoy our Chinese folk culture.

Final Year Design Project, HKUST

Group Leader 2008 - 2009

Designed and prototyped a remote controllable vertical take-off and landing (VTOL) aircraft with a tilt propeller. The fuselage was heavily modified from the RC model of a P-51 twin mustang. The wings are newly designed through the structural aerodynamic finite element analysis (FEA) tools, ANSYS. Prototypes of the wings and other parts of the airplane were built by the team. There were fins located at the downstream of the propeller, controlled by the computational program to remain its stability status. The airplane was tested in the wind tunnel for aerodynamic properties and in the field for VTOL stability.

Hong Kong Dog Rescue (HKDR), Hong Kong

Volunteer 2008 - 2009

Registered dog walker and kennel worker of HKDR, whose main duties were taking care of the homeless dogs and providing certain medical care until being adopted.

Skills and Interests

Computer Aided Design Tools:

- ***3D Modeling & System Design:*** SolidWorks, UG NX, CATIA, Simulink
- ***Design Verification:*** ANSYS, Comsol Multiphysics, NI LabVIEW
- ***Project Management:*** SIEMENS Teamcenter, MS Office Project & Visio
- ***Data Analysis and Statistics:*** MATLAB, Mathematica, SAS, SPSS
- ***User Interface Development & Image Manipulation:*** Qt (with OpenGL and C++), Autodesk 3ds Max
- ***Office & Daily Practice:*** MS Office (Word, Excel, PowerPoint, Publisher), Inkscape Vector Drawing, LaTeX

Career Interests:

- Product design (mechanical, electronic, and hydraulic)
- Lean manufacturing evaluation and design, organization management and evaluation, industrial field related human factor
- Optimal spatial arrangement design (container loading, shipping, packaging, logistic related issues)

Other Interests:

Driving, traveling, cooking, badminton, squash, soccer