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INTEGRATION OF PHYSICAL SIMULATIONS IN STATIC STABILITY ASSESSMENTS FOR PALLET LOADING IN AIR CARGO

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ABSTRACT

In the air cargo context, pallet loading faces substantial constraints and item heterogeneity. The stability constraint in the pallet loading problem is highly important due to its impact on the efficiency, security, and resulting costs of an air cargo company. In information systems that support pallet loading, physical simulations provide a realistic approximation of a pallet's stability. However, current approaches neglect the opportunity to integrate physical simulations in underlying solvers. In this research, we propose and compare two approaches for integrating a physical simulation as a fixed component of the problem-solving heuristic and include irregular shapes. Our results achieve runtimes that meet air cargo requirements; therefore, assumptions about the cargo, e.g., shape assumptions, can be relaxed.

1 INTRODUCTION

Modern supply chains consist of efficient sequences of highly interrelated process steps. Logistics play an important role in these chains, connecting different pieces of the chain in a seamless manner. The air cargo industry plays an important role in world trade, as it connects overseas markets (Olsson et al. 2020). From 2014 to 2019, cargo volumes increased by approximately 20 % (IATA 2019). As world trade is expected to grow in the next decades, increasing air cargo volumes and, therefore, an increasing number of aircrafts are needed to meet transportation demands (Airbus 2019). However, global air transport caused approx.-imately 2.4 % of global CO_2 emissions from fossil fuels in 2018, with increasing trends (Graver et al. 2019). In total, air cargo companies are facing numerous challenges to increase operational efficiency while reducing costs to achieve operational, economical, and ecological goals in the future (Döppner et al. 2018).

One key task in air cargo operations is the loading of cargo items onto pallets in order to reallocate and distribute the goods shipped. The problem of efficiently loading a pallet is a practical problem commonly faced in the logistics industry. Currently, palletizing workers receive little support from information systems; instead, the efficiency and outcome of this work are determined by the skills and knowledge of individual palletizers. In scientific literature, this problem is referred to as the pallet loading problem (PLP) (Dowsland 1987). A good PLP solution, based on cargo arrangement on the pallet, leads to a high space utilization. Pallet loading efficiency can achieve significant cost savings in the supply chain, in terms of transportation and warehouse costs (Zúñiga et al. 2011).

A PLP solution (also called a layout) is considered to be good if it not only takes advantage of the given resources as efficiently as possible, but is also applicable in a practical context. To increase the practical relevance of solutions for this problem, several constraints have been imposed. In the literature, a constraint that is particularly relevant (Bortfeldt and Wäscher 2013; Ramos et al. 2016b) "yet inconsistently dealt with" (Zhao et al. 2014) is the stability constraint, imposed to preserve the (partly) stacked cargo on the pallet from collapsing (Bischoff 1991; Parreño et al. 2008; Ramos and Oliveira 2018). A layout is statically (or vertically) stable if the loaded items can "withstand the gravity force acceleration over them" (Junqueira et al. 2012), such that the items retain their loading position and do not slide, rotate, tip, or fall (Ramos et al. 2015). Static stability is considered for situations in which the pallet is not being moved. In contrast, if a pallet is being moved and the loaded items withstand the inertia of their bodies, the layout is considered dynamically stable (Junqueira et al. 2012). An unstable pallet can result in damaged cargo and even personnel injuries during transport or during the loading and unloading of cargo items (Bortfeldt and Wäscher 2013; Zhao et al. 2014).

Currently, the integration of physics simulations in problem-solving heuristics is usually not considered due to runtime complexity, as each solution has to trigger at least one simulation, which in turn affects the runtime of the overall heuristic (Ramos et al. 2015). In the air cargo context, this problem is further complicated by a strong heterogeneity of cargo items (in size and shape) and complex build-up shapes (pallet contours) for air cargo pallets. Additionally, loading constraints based on strict aviation safety regulations must be considered (IATA 2018). The increasing standardization of packing boxes has led to more rectangular packing boxes, in which irregular- or complex-shaped cargo is packed. This evolution has simplified handling and placement efforts, but comes at the expense of much wasted space.

In this study, we tackled the problem of integrating a physical simulation within an information system that supports pallet loading for air cargo. The information system applies a genetic algorithm (GA), which, in our case, acts as a solving metaheuristic for a set of strongly heterogenous, irregular cargo, such that the overall runtime of the optimization is limited to a reasonable wall clock time. Therefore, our research question is as follows: *How can a physical simulation for a realistic assessment of the static stability constraint be efficiently integrated into an information system to support pallet loading for air cargo?*

The remainder of this paper is structured as follows: The following section provides a detailed description of the PLP, the stability constraint, the handling of irregular cargo, and the physical simulation approach. In the related work section, existing simulation approaches for studying cargo stability are presented. Subsequently, we specify our problem to the air cargo context. In the next section, we explain our physics simulation approaches; afterwards, the results of our tests are set forth, followed by a discussion of our work. Finally, we draw conclusions and elaborate on future research in this field.

2 THEORETICAL BACKGROUND

2.1 Pallet Loading Problem

The PLP belongs to the family of three-dimensional cutting and packing problems, in which a set of small items must be grouped and assigned to a set of larger items, such that all small items lie orthogonally within the large object and the small items do not overlap. In this research, the PLP can be further classified from a distributor's point of view as a single knapsack problem (SKP) (Wäscher et al. 2007). The SKP aims to pack a strongly heterogenous set of items with varying dimensions on a single pallet such that the total value of the loaded items is maximized. The value of items is often directly proportional to their volume. A set of small items is considered to be strongly heterogenous if only a few items are of identical shape and size (Bortfeldt and Wäscher 2013). Because the PLP is closely related to the container loading problem (CLP) class, we also consider established results for the task of container loading as we address the PLP. In both cases, a logistic agent aims to minimize the handling effort and time. In contrast to the PLP, research on the CLP assumes that the primary object is a metal container with rigid walls providing lateral support for the cargo. Such rigid side walls are usually replaced by a safety net on pallets.

2.2 Static Stability

The current state of the literature on static and dynamic stability in the PLP was reviewed by Ramos and Oliveira (2018). The authors classified previous static stability assessment approaches into the categories of full base support, partial base support, and static mechanical equilibrium. Both full and partial base support approaches ensure that a minimum proportion of the lower face of each cargo item is supported from below (e.g., from an underlying item or the floor) (Ramos and Oliveira 2018). An equilibrium for the bodies is achieved if the sum of all forces acting on the cargo item is zero and if the sum of the moments of all forces for each part of each item is zero (Hibbeler 2010). Studies employing static mechanical equilibrium calculations are currently focused on two-dimensional packing problems or consider rectangular-shaped items (Queiroz et al. 2018; Queiroz and Miyazawa 2014; Ramos et al. 2016a).

The assessment of static stability for a strongly heterogenous set of rectangular and non-rectangular items can be very complex, as several physical interdependencies must be considered, such as the weight distribution or collision detection for different shapes. To cope with this complexity, researchers have considered numerical simulations using physics engines to assess the stability rather than applying a mathematical formulation of static equilibrium calculations (Martínez et al. 2018; Oliveira et al. 2017).

2.3 Irregular Item Shapes

In this research context, an irregular geometric body should not be interpreted in a mathematical sense (where each angle is fixed at 90° and each side has the same length), but includes every possible shape type, with the exception of rectangular items, cylinders, and spheres (Wäscher et al. 2007). Few studies have examined irregular placement problems for the two-dimensional case, while research on the three-dimensional case is even more scarce and primarily focuses on item placement.

Egeblad (2009) provided a heuristic specifically designed for the container loading of irregular shapes. This heuristic incorporates balance and inertia moments as constraints for the placement and minimizes the overlap of items. In a subsequent paper, Egeblad et al. (2010) examined the container loading of irregular shapes from the viewpoint of a furniture producer. The authors divided the input items into categories of large (mainly irregular items), medium (boxes), and small (boxes). They employed multiple heuristics for each shape type, and the average utilization factors over all shapes reached approximately 91 %.

Martinez-Sykora et al. (2017) tackled the two-dimensional bin packing problem, which allows free rotations of the items, inspired by a real-world case.

2.4 Physical Simulation

To address the PLP with realistic physical feedback, a physical simulation can be used to build up a virtual image with physical laws similar to those in a real-world context. A physics engine is a software framework that can simulate physical effects in computer applications such as games, animations, or scientific simulations (Hummel et al. 2012; Oliveira et al. 2017). The findings of Martinez-Franco and Alvarez-Martinez (2018) revealed that a real-time physics engine can approximate the results of high-precision, deterministic simulation software in a fraction of the time with a reasonable degree of precision. A real-time physics engine can compute the collisions of hundreds of rigid body spheres in a matter of milliseconds (Hummel et al. 2012). Assessments of dynamic stability are primarily conducted by real-time physics engines.

Ramos et al. (2014) and Oliveira et al. (2017) developed a simulation software for evaluating the dynamic stability of container cargo. The physics engine Bullet served as the basis for the real-time simulation of dynamic stability, which allows one to analyze and adjust external forces during transportation and can handle boxes of different sizes. However, the simulation was not integrated in a solution-generating heuristic for loading problems (Bracht et al. 2016).

Bracht et al. (2016) reported the integration of a dynamic stability verification using the physics engine Open Dynamics Engine in a biased random-key genetic algorithm (BRKGA) metaheuristic. Their results revealed that the physics simulation consumes most of the processing time, preventing the BRKGA heuristic from reaching a high level of solution quality and decreasing its convergence towards satisfactory layouts. The authors noted that the simulation parameters should be adjusted in order to increase speed and reduce accuracy.

Recent work by Martinez-Franco and Alvarez-Martinez (2018) indicated that the dynamic stability can be evaluated with satisfactory precision by using a real-time physics engine instead of a dedicated physical simulator. In their approach, the authors developed a simulation tool based on the games engine Unity, which utilizes the integrated physics engine PhysX, and compared the simulation results to those of the dedicated simulation software Autodesk Inventor. The authors concluded that the real-time physics engine produces simulation results with a sufficient degree of precision. Furthermore, the real-time physics engine was able to conduct the simulation in only a fraction of the time required for the dedicated simulator (8 s vs. 17 min).

3 RESEARCH CONTEXT: PALLET LOADING IN AIR CARGO

Pallet loading for air cargo is characterized by a number of constraints. For example, strict aviation safety regulations and a defined build-up of pallet contours must be followed. In addition, there is considerable time pressure for the build-up of the pallets. In collaboration with a major German air cargo company, we conducted joint workshops with experts, observed operations on-site at an air cargo hub, and iteratively conducted interviews with palletizers for several months.

3.1 Size and Shape Heterogeneity

In an air cargo hub, a confluence of cargo arrives and is processed for further air transport to its final destination. Because air transport is one of the most expensive modes of transportation, items are often valuable, dangerous, perishable, or urgent (Brandt and Nickel 2019). In general, air transportation is especially advantageous for time-sensitive cargo that has a high value-to-weight ratio (Zhang and Zhang 2002). During our air cargo hub visits, we observed a tremendous diversity of cargo items and pallet contours (Figures 1 and 2). The items differed in shape, packaging material, weight, load capacity, and substructure. Most items had a rectangular shape and frequently came pre-palletized on a wooden pallet. Irregular item shapes are observed less often (Brandt and Nickel 2019), but require a higher loading effort because they are not easy to place onto the pallet. Cargo items must be arranged on a pallet such that the final layout fits a defined pallet contour, while the pallets vary in type and size. For a container with rigid metal walls, the contour is already fixed.

Figure 1: Built-up pallet with a defined contour.

Figure 2: Assortment of items on a pallet.

To the best of our knowledge, no frequency estimation of individual cargo items exists for an air cargo hub. According to the results of our expert workshops, approximately 95 % of cargo items are rectangular, which may be due to the ongoing standardization of packaging material. To protect items from damage during transport, many natively irregular items, such as machine parts or furniture, are packed in rectangular-shaped boxes. Next to boxes, sacks and barrels appear most often. Depending on the origin of the cargo, items arrive pre-palletized on a wooden pallet or grouped into multi-items.

3.2 Consideration of Constraints in Air Cargo

When air cargo pallets are loaded, major constraints must be considered. One such constraint is the time window in which a pallet build-up must be completed. In addition, loading rules must be strictly followed in order to ensure aviation safety at all times.

Cargo items arrive at the air cargo hub at different time intervals until shortly before flight departure. Depending on the time window until build-up, a PLP heuristic can run for a longer or shorter amount of time. On the one hand, runtime is a serious issue for a metaheuristic with a desired target runtime of several minutes up to one hour. On the other hand, metaheuristics generally provide better results when they can run for a longer time.

Additionally, a specified set of strict aviation safety regulations exists for pallet loading in air cargo, which are primarily standardized by the International Air Transport Association (IATA). Briefly, this set consists of six loading constraints that must be fulfilled by a built-up pallet. Only when all six loading constraints are met, the pallet may be loaded into an aircraft for transport. These six aviation safety constraints are related to stability, floor load, maximum weight, contour, balance, and incompatibility of cargo items, as described in detail in the IATA Cargo Handling Manual (IATA 2018). This research primarily focuses on the evaluation and measurement of cargo stability, which is one of the most important constraints and also the most difficult constraint to tackle when seeking realistic results.

4 SOLUTION APPROACH

To evaluate the static stability for a set of strongly heterogenous items with irregular shapes, we follow the simulation-based approach with a physics engine employed by, e.g., Bracht et al. (2016). A physics simulation can evaluate the static stability for arbitrary shapes beyond boxes, including irregularly shaped items. The minimum support or static mechanical equilibrium approach may obtain good and computationally fast solutions, as shown by, e.g., Ramos et al. (2016a). However, both approaches rely on assumptions about cargo shapes, e.g., rectangular items. Real-time physical engines can relax some of these assumptions, as they can hold an inertia tensor for each supported shape, including complex shapes. Furthermore, simulations can be invoked for each loading state to ensure loading and unloading stability during build-up (Bracht et al. 2016).

4.1 Applied Heuristic

Our underlying information system performs heuristic calculations on the basis of artificial intelligence to find a practical solution. A high-level representation of the design and architecture of the information system is described in Lee et. al (2020). In detail, a GA is applied as a metaheuristic because the research context contains a high amount of complexity, considering the inclusion of strongly heterogenous and irregular shapes for items and pallet contours. Similar to neural networks and fuzzy logic, GAs belong to the research field of classic computational intelligence. They were chosen because of their ability to move freely through the solution space without any contextual information except for an assessment function (Goldberg 1989). A GA starts with a randomly seeded population and recombines, mutates, and selects members of the population during iterative generations, therefore creating better fitted solutions by the end of the running time in comparison to the nearly arbitrary starting solutions. As GAs perform well in general, when the solution space is constrained, is noisy, or contains a large number of local optima (Kramer 2017), they are well suited to provide a good solution for an NP-hard problem, such as the PLP. The goodness-of-fit of a single solution is assessed using self-defined fitness functions that can be formulated with a variable degree of complexity and sophistication. Because the fitness functions are the only measurement of progress for the algorithm (Kramer 2017), the solutions' fitness values for a given problem depend on fitness functions that can create rapid and realistic feedback to allow the heuristic to reach a steep learning curve and to obtain a precise understanding of the problem context.

The feedback from the assessment function should be as sophisticated as possible, but also influences the overall runtime. Thus, we modelled the stability simulation within the fitness function of the GA as an assessment criterion. The input from the GA into the fitness function for the assessment criterion consists of the cargo layout, with the assessment score for the layout as the output. The input is defined as the phenotypic representation of the built-up pallet with its meta-information and details about each cargo item, such as the shape, dimensions, and weight, and its placement on the pallet, e.g., x, y, and z coordinates and loading sequence. Figure 3 shows the supported shapes along with their identifying shape information. Because a myriad of shapes can be found in practice, our information system considers two irregular shapes in addition to the regular rectangular shape of a box and a cylinder: L-shape, and polygon prism. A cylinder best approximates the shape of a barrel or metal bar, while L-shapes resemble furniture or machine parts, and polygon prisms allow for a variable two-dimensional base shape with a fixed height. Therefore, the information system does not support arbitrarily complex, three-dimensional meshes. The four shape types can be classified as regular (box, cylinder) and irregular (L-shape, polygon prim) (Wäscher et al. 2007).

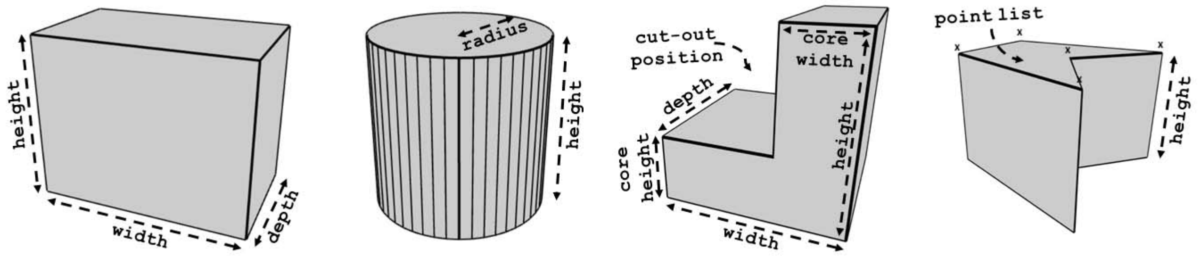

Figure 3: Item shapes supported by our information system.

We sought to test our approach under conditions that reflect practical situations to the greatest extent possible. Thus, the six aviation safety constraints are incorporated into the GA as assessment criteria, including the stability constraint. Additionally, further constraints are considered such as item orientation, item priorities, grouping (as several items may be assigned to a single airway bill (AWB) and, therefore, must be transported together), and stacking (Bortfeldt and Wäscher 2013; Pollaris et al. 2015; Zhao et al. 2014). The overall fitness is calculated as the weighted sum of all assessment criteria, and the stability assessment criterion returns to the GA a single floating-point assessment value, capturing the degree of stability of the assessed pallet. As the stability assessment value is the only indicator driving the GA to better, i.e., more stable, solutions, it must sensitively measure the degree of stability of the built-up pallet. Combined with a high weight in the fitness function, this approach leads to an incentive for stable solutions and a penalty for instable layouts.

4.2 Assumptions

As there is no meta-information about the cargo and to limit the runtime complexity of our physics simulation, we imposed several assumptions. First, we modelled the cargo items as non-deformable rigid bodies, which enables the utilization of computationally cheaper rigid-body physical laws in contrast to the more expensive soft-body physics. We did not include additional devices that are used in air cargo operations to secure the pallet, such as safety straps or filler material. The uniform gravitational acceleration is 9.81 m/s^2, and the coefficient of friction is fixed at 0.2 for both static and dynamic friction. The coefficient of restitution is fixed at 0.01. The cargo's density is fixed, indicating that its weight is equally distributed within the item (Martinez-Franco and Alvarez-Martinez 2018). If provided, corresponding meta information can be easily integrated into the simulation, further enhancing its fidelity to real-world applications.

4.3 Simulation Approaches

We proposed and tested two types of simulations. In the first approach, a pallet is evaluated in a fully built-up state. In the second approach, the simulation is iteratively performed for the items placed on the pallet, triggering a short simulation for each newly added item. To ensure that only statically stable pallets are within the assessment function's output, we introduced a static stability check (*SimCheck*) that evaluates the partially loaded pallets. This verification is modelled as a hook after the heuristic is terminated and, therefore, has no influence on the solution quality; it merely eliminates unstable solutions. The *SimCheck* is iteratively performed for the items placed on the pallet, triggering a simulation of 10 s at 60 Hz for each newly added item. The *SimCheck* returns a score based on the amount of spatially displaced items as a proportion of all loaded items.

As mentioned previously, the first approach (*Sim1*) evaluates the pallet in its fully built-up state. Thus, as a first step, each item of the complete layout is placed on the pallet. Afterwards, the simulation performs time steps to simulate a short amount of real time. With this approach, the static loading stability for each intermediate state of the pallet is not asserted. However, this approach triggers only one simulation per pallet and best mirrors the structure of the GA, which mainly handles complete solutions. The pseudocode for the simulation approach (*Sim1*) is given in Figure 4.

```
function sim1(layout){
   foreach item: layout
      physicsWorld ← placeItem
   physicsWorld ← stepSimulation
      foreach item: placedItems
         delta ← euclid_distance (position, origin)
         if(delta > item_movement_epsilon) //item displaced
            displacedItems += 1
   return ((totalItems - displacedItems) / totalItems)
};
```

Figure 4: Pseudocode of the approach with only one simulation per built-up pallet (*Sim1*).

The second approach (*Sim2*) is derived from the *SimCheck* module, but simulates a shorter amount of real time and uses a lower simulation resolution. This approach best reflects real-world loading conditions and guarantees static stability for each partially loaded solution. The drawback of this approach is the higher quantity of simulations; for p items loaded on the pallet, p simulations must be performed. We added an early return from the algorithm for the case in which the next placed item causes a spatial displacement of an already placed item. This feature limits the runtime by directly inhibiting unstable solutions, which do not require further investigation. The second simulation approach (*Sim2*) is described in pseudocode in Figure 5.

```
function sim2(layout){
   foreach item: layout
      physicsWorld ← addItem
         foreach item: placedItems
            delta ← euclid_distance (position, origin)
            if(delta > item_movement_epsilon) //item displaced
               return placedItems / totalItems
      physicsWorld ← stepSimulation
   return 1
};
```

Figure 5: Pseudocode of the approach with simulation after each item placement (*Sim2*).

For the stability assessment score calculated by both approaches, we adapt the number of fallen boxes (NFB) metric, introduced by Ramos et al. (2015). The NFB states that a box is fallen if its value on the z-axis after the simulation differs from its previous value. The NFB is applicable to more complex shape types, beyond boxes. The spatial displacement can be accurately and reliably measured, regardless of the shape of a cargo item. We extend the NFB criterion to the displacement along the x-, y-, and z-axes and utilize the Euclidean distance dimension.

For each item, we calculate the difference Δ between an item's original position and its position in the simulation steps as the Euclidian space distance. To overcome small simulation errors and jittering, we introduce a small threshold value ε, which must be exceeded by a cargo item's position in order for the item to be marked as displaced (Bracht et al. 2016). The sum of the displaced items feeds into an overall fitness value for the static stability of a layout, which must be normalized between zero (unstable) and one (stable).

In both simulation approaches, for each layout, we simulate 4 s of real time, as it is reasonable for a spatial displacement (bending, falling) to occur within this time frame. To achieve a high simulation speed, we reduced the resolution of the integrator step by increasing the fixed timestep value of the step function, which simulates the amount of time (4 s) since the last step, as advised by Bracht et al. (2016). Thereby, the equation $timestep < maxSubSteps * fixedTimeStep$ must be fulfilled to ensure that the simulation works correctly. A lower accuracy indicates that the internal clock ticks are lengthened and the number of internal simulations decreases. In our case, 80 internal simulation loops were performed with a fixed internal time step length of 0.05. For real-time physics simulations applied in games or modeling tools, physics engines usually run at 60 Hz.

5 SIMULATION RESULTS

5.1 Test Instances

To achieve our research goal, the static stability of heterogenous, irregular cargo was evaluated with a focus on the practical relevance of the generated solutions. To the best of our knowledge, within the context of air cargo, there is no test set for the PLP that accurately reflects the real-world complexity at an air cargo hub. The closest approximation thus far was reported by Brandt and Nickel (2019), who created a set of instances based on booking data from a large German air cargo company. As the booking data mirror the real volume bought by clients, these data provide a good approximation of the outer dimensions, weight, orientation restrictions (i.e., how an item can be rotated), loading capacity on top, priority, affiliation of an item to an item group (within an AWB), and incompatibilities between special item characteristics (e.g., dangerous goods, perishable goods, living animals). Nevertheless, important aspects are missing in the data, e.g., physical meta-information such as the weight distribution, center of mass, packing materials, or information about underlying wooden pallets. Because the volume is always indicated in the outer bounding box of a cargo item, no information about the specific shape or silhouette is provided.

In the literature, other data sets and testbeds have been reported, e.g., Bischoff and Ratcliff (1995), but are designed to challenge the ability of a container loading algorithm to solve a problem and generate high load factors. These test sets are artificially generated, are not based on realistic data, and incorporate an insufficient amount of meta-information, which is key for a solution algorithm to generate practical, relevant solutions. Therefore, we based our test data set on the instances derived by Brandt and Nickel (2019). Because the item shapes are not specified, we replaced a randomly selected, fixed share of items with irregular shapes of approximately the same size, such that the volume does not exceed that of the bounding box.

We considered three different types of scenarios. In the first scenario (A), all items are of rectangular shape. In the second scenario (B), the estimated number of 5 % irregular shapes is incorporated, which may reflect the standard process, in which the great majority of items are rectangularly shaped with a small fraction of irregularly shaped items. In contrast, the third scenario (C) mirrors a more complex, stressful loading case, in which 20 % of the items are of non-rectangular shape.

The input items given by Brandt and Nickel (2019) belong to a flight segment, which might consist of multiple flight legs; therefore, the items do not fit on a single pallet. Because we focus on single-pallet loading and output maximization, the amount of input items and pallets must be limited, such that the algorithm has a sufficient number of items to achieve a high load factor, but without too many choices.

Finally, our evaluation data set contains one randomly selected test instance from Brandt and Nickel (2019) with one randomly selected pallet and 50 randomly selected input items for each irregularity scenario.

5.2 Computational Results

Table 1 shows the computational results for each scenario. We coded the GA in Java and utilized the JBullet library (JBullet 2010), which is a Java implementation of Bullet (Bullet Physics Library 2019). The experiments were conducted on a common consumer hardware using an AMD Ryzen ThreadRipper 2950X with 3.5 GHz, 16 cores, 32 threads, and 32-MB cache capacity. We used Ubuntu 18.04 and a total of 64 GB DDR4 2133 MHz/PC4-17000 CL13.

We fixed the population size of the GA to 8,000 and ran 300 generations. Each approach–scenario combination was tested 5 times (N=5). The mean values are displayed, along with their standard deviation in brackets. The values for load factor, non-rectangular shapes, stability assessment score, and load check assessment score are averaged over the last population. The load factor mirrors the volume used on the pallet compared to the overall available volume bounded by the pallet contour. The non-rectangular shape value indicates the ratio of included non-rectangular items to all items in the solution. The stability assessment score is obtained by the respective simulation approach used (see Section 4.3). Additionally, the *SimCheck* score is displayed as an indicator of how accurately the approaches capture stability. These values are obtained for each member of the final population after GA termination. The mean runtimes for the respective simulation approaches are (in ms) 66.51 (34.83) for *Sim1* and 44.54 (30.93) for *Sim2*.

Table 1: Computational results for each scenario.

Scenario	Simulation Approach	Overall Runtime (s)	Load Factor	Non-Rectangular Shapes	Stability Assessment Score	SimCheck Score
Irregular 0 (A)	Sim1	801.2 (167.6)	0.77 (0.05)	0	1	0.86 (0.06)
	Sim2	923 (417.8)	0.75 (0.05)	0	1	0.89 (0.07)
Irregular 0.05 (B)	Sim1	1554.6 (232.2)	0.61 (0.01)	0.04 (0.013)	0	0.79 (0.12)
	Sim2	1083.6 (131.8)	0.60 (0.02)	0.03 (0.004)	1	0.81 (0.12)
Irregular 0.2 (C)	Sim1	3193.6 (430.8)	0.73 (0.01)	0.15 (0.013)	0	0.63 (0.10)
	Sim2	2097.8 (178.6)	0.68 (0.02)	0.13 (0.036)	1	0.78 (0.13)

The computational experiments reveal a number of insights. First, the overall runtime of the solution heuristic differs for each scenario. This finding is not surprising, as irregular items are harder to treat in placement heuristics and physical simulations, with more vertices and faces in comparison to the geometrically simple shape of a box. However, the overall runtime meets the time requirements of the air cargo context.

Second, the physics simulations do not prevent the heuristic from achieving an acceptable load factor value. The load factors are surprisingly constant, with little deviation. In the air cargo context, the complex problem requires multiple optimization targets besides the load factor. Nevertheless, a higher load factor is always a better output, as long as all relevant constraints are met.

Third, the algorithm and the stability simulation can both cope with the complexity of irregular shapes, as can be seen in the inclusion ratio for non-rectangular shapes. As the number of non-rectangular input items increases, the ratio of irregular items included in the solution increases as well.

Fourth, for scenarios with irregular shapes, the GA cannot find solutions that fit the *Sim1* approach, resulting in a low assessment value for the static stability of the last generation. In contrast, the *Sim2* approach achieves a high assessment score for all scenarios. To illustrate this finding, Figures 6 and 7 present sample solution layouts obtained by the *Sim2* approach. This result may be due to the more sensitive measurement of the stability of partially built-up pallets. Interestingly, on average, the *Sim2* approach is faster. This higher speed may be due to a large share of layout iterations that produce a spatial disposition and, therefore, cause an early return from the assessment value. Thus, we conclude that the *Sim2* approach better achieves the goal of static stability, as it is not only faster but considers all partially built-up states of the pallet and, therefore, creates a more sensitive feedback for the solving heuristic.

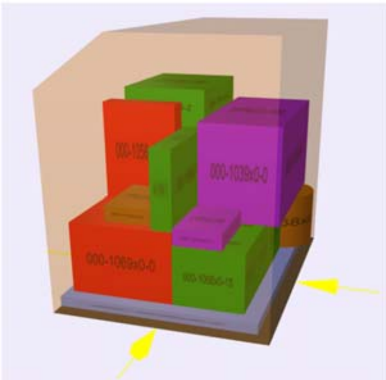

Figure 6: Partially built-up pallet achieved by the *Sim2* approach.

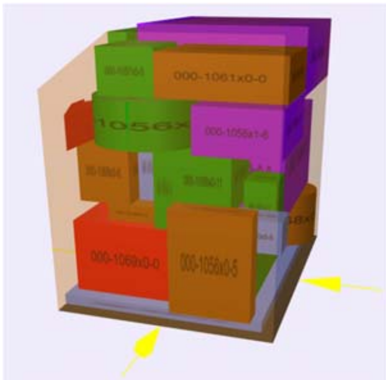

Figure 7: Built-up pallet achieved by the *Sim2* approach.

5.3 Limitations

Despite its satisfying results, our research has limitations. We modelled only four different shapes; however, in practice, many more shapes exist, including complex, non-primitive bodies, such as turbines or cars. We did not include wooden pallets, which were observed for a large share of pre-palletized items, altering their overall shape. Because we performed only a small sample of computational experiments, our inferential conclusions are limited. Moreover, the reduction in simulation resolution reduces the overall runtime, but also reduces the engine's precision, which could result in missed collisions between rigid bodies.

6 CONCLUSION AND OUTLOOK

Our research demonstrates how the confluence between physics simulations and heuristics can be organized to solve the PLP while coping with the complexity of strongly heterogenous cargo items with irregular shapes. In the future, we would like to evaluate the runtime and precision of our physical simulation, determining practical implications for usage in real-world applications. We emphasize the need for a realistic test data set drawn from the air cargo context, as such data would reflect a special type of PLP with additional, real-world complexity in terms of desired runtime and item heterogeneity. Data regarding the shape and frequency of cargo are desirable as well as other meta-information, e.g., the packing material or center of mass. The increasing capabilities of general-purpose GPU (GPGPU) provide an interesting opportunity to further parallelize and accelerate physical simulations. In addition to GPGPU, physical predictions using machine learning techniques are an emerging topic in the field of computer science and may also be applicable to stability simulations.

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