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Designing and Testing Modular Karakuri Dynamic and Static Rack for Autonomous Material Handling Efficiency

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Abstract

This study addresses the gap in modularizing Karakuri dynamic trolley racks and static two-level racks for autonomous material handling by developing an optimized design framework to enhance mechanical reliability and material flow efficiency. Two designs were proposed, Design-A and Design-B, with selection based on budget savings and design simplification for integration with Automated Guided Vehicles (AGVs). Mechanization analysis focused on critical mechanical components, while performance tests assessed box transfer times and speeds under loads of 5, 10, and 15 kg on dynamic trolleys and 0 kg on static racks. Design-B was selected for its 50% reduction in material usage, elimination of compressed air dependency, and a mechanical stopper system enabling simultaneous box movements, unlike Design-A's sequential pneumatic process. Performance tests across Tracks B, C, D, and E revealed wooden boxes achieving higher final speeds (0.7-0.8 m/s) than plastic boxes (0.53-0.6 m/s) on Track B due to smoother surfaces, with speeds ranging from 0.25 m/s to 1.74 m/s across tracks, influenced by initial speed and queue position. Design-B's swing mechanics and triggers ensured reliable, adaptable box movement with minimal oversupply risks. These findings validate Design-B as a cost-effective, scalable solution for autonomous material handling in lean manufacturing environments.

Keywords: Karakuri, dynamic trolley racks, static two-level racks, modular design, Automated Guided Vehicle (AGV).

Introduction

Material handling is any activity that requires force applied by a person in the process of lifting, pushing, pulling, carrying, lowering, or holding a material. Karakuri is a material handling concept applied in Japanese industry. Karakuri is a low-cost industrial automation mechanism that helps increase productivity and reduce company costs [1]. Karakuri means a skilled mechanism. It is a method that utilizes only mechanical energy derived from gravity, without the need for electricity, hydraulics, or pneumatics, and is also efficient and easy to maintain [2]. It utilizes inclined planes and the force of gravity, which humans often utilize in carrying out their activities. It can be a solution to increase industrial process productivity while still considering ergonomic factors, and it also requires low costs and simple techniques [3, 4]. One example is the karakuri kaizen system, which is used to simplify the process of moving goods [5, 6]. Karakuri enables operators to work more efficiently without requiring them to move. Karakuri kaizen can forward objects or workloads to other workstations, thus providing an efficient, simple, and low-cost technical solution [7]. The use of karakuri saves 50 to 80% compared to comprehensively automating the production process, while maintaining the same level of efficiency [8].

In various sectors, such as the tofu processing industry [9], pineapple processing industry [10], water jacket core mold manufacturing process [11], mineral water gallons [3], automobile oil seal manufacturing industry [12], or wire rope industry [4], the use of karakuri design has been widely practiced. Numerous additional sectors have adopted karakuri kaizen as an Industry 4.0 solution [13] and lean manufacturing techniques for corporate sustainability [14].

A specific type of karakuri that utilizes pulling mechanisms or is propelled by gravity rollers for smooth motion is the dynamic trolley rack. In contrast, static two-level racks are commonly used for material organization in warehouses or assembly lines because they provide dependable, high-density storage alternatives. Recent studies have shown that dynamic supports flexible material transport and offers a customizable rack for various load requirements. However, while these systems are widely applied, their design optimization and performance under specific industrial conditions remain underexplored. The use of karakuri with an Automated Guided Vehicle (AGV) can help the process of moving goods autonomously [15]. In general, the application of karakuri with AGV has been widely used by Japanese automotive companies. Despite these advantages, there are not many articles discussing karakuri design with AGV applications.

The existing literature on Karakuri dynamic trolley racks and static two-level racks predominantly emphasizes their applicability in lean manufacturing and fundamental design principles. There is limited exploration of how these systems can be modularized and applied AGV for moving goods autonomously. In previous research, it discussed the impact analysis on the design of Karakuri Kaizen using the FEA method [16]. The objective of this research is to develop an optimized design framework for Karakuri dynamic trolley racks and static two-level racks, focusing on enhancing mechanical reliability and material flow efficiency.

Method

3D working drawing design was created using Solidworks software [17]. In the karakuri kaizen design stage, two designs were considered for selection, namely Design-A and Design-B. The design selection was based on budget savings and design simplification. The karakuri design is also intended to be used fully autonomously, and can be attached to an Automated Guided Vehicle (AGV). So that, a mechanization analysis was carried out on critical mechanical parts. Performance tests were also carried out to determine the travel time in 1 cycle and the speed of the box launch.

The performance test was carried out with a load of 5, 10, and 15 kg on the box when the box was slid from the dynamic trolley to the static rack. The load was 0 kg when the box was inserted into the static rack to wait in line to be picked up by the dynamic trolley. The design details and manufacturing process were not shown; only the 3D assembly model and the shape of the karakuri kaizen dynamic trolley rack and the finished two-level static rack, the design and mechanism of the stopper, and the testing of the goods transfer time were the focus of this study.

Fig. 1. Example of I-Lite Component Parts

Fig. 2. Example of I-Logic Component Parts

Some of components used to design karakuri are I-Lite and I-Logic. The shape of the I-Lite component can be seen in Figure 1, and the I-Logic can be seen in Figure 2. The types of components required to design a karakuri are shown in Table 1. These components were reverse engineered to design the entire karakuri system.

Table 1. Components are used for Karakuri Design

Components Name	
I-LOGIC pipe	I-LITE pipe
I-LOGIC HJ-2 H-2/H-3	BOX
I-LOGIC HJ-1	I-LITE LJ-1
I-LOGIC HJ-13	I-LITE LJ-14
ROLLER_4014WH	ROLLER_4014WH
GUIDER_PA-403C	LOCKER_PLATE_1
STATIC_WHEEL_CT-714FL	BALLAST
DYNAMIC_WHEEL_CT-714SL	FOOTER_INSERT_NUT_1210S
CASTER_STRAP_MT-5109	ADJUSTER_SMALL_MT-3012S
PLACON MOUNT-E PM-4010E	I-LITE_END_CAP
PLACON MOUNT-B PM-4010B	PLASTIC_END_CAP PJ-110

Design and Manufacture

There are two proposed designs. The first is Design-A with rack static dimension 600 mm x 1760 mm x 902 mm and rack dynamic dimension 783 mm x 916.14 mm x 1056 mm. Using two pneumatic cylinders and material pine wood, AISI 302 HT Grade B, and aluminum. While second is Design-B with rack static dimension 600 mm x 1630 mm x 1098 mm and rack dynamic dimension 782 mm x 932 mm x 1204.4 mm. Using fully mechanical stopper and material pine wood, AISI 302 HT Grade B, and aluminum.

The most significant difference is found in the static racks, where Design-A uses pneumatics to move boxes from the top to the bottom. The movement of goods in Design-A uses pneumatics, so the process cannot be simultaneous, making the movement process longer. Design-B, on the other hand, does so mechanically. Also, Design-B has the advantage of not requiring a compressed air source, making it easy to change the layout without having to think about the compressed air source (easy to move).

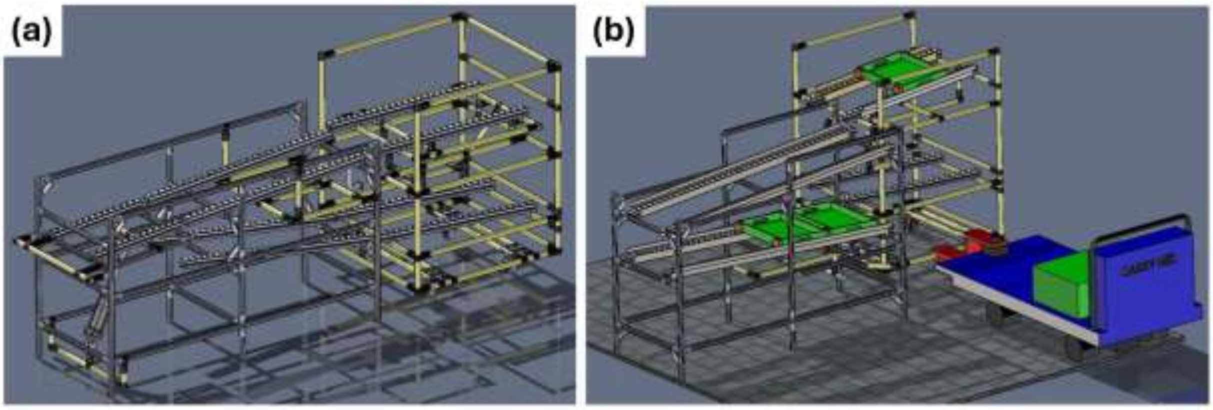

Fig. 3. Three Dimensional Modelling Karakuri (a) Design-A and (b) Design-B

Design A requires more material usage. Design B, on the other hand, optimizes the amount of material usage to reduce costs. The material requirements cost in Design-B is reduced by up to 50% compared to the requirements cost in Design-A. After design considerations, with a focus on material usage and cost efficiency, Desing-B was selected. A summary of the Design-A and Design-B specifications can be seen in Table 2 below.

Table 2. Material spesification and chemical composisiton *Nozzle* (AISI 1045)

Criteria	Desing-A	Design-B
Rack Static Dimension	600 mm x 1760 mm x 902 mm	600 mm x 1630 mm x 1098 mm
Rack Dynamic Dimension (Trolley)	783 mm x 916.14 mm x 1056 mm	782 mm x 932 mm x 1204.4 mm
Main Moving Parts	2 Cylinder Pneumatic	Fully Mechanical Stopper
Material	Pine Wood (Pinus Strobus), Stainless Steel AISI 302 HT Grade B, Aluminum	Pine Wood (Pinus Strobus), Stainless Steel AISI 302 HT Grade B, Aluminum

Figure 4(a) shows the main components of a static rack, including rollers, footers, joints, and mechanical stopper supports. Figure 4(b) shows the main components of a dynamic rack, which includes rollers, joints, mechanical stoppers, and fixed wheels.

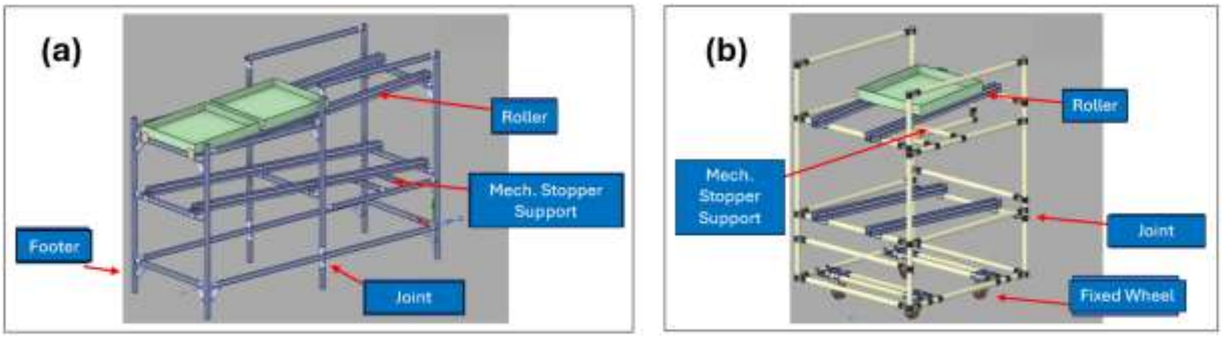

Fig. 4. (a) Static rack design and (b) Dynamic rack design

Figure 5 provides an illustration of how the process of moving goods using AGV. Where AGV carries dynamic rack to carry goods. Empty boxes are manually inserted by the officer at the bottom of the static rack. The position of the goods moving from the dynamic rack to the static rack which is on the right side of the direction of travel indicated by the red arrow. The process of moving boxes with parts and empty boxes occurs simultaneously. After that, the AGV can walk to the supply rack which is to the left of the dynamic rack. The process of moving the supply rack is similar to moving empty boxes, except that it's at a higher position. Please note, this article does not discuss supply rack design. Then the AGV travels back to the other static rack posts, where there are multiple static racks and many assembly lines in one building.

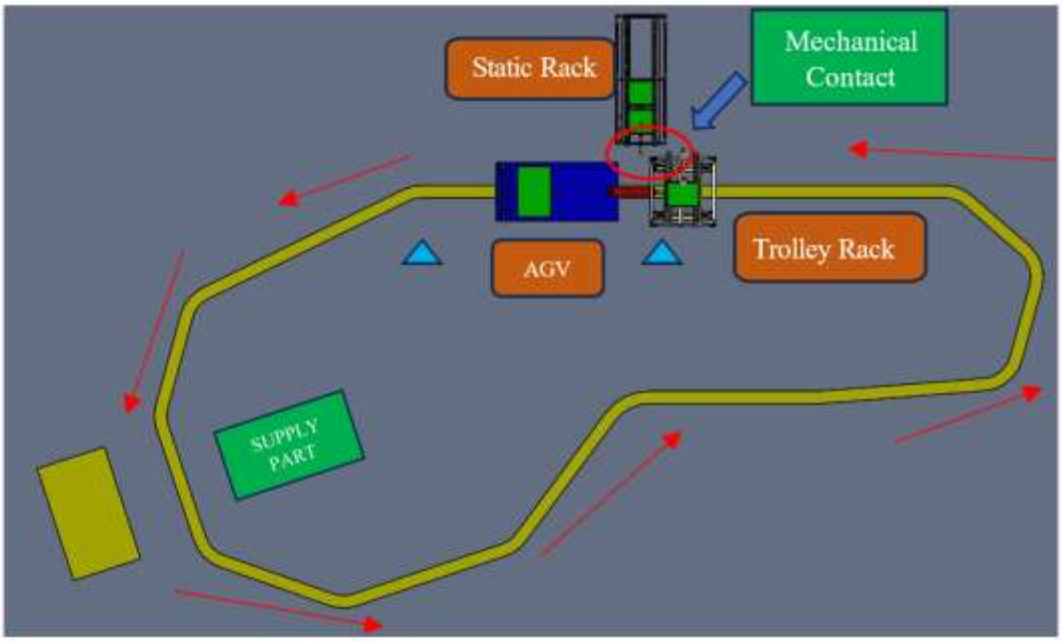

Fig. 5. Illustration of Karakuri Movement when using AGV

The process of moving goods (boxes containing parts) from dynamic rack to static rack and empty boxes from static rack to dynamic rack can be seen in Figure 6. In Figure 6(a) show the trigger process occurs when mechanical contact occurs between the swing mechanics and the pipe, so that the mechanical stopper rotates, allowing the box to move (see Figure 7). Mechanical stopper is a swing part, while trigger is a static part. On the dynamic rack there is a mechanical stopper at the top and a trigger at the bottom. Meanwhile, on a static rack, the trigger is in the top position and the mechanical stopper is in the bottom position. The swing movement process can be seen in Figure 7(a,b).

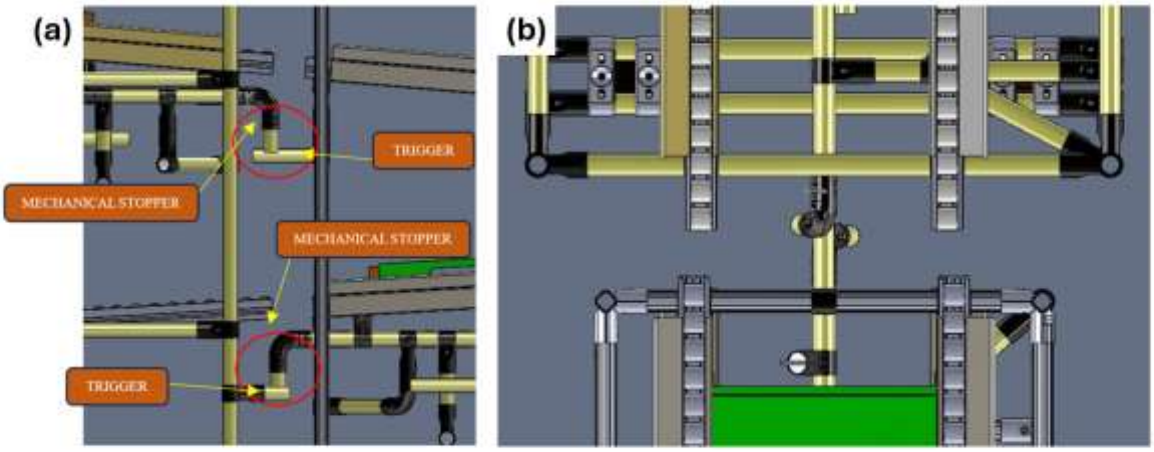

Fig. 6. (a) Location of the contact process on the mechanical stopper, (b) upper view of the mechanical stopper

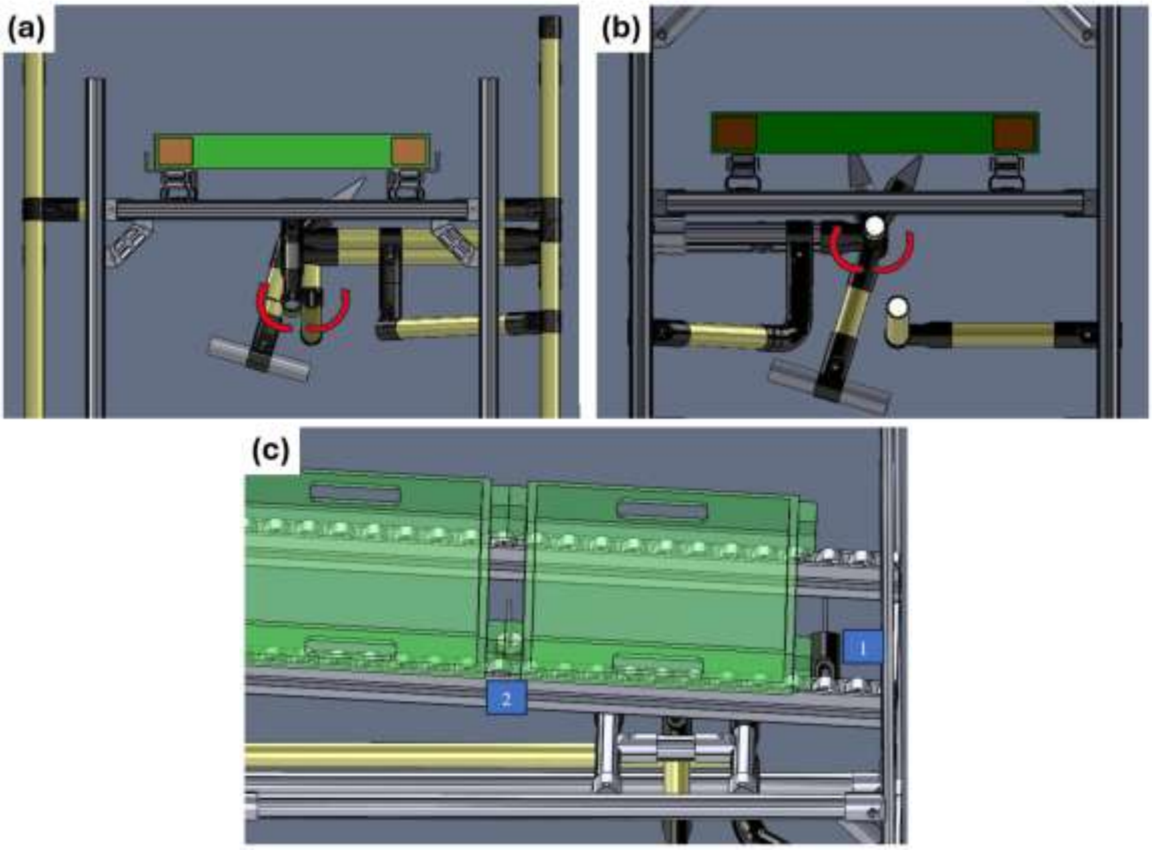

Fig. 7. (a) Mechanical stopper mechanism on dynamic rack, (b) mechanical stopper mechanism on static rack, (c) gap between static rack boxes.

Figure 7(c) shows the gap for the mechanical stopper to stop the second empty box. This allows empty boxes to be moved one at a time. This mechanism can be improved to accommodate more than one box depending on the situation. It also prevents an oversupply of empty boxes on dynamic racks. The manufacturing process is not discussed, because the fabrication process is relatively simple.

Machine Testing Performance

Time measurement testing on Track A was not performed because it occurred from the supply rack to the dynamic rack. Track B is the process of moving from the dynamic rack to the end of the static rack with an initial speed of 0 m/s. Data collection on Track B was conducted four times at loads of 5, 10, and 15 kilograms. The boxes used varied between plastic and wood. Meanwhile, on Tracks C, D, and E, only a plastic box with a load of 0 kilograms was used and data was collected 4 times. Track details can be seen in Figure 8.

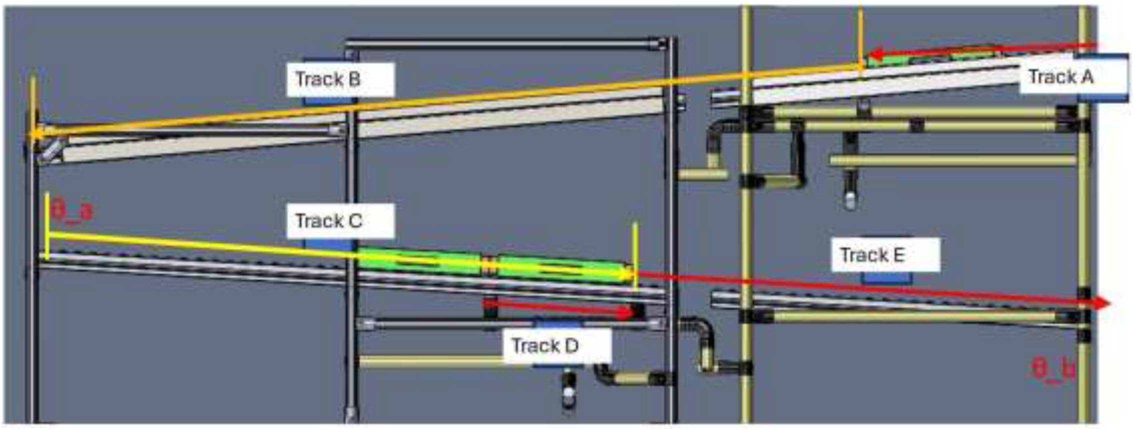

Fig. 8. Track *box* (A), (B), (C), (D), and (E) [16]

With a fixed distance, and time measured manually, the speed of the box on Track B can be calculated. At a load of 5 kilograms, the average final speed of the box before hitting the end of the barrier (retainer) is 0.72 m/s, while at 10 and 15 kg it is 0.77 and 0.73 m/s. This speed difference occurs because the time measurements were performed manually. Human error plays a significant role. However, the speed range is 0.7-0.8 m/s, indicating that the final speed of the wooden box is unaffected by the load. Complete data on test results can be seen in Table 3.

Table 3. Track B – Wooden Box

WOODEN BOX			
Load (kg)	**Distance (m)**	**Time (s)**	**Speed (m/s)**
5	1.97	2.82	0.69858156
5	1.97	2.83	0.696113074
5	1.97	2.63	0.74904943
5	1.97	2.69	0.732342007
		Average	0.719021518
Load (kg)	**Distance (m)**	**Time (s)**	**Speed (m/s)**
10	1.97	2.43	0.810699588

10	1.97	2.43	0.810699588
10	1.97	3.02	0.652317881
10	1.97	2.44	0.807377049
		Average	0.770273527
Load (kg)	**Distance (m)**	**Time (s)**	**Speed (m/s)**
15	1.97	2.56	0.76953125
15	1.97	3.09	0.637540453
15	1.97	2.43	0.810699588
15	1.97	2.75	0.716363636
		Average	0.733533732

The speeds of the plastic box for loads of 5, 10, and 15 kg, respectively, are 0.53, 0.58, and 0.6 m/s. There is a slight difference in speed between the plastic boxes, though not significant. This could be due to the heavier weight creating more stable pressure, allowing the rollers to rotate more effectively. Complete data on test results can be seen in Table 4. When comparing wooden and plastic boxes, the wooden box had a higher final speed of 0.1-0.2 m/s. The slippery surface of the wood in this research situation could be a significant factor influencing the final speed results. The flatter and more even surface of the wood was also a determining factor. Meanwhile, the plastic box had thin protrusions on the bottom, resulting in less surface contact with the roller.

Table 4. Track B – Plastic Box

BOX PLASTIK			
Load (kg)	**Distance (m)**	**Time (s)**	**Speed (m/s)**
5	1.97	3.63	0.542699725
5	1.97	3.74	0.526737968
5	1.97	3.95	0.498734177
5	1.97	3.63	0.542699725
			0.527717899
Load (kg)	**Distance (m)**	**Time (s)**	**Speed (m/s)**

10	1.97	2.93	0.672354949
10	1.97	3.55	0.554929577
10	1.97	3.76	0.52393617
10	1.97	3.37	0.584569733
			0.583947607
Load (kg)	**Distance (m)**	**Time (s)**	**Speed (m/s)**
15	1.97	3.44	0.572674419
15	1.97	3.16	0.623417722
15	1.97	3.28	0.600609756
15	1.97	3.22	0.611801242
			0.602125785

Box on Track C is assumed to have no boxes parked waiting. The results on Track C varied significantly because some used initial speed and some did not. When using the initial speed, the time required was less than 1 second. Without the initial speed, it took 1.7 seconds, and with the slow initial speed, it took 1.2 seconds. The initial speed is determined by humans and cannot be measured. So the final speed of the plastic box varies from 0.88-1.74 m/s. Complete data on test results can be seen in Table 5.

Tabel 5. Track C – Plastic Box

Long Track (C = 1.5 m) Box KAYU			
Load (kg)	**Distance (m)**	**Time (s)**	**Speed (m/s)**
0	1.5	1.7	0.882352941
0	1.5	1.25	1.2
0	1.5	0.86	1.744186047
0	1.5	0.93	1.612903226
			1.359860553

The box on Track D is the box that is queued or the box position is right after the first box (second box). So the path on Track D is short. There is no initial speed in this case. The average final speed is 0.25 m/s when hitting the mechanical stopper. Complete data can be seen in Table 6.

Table 6. Track D – Plastic Box

Short Track (D = 0.33 m) Box KAYU			
Load (kg)	**Distance (m)**	**Time (s)**	**Speed (m/s)**
0	0.33	1.32	0.25
0	0.33	1.39	0.237410072
0	0.33	1.19	0.277310924
0	0.33	1.32	0.25
			0.253680249

Track E is the movement of empty boxes from the static rack to the dynamic rack. There is no initial speed on this track. The average final speed is 0.45 m/s before hitting the end of the barrier (retainer) at dynamic rack. Complete data can be seen in Table 7.

Table 7. Track E – Plastic Box

Long Track (E = 1.06 m) Box KAYU			
Load (kg)	**Distance (m)**	**Time (s)**	**Speed (m/s)**
0	1.06	2.24	0.473214286
0	1.06	2.25	0.471111111
0	1.06	2.57	0.412451362
0	1.06	2.36	0.449152542
			0.451482325

Conclusion

Design-B was selected over Design-A due to its cost efficiency and operational advantages, primarily its reduced material usage by up to 50% and the elimination of the need for a compressed air source, allowing for easier layout reconfiguration. The mechanical stopper system in Design-B enables simultaneous movement of boxes, unlike the sequential pneumatic process in Design-A, resulting in faster and more flexible operations. Performance testing on Tracks B, C, D, and E demonstrated consistent functionality, with wooden boxes achieving higher final speeds (0.7-0.8 m/s) compared to plastic boxes (0.53-0.6 m/s) on Track B, likely due to the smoother surface of wood. Tracks C, D, and E showed varying speeds influenced by factors such as initial speed and queue position, with final speeds ranging from 0.25 m/s to 1.74 m/s, highlighting the system's adaptability to different conditions despite manual measurement errors. The mechanical design of Design-B, coupled with its effective use of swing mechanics and triggers, ensures reliable box movement with minimal oversupply risks, as demonstrated by the controlled transfer of empty boxes. These results validate Design-B's suitability for efficient, cost-effective, and adaptable material handling in dynamic and static rack systems, making it a practical choice for scalable assembly line operations.

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