Development of a Multi-Layer Bi-Directional Gravity Conveyor Based Storage System for Continuous Storage and Retrieval of Bins in Buffer Zones

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Abstract. Optimizing space utilization in manufacturing plants is crucial for enhancing production throughput, particularly in buffer storage zones where products must be temporarily stored between processes operating at different rates. Conventional single layer storage methods are often unable to accommodate fluctuating production outputs leading to bin overflow and inefficient use of available space. This paper presents the development of a multi-layer bi-directional gravity conveyor–based storage system designed to maximize buffer zone capacity within a compact footprint. The proposed system integrates three levels of gravity flow beds with a compact vertical conveyor for continuous movement of bins between levels, eliminating the need for forklifts for loads up to 100 kg. The system was designed to occupy a floor space of 7 m × 3 m × 6.5 m and achieve a maximum storage capacity of 6 tons. Finite element analysis (FEM) was used to verify structural reliability, confirming stresses and deflections within safe operating limits. Compared to conventional single-level storage, the proposed system achieves up to three times higher storage density. The design ensures a scalable and energy efficient storage system with high throughput.

Keywords: Bi-directional gravity conveyor, Buffer-zone optimization, Continuous storage/retrieval.

1 Introduction

In the dynamic manufacturing industry efficient material handling and storage solutions are essential for optimizing production operations. Batch production lines generate large volumes of work-in-process inventory creating the need for temporary buffer zones that can absorb rate fluctuations [1]. Traditional buffer zone storage floor stacking and single level static racks fail to leverage available vertical space and often rely on forklifts increasing labor costs and safety risks [2].

Industrial storage solutions have evolved from simple pallet racking to automated systems. Pallet racking introduced the ability to stack items vertically but still depends on powered lift trucks for access and leaves underutilized [2]. Automated Storage and Retrieval Systems (AS/RS) and shuttle-based solutions further increase density and throughput by integrating conveyors, robotics and control systems yet they need high capital and maintenance costs and often require extensive bay modifications [3].

A multi-deep rack unit-load AS/RS introduce that uses DMM conveyors to rotate and present loads to a single S/R machine [4]. This design minimizes rack footprint and reduces travel time for the S/R unit, however throughput is constrained by the acceleration/deceleration cycles of powered conveyors and energy consumption remains high.

A bi-directional flow rack system introduced where adjacent columns slope in opposite directions allowing direct storage and retrieval on the same rack face [5]. While BFR improves selectivity over single-face flow racks it necessitates handling machines at both ends consuming additional aisle space and introducing traffic conflicts in confined production areas.

Xiaofei Kou et al. [6]. propose a parallel storage system combining vertical screw conveyors, rail-guided vehicles (RGVs) and belt conveyors for simultaneous storage and retrieval. Their configuration minimizes unit-load travel times and maximizes storage capacity yet the reliance on powered conveyors and RGV infrastructure leads to significant energy use and floor-space occupation.

Broers & Balk [7] develop helical conveyor buffers that use spiraled paths to both store and transport products within a compact vertical envelope. Although these conveyors effectively utilize height, they require a high initial investment, complex control systems, and higher energy consumption compared to passive gravity alternatives. A shuttle-based AS/RS where autonomous robots and multilevel conveyors dynamically allocate storage slots [8]. While delivering high throughput and flexibility this approach demands substantial capital for robots, power infrastructure and centralized controls making it less viable for smaller batch-production plants. A multilevel vertical conveyor system employing continuously looping support platforms guided by rails was introduced later [9]. These platforms interface with transfer devices to move units between levels, achieving dense vertical buffering but requiring motors on each tier and complex synchronization to maintain smooth operation.

Despite these advances a gap remains for a storage solution that achieves high density and throughput without relying heavily on powered conveyors, robotics or extensive infrastructure. This study addresses this gap by proposing a Multi-Layer Bi-Directional Gravity Conveyor Storage System that uses the vertical space within buffer zones through the integration of three stacked gravity conveyor levels with a compact vertical conveyor. The gravity conveyors are centrally hinged and hydraulically actuated to achieve a controlled 4° tilt enabling bins up to 100 kg to move by gravity for both storage and retrieval. The design leverages passive motion, controlled sequencing and compact vertical transfer to maximize density while minimizing energy use and eliminating forklift dependence.

This research aims to develop a flexible and adaptable storage solution that maximizes vertical space utilization in buffer zones, reducing the overall floor footprint required for storage and provides an energy-efficient alternative to conventional powered AS/RS systems.

2 Methodology

2.1 Bi-directional gravity conveyor rack Design

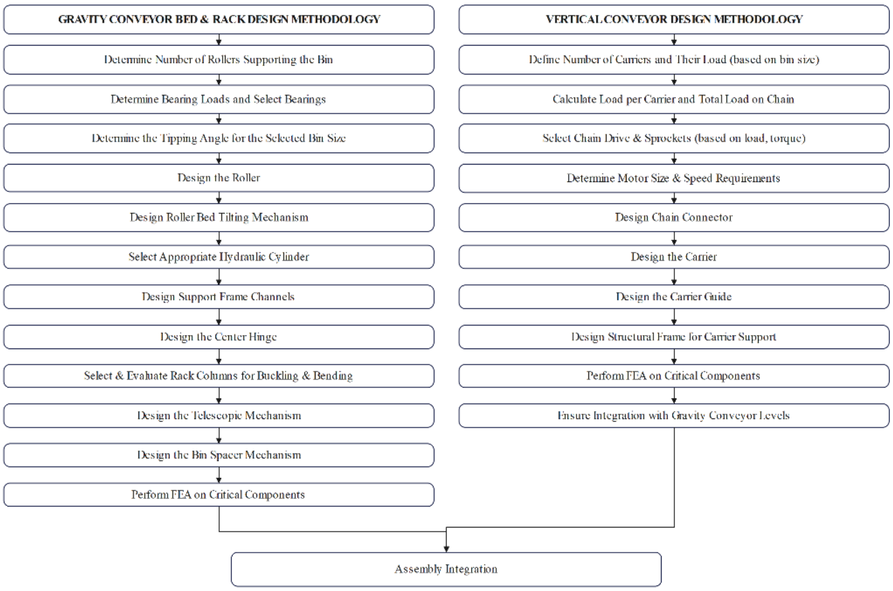

Fig.1. Design methodology

The design methodology was structured into two primary subsystems (Fig. 1): the bi-directional gravity conveyor rack and the vertical conveyor system. The process for each followed a systematic approach from requirement analysis and conceptual design to detailed component selection and validation

Design parameters. The bi-directional gravity conveyor rack was designed with a bed length of 5 m, hinged at the center to allow tilting. It accommodates storable bins with a maximum size of 600 × 400 × 320 mm and mass up to 100 kg, and a minimum size of 600 × 400 × 200 mm with mass up to 65 kg. To ensure stability, each bin maintains contact with at least three rollers, supported by a roller base width of no less than 600 mm. The frame channels are rated for a dynamic load capacity of 1 000 kg, while the total dead weight of each bed is restricted to ≤ 500 kg. Side guides are integrated to prevent lateral material displacement during operation, and bed rotation occurs about the central hinge to enable controlled bi-directional flow.

Gravity roller layout design. Different configurations of roller bed layouts were evaluated with the number of rollers supporting the bin ranging from 3 to 20. A double row configuration with a 100 mm pitch layout was selected. At any given time 8 rollers will be in contact with the surface of the bin. The working load on each roller is 125 N.

The inclination angle of the gravity conveyor.

$$F_{net} = F_g - F_r - F_{br} - F_K$$

Where F_g is the Gravitational force component, F_r is the rolling resistance of the roller, F_{br} *is the bearing* friction, and F_k is the kinetic resistive force on the roller. Setting acceleration(a)=0 in the derived equation below solves for the minimum angle to initiate motion.

Acceleration of the bins.

$$a = g \times \left(\sin x - \frac{\cos x \times c}{r_{roller}} - \frac{\cos x \times \mu \times r}{r_{roller}} - \frac{m_r \times n \times \mu \times r}{m \times r_{roller}} - \frac{n \times I \times \left(\frac{V}{r_{rolller}}\right)^2}{m \times l \times g} \right)$$

The tilt angle required for motion initiation was calculated for a high-density polyethylene (HDPE) roller with a 70 mm diameter, 100 mm length, and a 6200 LLB (Light Load Ball) bearing, the roller mass is m_r=0.311 kg, with n=10 rollers. The bearing friction coefficient is μ=0.0015. Based on computer-aided design (CAD) data, the moment of inertia is I=0.94kg\mm^2. In the absence of specific rolling resistance data for HDPE, a resistance coefficient of 0.70 mm is assumed.

To control terminal velocity to a maximum of 1.5 m/s, magnetic break rollers are placed on either side in the middle of the gravity conveyor. According to the paper [10],

$$F_{net} = F_g - F_r - F_{br} - F_K - F_T$$

Where F_T is the resisting force in the brake roller, β is the Coefficient of magnetic viscosity, D_{BT} is the distance between the roller center to the center of the permanent magnets, ω_{rel} is the relative velocity between the copper disc to the permanent magnets, and u is the gear ratio of the multiplier.

$$F_T = \beta \times \frac{2v}{D_{MP}} (1 + u) \times \frac{D_{BT}}{2}$$

Considering the physical constraints of the mechanism, the tilt angle of 4 degrees is selected. The resulting acceleration in the normal gravity roller region is $a = 0.46 ms^{-2}$ and in the brake roller region is $a = (0.46 - 0.6 \times v) ms^{-2}$.

Gravity roller design. The different configurations of roller material and diameter are evaluated with the inclination angle equation using MATLAB. HDPE material was selected as the roller material since it had sufficient strength, wear resistance, toughness and cost effectiveness. 6200 LLB bearing was selected. It has a static load limit of 435 N which is higher than the required load and since four bearings are in a row it is effective against moderate impact loads. The roller shaft is designed considering the load parameters of a single roller with S275 J0 grade mild steel.

Gravity roller bed frame channel design. The structural support for the roller bed was designed for the worst-case loading scenario. Comprehensive load calculations across all bed positions identified the highest stress condition when the bed is horizontal and loaded on one side, resulting in a maximum bending moment of 2.303 kNm on a single channel. The minimum required section modulus was calculated from this value, leading to the selection of a standard CH 80 x 8 channel (ISO-657-11-1980) for the frame design.

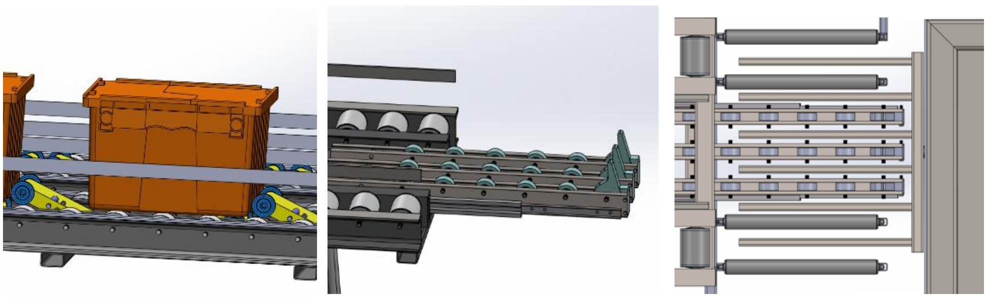

Fig. 2. Bin flow control mechanism

Hydraulic cylinder selection. The hydraulic cylinder mounting points were optimized through kinematic analysis to lift the roller bed. The base mount was fixed at 1.25 m horizontal and 0.5 m vertical from the pivot, and the rod mount at 0.75 m horizontal from the pivot, minimizing the required stroke and force. An iso standard 6020-2 hydraulic cylinder with 50 mm bore 22 mm rod diameter with MP5 mountings provides a controlled 4-degree tilt angle for the gravity conveyor beds enabling storage and retrieval from a single point

Rack structure design. Static stress, buckling and deflection calculations were performed with 3d free body diagram with nodal loads to compute the maximum stress of each profile. The minimum section modulus of each section was calculated and standard sections were selected for the design. According to the calculations, the ISO 657/14-1982 standard hot-finished 120 × 80 × 5 mm rectangular hollow section was selected as the column profile, with a 300 × 300 × 20 mm base plate.

Telescopic Bed and Stopper Mechanism Design. The telescopic bed was designed to act as a dynamic bridge between the vertical conveyor carrier and the fixed gravity roller bed (Fig.2.a). It was designed to handle a 140 kg dynamic load and extend 500 mm. The pivoting stopper roller assembly is located at the end of the telescopic rails. The rollers pivot down under bin load and return to their stopping position via a tension spring once the bin passes. This provides a purely mechanical stopping mechanism without requiring sensor intervention.

Bin Spacer and Sequential Flow Control Mechanism Design. A passive mechanical system was designed to maintain consistent spacing between bins on the gravity conveyor (Fig. 2.). The device is a symmetrical lever-based mechanism installed at intervals along the conveyor length. The roller on one side pivots down under the bin load, creating a stop for the next bin. It returns to its original position via a tension spring once the bin passes.

2.2 Vertical conveyor design

Design parameters. The vertical conveyor was designed with a maximum load capacity of 100 kg per carrier, supported by a total of four carriers operating along the system. It provides a vertical lift height of 4.5 m with sprockets limited to a maximum radius of 0.6 m. The conveyor operates at a controlled speed of 0.1 m/s, while tensioning is achieved through the bottom sprocket, which acts as a gravity-based tensioner. Each carrier has a self-weight of 20 kg, and the bottom sprocket assembly contributes an additional 100 kg to the system mass.

The total load on the driving side of the chain. The total load acting on the driving side of the chain was determined by considering the combined effect of loaded and empty carriers, as well as the chain's self-weight and the bottom sprocket, which functions as a tensioner. To account for resistance, frictional effects were assumed to be 20% of the net driving load. Combining these factors yielded the total design load (F_T) of 4139.82 N.

Chain selection. The chain bracket shearing calculations were performed and the minimum diameter needed for the chain pin was determined. The chain type was selected based on the tension requirement and the shear strength of the chain pin, since the carrier is connected to the chain through the chain bracket and the chain pin.

Total power needed. The required power was calculated based on this force and the designed speed V= 0.1 ms^{-1}.

$Power\ needed = F_T \times V = 4139.82\ N \times 0.1 ms^{-1} = 413.98\ W$

Applying application factors K_1 = 1.25, for variable load with mild shock, K_2 = 1.5, for periodic lubrication, K_3 = 1.1, for 10 hours per day;

$Design\ Power = 364.9\ W\ \times 1.25 \times 1.5 \times 1.1 = 853.84\ W$

Drive Train Selection. The vertical conveyor is driven by a 1.1 kW motor coupled to a cyclo gear drive, providing an output torque of 4770 Nm to overcome the calculated demand. This drive train rotates a 100-tooth sprocket directly mounted on the output shaft. Power is transmitted to the carrier assembly via an endless loop of 20 B roller chain.

Tensioning and Idler System. The bottom sprocket functions as an idler to maintain chain tension. It is mounted on a 60 mm diameter shaft supported by roller bearings. The entire idler sprocket assembly is mounted within a shaft block that restricts its rotation but allows vertical movement. The assembly is hung under gravity, providing an automatic and maintenance-free tensioning solution for the chain drive.

Carrier design. The carrier was designed to accommodate the bin size and the layout of the carrier is designed to pass through the telescopic bed and the roller conveyor at the bottom (Fig.2.c). Load calculations were performed considering the pivot points and load conditions. The carrier bed profile and the shaft parameters are selected based on the values.

Chain-Carrier Connection. The carrier is connected to the chain at four points. The two middle connection points feature a 2 mm longitudinal slot. Rubber bushings installed at these mounts ensure the connection returns to its neutral position during straight-line travel, dampening vibrations and ensuring smooth engagement.

Linear guide. The load supported by each guide roller is calculated considering full load conditions. A U-grooved roller with sufficient load capacity is selected, along with the rail section. The primary linear guide consists of an 8 mm round mild steel bar. Each carrier linear guide features 8 U-grooved rollers, fixed with eccentric nuts to adjust the contact and facilitate easy dismantling. A secondary rear guide roller, fabricated from a 20×20×3 mm hot-rolled steel angle profile, ensures the carrier bed remains horizontal throughout its entire loop trajectory. The main vertical conveyor frame rigidly supports both guide structures.

2.3 System Integration and Operational Workflow

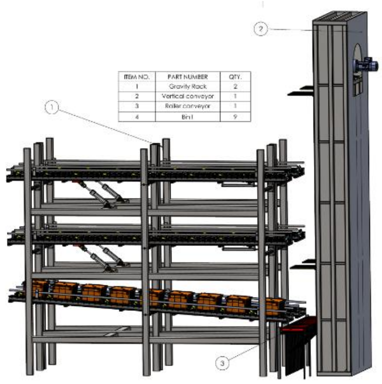

Fig. 3. Design of the multi-layer gravity conveyor-based storage system

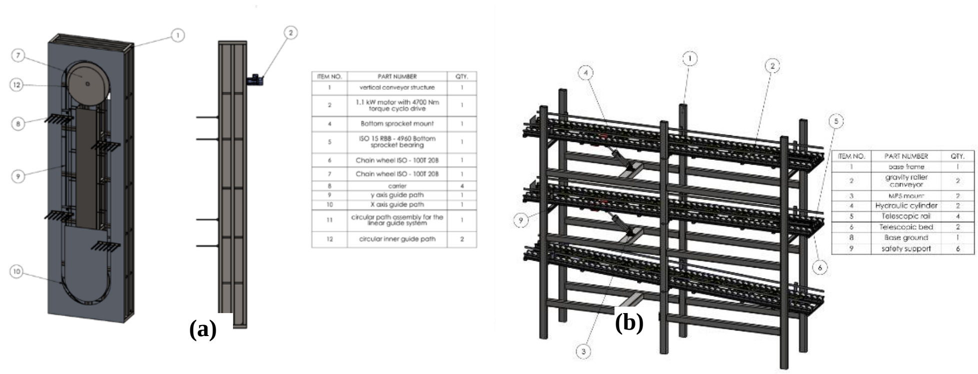

Fig. 4. Design of the vertical conveyor (a) and the gravity rack (b)

The system operates on a Last in First Out (LIFO) principle increasing space utilization within the defined footprint. A combination of limit switches, sensors and pneumatic/hydraulic actuators governs the operational sequence.

Storage Operation. The system features two infeed points (Fig.3): one on the right-hand side of the gravity rack and another on a powered roller conveyor positioned between the rack and the vertical conveyor. The storage sequence is initiated upon the placement of a bin at an infeed point. The powered roller conveyor transports the bin to a pre-aligned position adjacent to the vertical conveyor. The target gravity bed is inclined at 4 degrees.

The vertical conveyor lifts the bin to the designated storage level (Fig.4.a). At the storage level, the telescopic bed extends 500 mm. As the carrier passes through, it precisely transfers the bin onto the gravity conveyor bed. The bin moves along the 4-degree inclined gravity bed until its impact energy is absorbed by an elastic shock absorber on the end stopper (Fig.4.b). An active stopper mechanism ensures sequential spacing between bins. The first bin depresses one end of the stopper, causing the other end to lift and act as a barrier for the subsequent bin, preventing collisions. This process continues until the level is full. Once a level reaches its capacity, a counter signals a pneumatic actuator to lock the stored bins in place, securing them for storage.

Retrieval Operation. To retrieve a bin, the target gravity bed is inclined to 4 degrees, and its telescopic bed is extended. A sensor near the telescopic bed triggers the retraction of the pneumatic actuator, releasing a single bin. The active stopper immediately engages to halt the following bins, maintaining orderly sequential movement. The released bin moves down the inclined bed onto the extended telescopic rails. The last three rollers on this rail pivot to act as a stopper, ensuring the bin is correctly positioned for acquisition. The vertical conveyor carrier collects the bin from the telescopic bed and transports it downwards. The bin is discharged onto the powered roller conveyor, which transports it to the outfeed point for collection.

Finite Element Analysis (FEA). Critical components from both subsystems including the roller bed frame channels, rack columns, carrier brackets and structural connections were modelled in SOLIDWORKS 2021 software. Static structural FEA was performed to validate the design, applying operational loads and boundary conditions. The analysis focused on evaluating factors of safety against yield and quantifying deflections to ensure they were within functional limits for reliable operations.

3 RESULTS AND DISCUSSION

3.1 Finite Element Analysis (FEA)

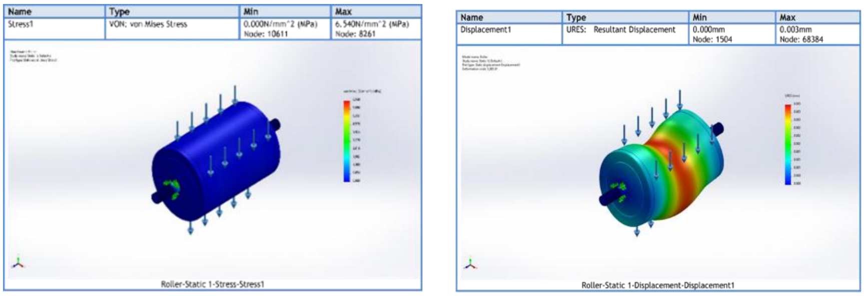

Fig. 5. Roller stress and displacement FEA

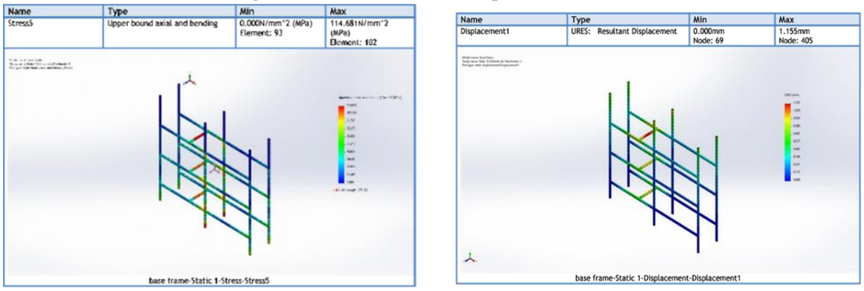

Fig. 6. Rack structure Upper bound axial and bending and displacement FEA

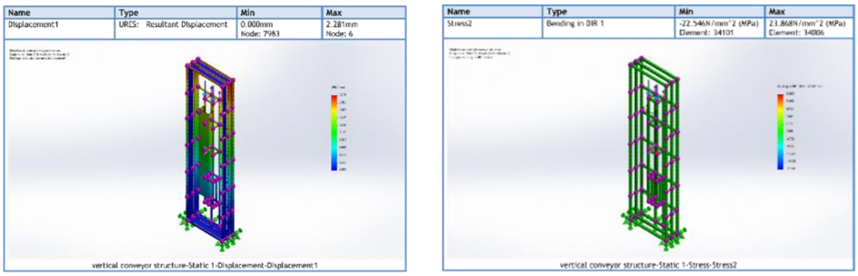

Fig. 7. Vertical conveyor structure static analysis

The structural integrity of critical components was validated through Finite Element Analysis (FEA) and manual calculations. As shown in Fig. 5, the maximum von Mises stress was found to be 6.54 MPa at the shaft mounting point. The maximum deflection is 0.003

mm at the middle. The design of the roller is considered safe since the deflection of 0.003 mm for a 140mm length does not exceed 1/500 of the span.

Fig. 6 shows the stress and deflection results of the rack structure considering the maximum capacity of the live load and force exerted by the hydraulic cylinder. The maximum bending moment calculated for the channel section was 2.303 kNm, producing a peak stress of approximately 114.7 MPa. This value lies well within the allowable stress for S275 J0 when applying a safety factor of 2.

The supporting structure of the vertical conveyor was analyzed under the combined dead load and live load (4 fully loaded carriers). The results are shown in Fig. 7. The stress and deflection values were found to be within the material limits of S275 J0 steel. Maximum deflections were less than 3 mm along the vertical span ensuring that the carrier guides remain aligned and functional. The FEA results of the assembly closely matched the analytical predictions done by manual calculations.

3.2 System Performance

The finalized design successfully meets all key objectives. The multi-layer design provides three distinct storage levels within a 7 m × 3 m × 6.5 m floor space. This configuration triples the storage capacity compared to floor stacking occupying the same factory floor area. The integration of limit switches, sensors and sequenced pneumatic/hydraulic actuators enables continuous and automated storage and retrieval from a single access point, reducing manual labor and improving throughput. The use of gravity for bin conveyance significantly reduces energy consumption compared to fully powered systems. The integration of a compact vertical conveyor with gravity-fed storage levels makes the solution modular and expandable, supporting gradual implementation in existing facilities without major plant modifications. The controlled tilt angle and magnetic brake rollers ensure safe and predictable bin velocities, while the FEA results comprehensively validate the structural reliability and safety of the entire system. Future work focuses on experimental validation through a scaled prototype, particularly to confirm real-world friction coefficients, braking effectiveness, alignment tolerances under continuous operation and the integration of a programmable logic controller (PLC) based automation.

4 Conclusions

This study presented the design and development of a Multi-Layer Bi-Directional Gravity Conveyor-Based Storage System to address the critical challenge of optimizing the storage density in manufacturing buffer zones. This system effectively triples the storage capacity within a compact floor space of 7m x 3m x 6.5m compared to conventional storage achieving a total capacity of 6 tons. Key innovations include the use of three vertically stacked levels of bi-directional gravity conveyors acting as dynamic storage beds combined with a continuous vertical conveyor for efficient bin transfer between levels. The gravity conveyors hinged centrally and tilted to a precisely calculated 4° angle via hydraulic actuators enabling bin movement solely through gravity for both storage and retrieval. This eliminates the need for forklifts for bins up to 100 kg. This passive movement principle along with controlled deceleration using magnetic brake rollers and active stopper mechanisms ensures safe and sequential LIFO operation while minimizing energy consumption. While the system has been validated analytically and numerically, future work focuses on experimental testing through a scaled prototype to evaluate real-world performance validation. Overall, the system provides a highly scalable, energy-efficient and space optimized solution for continuous storage and retrieval in buffer zones enhancing throughput and reducing operational costs associated with traditional methods.

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