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Simulation-based Optimization for Material Handling System: A Cement Plant Case Study

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Abstract: This paper addresses the optimization of material supply and handling using simulations. The primary objective is to reduce loader downtime by improving raw material procurement and revising the work schedule for material delivery and loader operations. Through the adjustments in the scheduling of raw material deliveries, excessive idle times of handling equipment are minimized. A simulation model is designed to compare the current state with the proposed optimized scenario. The reorganization reduced loader downtime by improving raw material procurement. The simulation results indicate a decrease in loader downtime, from 33% to 13% of total available time. The analysis of storage box occupancy reveals a notable increase in supply efficiency at the outdoor landfill. Adjustments enable the delivery of larger quantities of gypsum within shorter timeframes, maximizing stored material without exceeding storage capacity constraints.

Keywords: Simulations, optimization, material handling system, Tecnomatix Plant Simulation

1. Introduction

In the fields of industrial engineering and logistics, the efficiency and effectiveness of material handling systems are crucial for optimizing operations and enhancing overall productivity. The complexity of modern supply chains necessitates robust methodologies to design and optimize these systems, which often involve intricate interactions between various components such as transport systems, handling equipment, and storage systems. The issue of optimizing logistics processes within the material handling system is widely discussed in scientific papers. Many researchers have applied traditional analytical approaches to address various material handling issues. For instance, a research study by [1] focused on optimizing material procurement and storage layout. The authors presented a model optimizing material procurement and material storage on construction sites. Similarly, [2] dealt with the application of the Analytical Hierarchy Process, a multi-criteria decision-making tool, for the selection of appropriate material handling equipment for a local industry in order to optimize the overall system. Having an efficient and effective material handling system is of great importance to manufacturing and logistics industries. In that context, [3] applied hybrid multi-objective optimization algorithm based on Artificial Immune Systems for maintaining continuous materials flow and ensuring required material availability when needed. Similarly, [4] introduced a two-step optimization model to automatically identify optimal schedules for material handling activities in warehouses. Automated container terminals represent advanced facilities for container handling and are a current development trend. [5] proposed a novel approach to address integrated scheduling problems for automated quay cranes. In another study, [6] tackled the issue of minimizing material handling costs in manufacturing systems or warehousing facilities. Research on optimizing Vessel Turnaround Time has also contributed to the field, as demonstrated by [7]. Additionally, [8] employed a dynamic scheduling approach to optimize material handling operations in a robotic cell, while [9] presented a method for solving scheduling challenges in material handling for automotive mixed-model assembly lines.

However, traditional analytical approaches often struggle to account for the dynamic and stochastic nature of material handling systems. In response, simulation-based optimization has emerged as a powerful tool in tackling challenges posed by this system design. A literature survey on simulation techniques employed in production planning and control was presented in [10]. Based on the Recursive Optimisation-Simulation Approach, [11] developed a methodology to provide effective decision support for integrated production planning and scheduling. Similarly, [12] proposed a metaheuristic simulation-based optimization methodology to address shop floor material handling problem. Authors of [13] conducted experiments to optimize production programs using the FlexSim simulation program combined with OptQuest to identify cost-effective solutions. The streamlining of production logistics via the ExtendSim program was presented by [14], while [15] used and SIMUL8 software. The widely used tool for processes optimization is Technomatix Plant simulation, as described by [16], who used this Tecnomatix software support to optimize logistics flows. Furhter applications of Tecnomatix for optimizing logistics processes are discussed in [17-19].

This paper explores the application of simulation-based optimization in the context of material handling systems. The issue of inefficient utilization of material handling equipment is examined through a case study conducted at a cement plant. A revised schedule is proposed to enhance the coordination of material supply activities and shovel loader operations. The proposed solution is evaluated using Tecnomatix Plant Simulation software to determine its potential impact on operational efficiency.

2. Case Study Description and Problem Definition

The subject of this study is the cement plant in Turňa nad Bodvou, located in southern Slovakia near the Hungarian border. The plant operates continuously, 24 hours a day, seven days a week, producing cement as its final product. The production process relies on several raw materials, including limestone, clay, demetallized steel slag, artificial compact aggregate, granulated blast furnace slag, and gypsum.

The manufacturing process involves multiple stages. The process begins with the delivery of raw materials to the cement plant. Each production stage is color-coded to represent specific phases of the process. Red indicates the stages in which the raw materials are processed into raw material flour. Green denotes the clinker production phase, while blue represents the final stage, during which the main product, cement, is produced. Fig. 1 shows a detailed flow chart of the process.

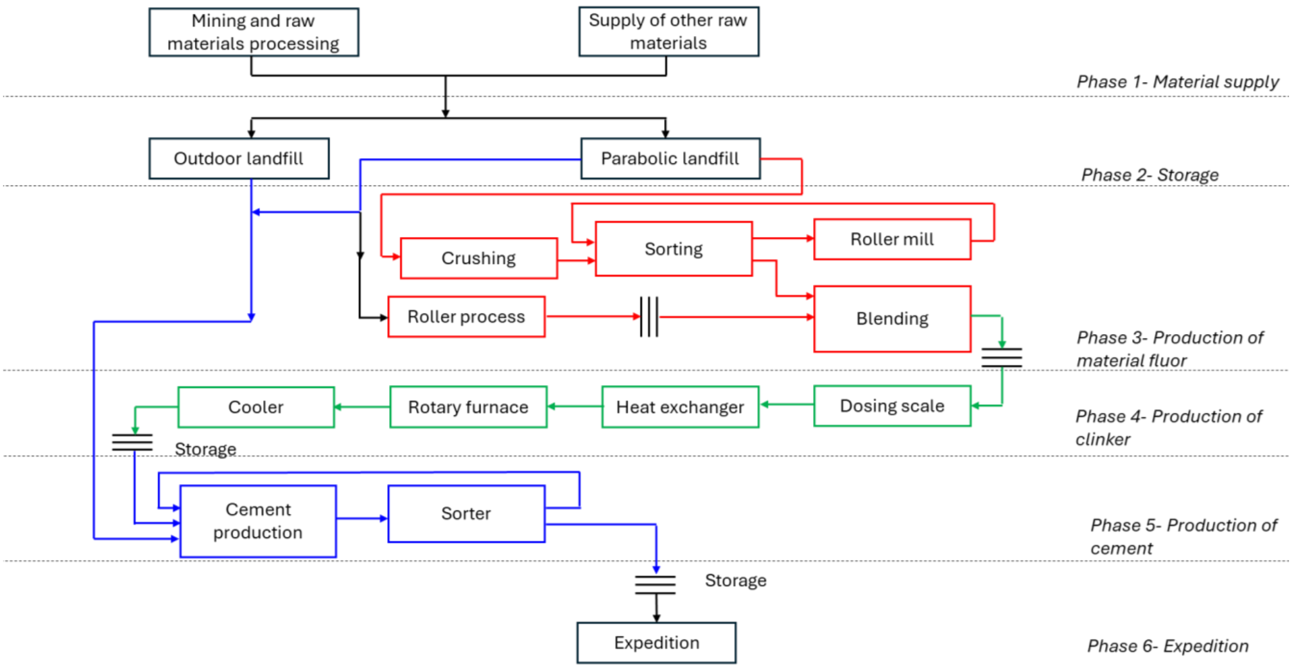


Fig. 1 Flow chart of the manufacturing process. Source: [20]

System analysis revealed serious deficiencies in material handling at the outdoor landfill. The outdoor landfill (Fig. 2a) is primarily used for storing raw materials that are used as cement additives. The primary handling equipment at the outdoor landfill is the front shovel loader CAT 926M (Fig.2b). With the help of the loader, all handling operations are carried out at the outdoor landfill, and its work schedule is adjusted to the supply of raw materials. The loader also performs dosing of raw materials for production, which involves the transfer and dosing of all types of raw materials stored at the outdoor landfill. In addition to the outdoor landfill, the shovel loader also operates in the clay pit, where it mixes limestone and slag with clay or performs other handling activities.

(a) (b)

Fig. 2 Outdoor landfill (a) and shovel loader (b). Source: [20,21]

Figure 3 illustrates the work schedule of the loader, which is directly influenced by the working hours of its operator. The loader's daily operation starts at 6:00 a.m. with the beginning of the morning shift. The initial task involves transferring gypsum into storage boxes after unloading from trucks. Subsequently, the loader assists in dosing gypsum and limestone required for the production processes. After loading limestone into boxes, the loader remains idle until additional handling operations are needed. This idle period includes a 45-minute lunch break and lasts from 12:15 p.m. to 1:30 p.m., except on Tuesdays, when it extends until 2:00 p.m. Another operational pause occurs between 4:30 p.m. and 7:00 p.m., during which a 30-minute operator shift change takes place. A similar shift change happens at the start of the day, from 5:30 a.m. to 6:00 a.m.; however, this is not shown in Figure 3.

Significant downtime (represented by the red sections in Fig. 3) observed in the loader's operational schedule is due to the dual responsibilities of the loader: operating at the outdoor landfill according to the material delivery schedule and traveling considerable distances to perform tasks at the clay pit. The extended waiting periods at the outdoor landfill occur because it is inefficient to relocate the loader to the clay pit between handling operations, as transit time alone exceeds 30 minutes. Consequently, the loader remains idle at the landfill for several days until the next operation.

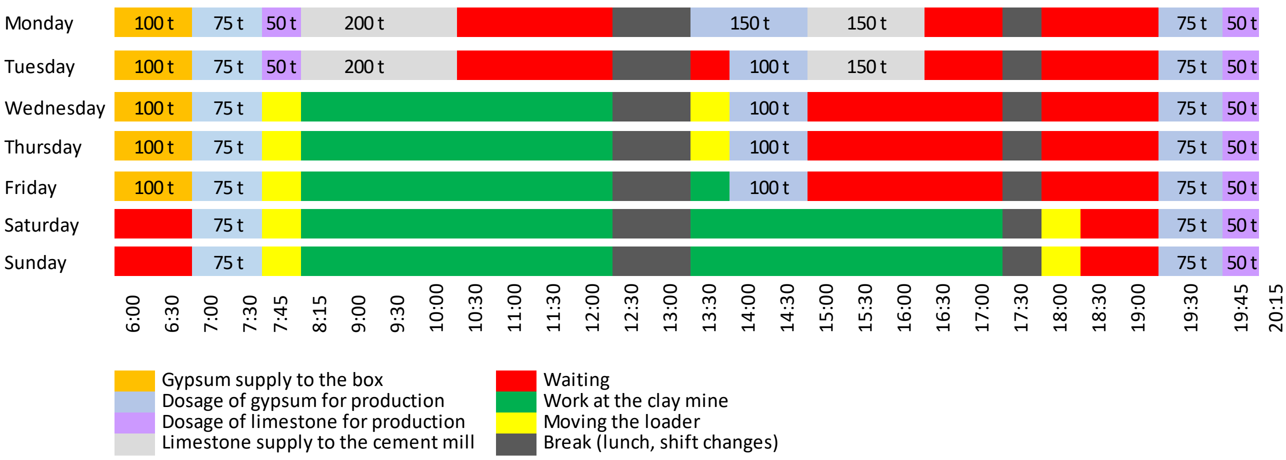


Fig. 3 Loader's work schedule-original state. Source: authors

The major issue with the outdoor landfill lies in the logistics of procuring input raw materials. Since the import of raw materials takes place every working day at two different times, the transfer of raw materials to storage boxes with the help of a loader is also carried out twice a day. However, this creates several hours of downtime in the loader's schedule. This downtime reduces the loader's efficiency, and logistics of raw material procurement are identified as the main shortcoming.

To address this problem, the solution will focus on optimizing the scheduling of raw material deliveries, with the main goal of minimizing the loader´s downtime.

3. Proposal for Material Supplies and Material Handling Optimization

The proposal to optimize supply logistics builds upon the previous idea of reorganizing the supply of raw materials. The most effective solution to the scheduling problem is to consolidate the delivery of raw materials into one or two days.

On Mondays and Tuesdays, after the delivery of limestone, the loader experiences downtimes, which provides an opportunity to plan the supply of gypsum during these downtimes. While gypsum is already being supplied on Monday and Tuesday in the current arrangement, the task is to shift the supply of this raw material from the remaining days, i.e., Wednesday, Thursday, and Friday, to these two selected days.

The total downtime on Monday and Tuesday amounts to 9 hours and 30 minutes. This time is sufficient to reorganize the raw material supply during these days. Taking all relevant factors into account, a revised loader work schedule was formulated (Fig. 4).

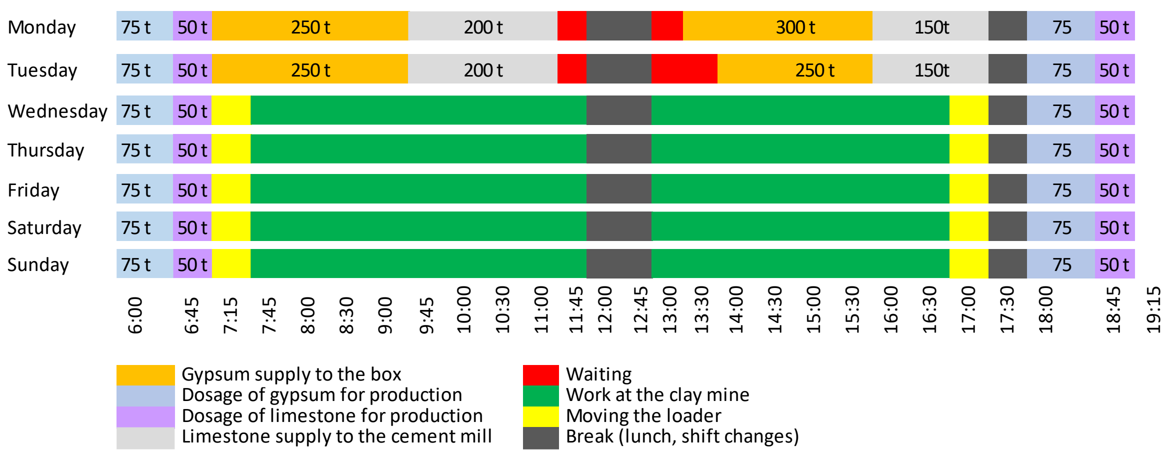


Fig. 4 Loader's work schedule- proposal. Source: authors

Fig. 4 illustrates a reduction in total downtime (represented by red periods), an increase in the loader's operational time at the clay pit (represented by green periods), and the reorganization of raw material supply over two days. By consolidating the gypsum supply on Mondays and Tuesdays, a significant decrease in downtime was achieved, enhancing the continuity and efficiency in the loader's operations.

It shall also be noted that the total working time has been reduced. In the original schedule, the loader´s operations concluded each day with the dosing of limestone at 20:15. Under the proposed plan, the loader now finishes 1 hour earlier, i.e., at 19:15. This reduction in working time results from rescheduling the raw material dosing for production, which has been moved one hour earlier.

4. Assessment of the Proposal by Simulation in the Tecnomatix Plant Simulation

4.1 Simulation Model of a Production Process in a Cement Plant

The simulation model concerns the total material flow of the cement plant. It encompasses all phases of the technological procedure outlined in Fig. 1, including clinker production and cement production. Following the development of the model, the current operational state is simulated. The simulation output includes a visualization of loader utilization and the occupancy levels of storage boxes at the outdoor landfill. The final step involves implementing the proposed changes into the simulation model and comparing the updated results with those of the original state.

Key time and capacity parameters related to loader operation:

1. One entity corresponds to one ton of material (applies to all types of material).
2. The capacity of outdoor landfill storage boxes is 700 tons of limestone and 1,300 tons of gypsum.
3. The front shovel loader can move (stack) 100 t of raw materials per hour. All loader handling activities, including raw material dosing for production, were derived from this data. Therefore, the operational time of handling one entity (i.e., one ton) is 36 s.

Fig. 5 presents a simulation model of the production processes within a cement plant. The central section of the figure represents the entire production workflow, including landfills. The right section of the figure contains objects that configure operational timing, while the left section includes objects that ensure the proper flow of entities. The shovel loader, highlighted by a red circle, plays a crucial role in maintaining this flow. Correct routing is achieved by assigning specific attributes to each entity using the Method functionality. Multiple identical entities pass through the loader, which directs them to subsequent locations based on their attributes.

The simulation runs for 60 days to account for the system's run-in phase and to eliminate the impact of the initial inactivity in system components. In the model, the loader is represented as a stationary object; however, its workload is continuously monitored. This is achieved by simulating the time required for handling operations, which serves as a key metric for assessing the loader's utilization.

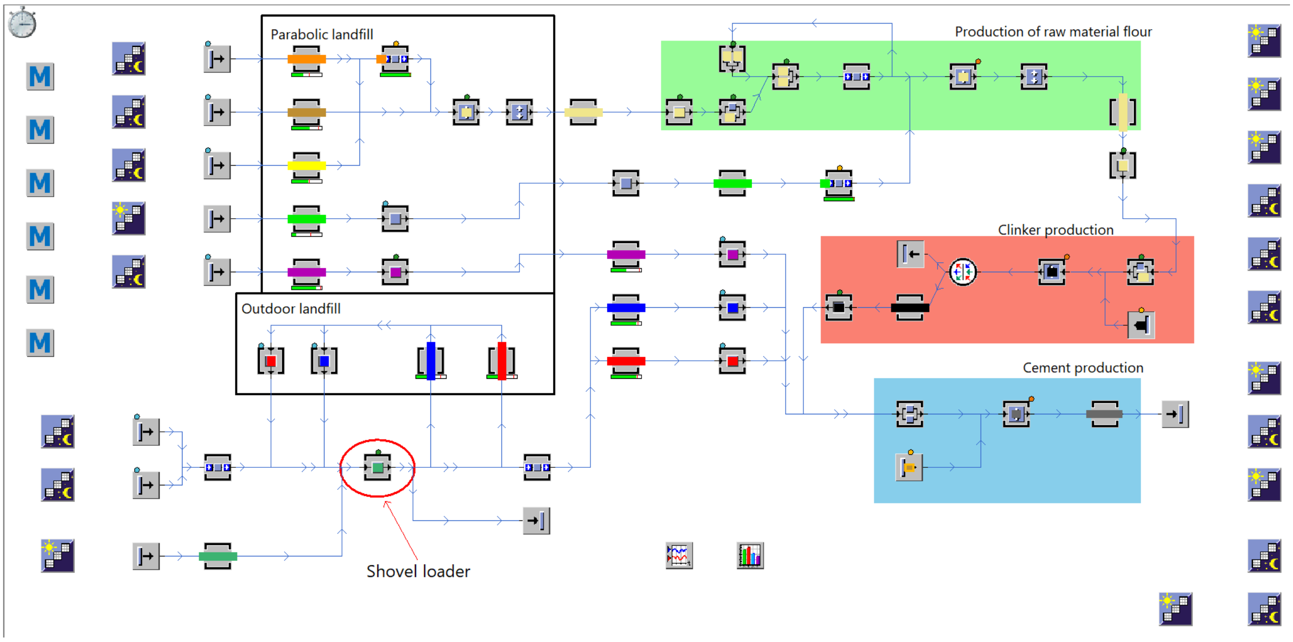


Fig. 5 Simulation model of the entire production process. Source: [20]

Fig. 6 provides a detailed illustration of the outdoor landfill, with the loader's handling operations represented using arrows. Three arrows, color-coded blue, red, and green, represent the flow of raw materials during various handling processes. The red arrow indicates the supply or stockpiling of raw materials into storage boxes, while the green arrow represents the material flow during the batching process for production. This batching process is regulated by objects labelled as "dosage". These simulated objects allow for the regulation of the quantity of raw materials and the timing of their dosing. The blue arrow shows the flow of raw materials during operations at the clay pit. As the loader is modelled as a fixed, immobile object in the simulation, the clay pit operations are adjusted accordingly, redirecting materials from the clay pit to the loader for processing.

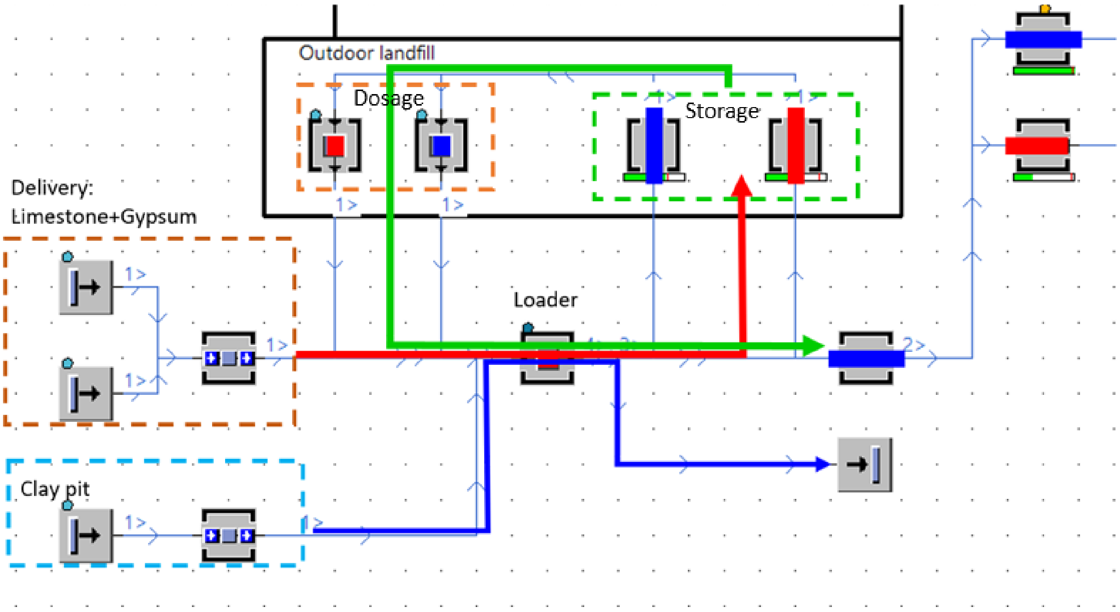
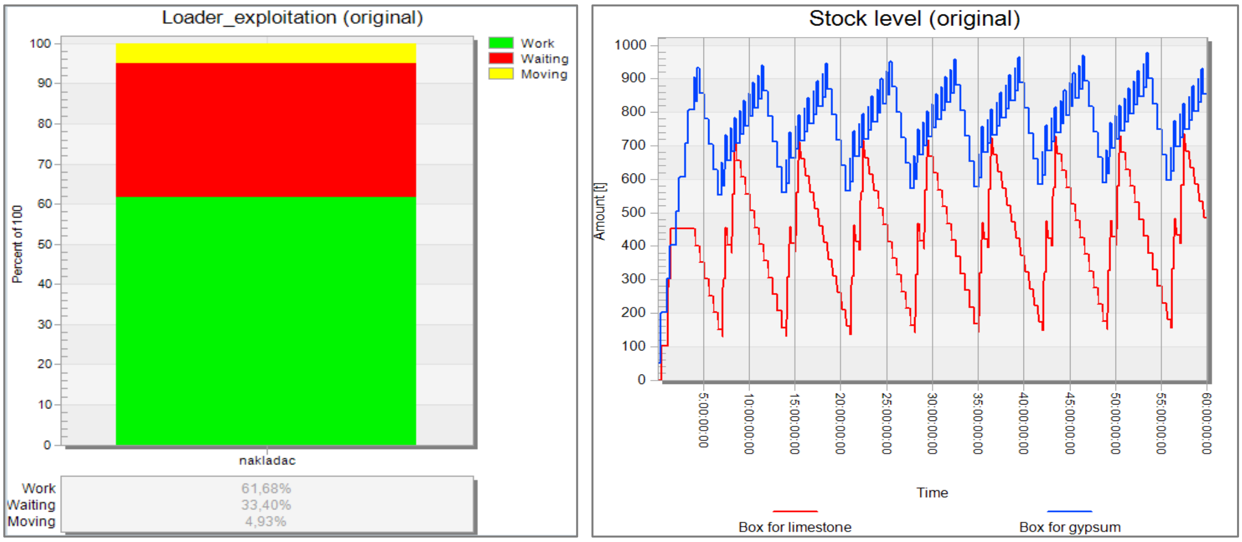


Fig. 6 Detail of the outdoor landfill and handling operations of the loader. Source: [20]

After the 60-day simulation, the performance of the loader and the stock levels were assessed through graphs. Fig. 8 displays the loader's utilization as a percentage and the occupancy levels of storage boxes in the system´s original state.



(a) (b)

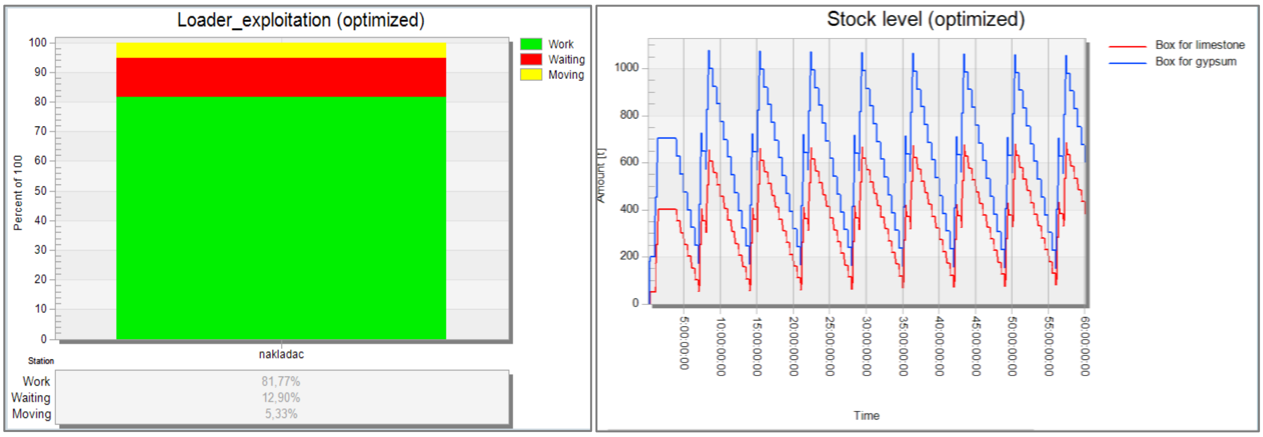
Fig. 7 Loader exploitation (a) and stock level (b) – original state. Source: authors

Fig. 7(a) indicates that the loader operates for 62% of the total available time, with 33% attributed to downtime and 5% to loader movements. The 62% working time encompasses the total duration of all handling operations at the outdoor landfill, including the supply and dosing of gypsum and limestone, as well as operations at the clay pit. The downtime percentage (33%) represents the total time spent in waiting periods, idle times, and shift changes. Although shift changes are not classified as downtime in the operational schedule, they are combined with downtime into one category in the graph. The remaining 5% accounts for the loader's transit time between the outdoor landfill and the clay pit, reflecting only the time spent in transit.

Fig. 7(b) provides a graphical simulation output, displaying the occupancy levels of storage boxes and tracking the supply and consumption of raw materials over time. The x-axis represents time in days, while the y-axis indicates the quantity of stored raw materials (entities). An upward trend in the graph indicates the supply of materials, whereas a downward trend reflects their consumption or dosing into production. The maximum storage capacity at the outdoor landfill is 700 tons for limestone and 980 tons for gypsum. Since the supply and dosing processes are constant and occur at consistent intervals in the simulation, the storage box occupancy follows a recurring seven-day pattern.

4.2 Implementation of the Proposal into the Simulation Model

The proposed optimization of material flow entails reorganizing the input raw material supply schedule without any physical modifications to the existing infrastructure. No new facilities were added, nor were any changes made to the locations of original operations. As such, the evaluation focuses solely on the outputs generated by the simulation model after implementing the proposed schedule. These outputs are compared with the results from the original configuration. The revised simulation model yielded the following outputs (Fig. 8).



(a) (b)

Fig. 8 Loader exploitation (a) and stock level (b) –proposal. Source: authors

The reduction in operational downtime of the front shovel loader is evident from the simulation output in Fig. 8(a). The loader´s work time increased to 82%, representing a significant increase of 20 percentage points compared to the original state. This increase is due to the extended working time at the clay pit. The time spent on loader movements remains constant at 5%, while the downtime now accounts for only 13% of the loader´s total operational time.

The proposal also led to changes in the storage box occupancy levels, as shown in Fig. 8(b). Since the proposal involves a reorganization of the raw material procurement, the most noticeable impact is observed during the supply phase, particularly in the gypsum storage box. The frequency of gypsum supply was reduced from five to two days under the new plan, resulting in a more substantial and rapid increase in stored quantities on each supply day. Consequently, the maximum stored quantities adjusted to approximately 1,050 tons for gypsum and 690 tons for limestone.

5. Conclusion

The proposed optimization of material supply and handling addressed the challenge of scheduling raw material deliveries to reduce excessive handling equipment's idle times. This goal required a reorganization of the input raw material supply. A revised work schedule for material deliveries and loader operations was developed, forming the basis for creating a simulation model. Following simulations of both the original and proposed scenarios, the loader's capacity and the occupancy levels of the storage boxes were assessed using graphical outputs.

The primary aim of this paper, reducing loader downtime, was successfully achieved through the reorganization of input raw material procurement. The revised schedule brought a significant reduction in downtime, with the proportion of idle time decreasing from 33% to 13% of the loader´s total available time. This improvement positively impacted loader utilization, which increased from 62% to 82%.

A comparison of storage box occupancy at the outdoor landfill revealed notable changes, particularly in the gypsum supply process. Under the proposed schedule, larger quantities of gypsum are delivered within a shorter period, leading to a more pronounced increase in stored material compared to the original state. Although this adjustment raises the maximum stored quantity, it does not exceed the available storage capacity.

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