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AUGMENTING AN INBOUND RAW MATERIAL HANDLING SYSTEM OF A STEEL PLANT BY UNCOVERING HIDDEN LOGISTICS CAPACITY

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ABSTRACT

This paper presents an approach for inbound logistics capacity design by uncovering the hidden capacities of a raw material handling system of an integrated steel plant. The traditional analytical approach to capacity augmentation overlooked the possibility of capacity extraction from the existing system which resulted in sub optimal capacity design affecting capital investments and operational expenditures. Using discrete event simulation, we designed a capacity augmentation mechanism which would seek to maximize the utilization of unloading equipments, address system wide congestion and bottlenecks, and better the route layout resulting in released capacity while promoting seamless material flow. Our recommendation included changes in operational procedures, rearrangement of rake scheduling mechanisms, redesigned route network and equipment layout coupled with modest addition of unloading capacity. Our simulation model also showed significant reduction in operations cost through congestion management in the railway networks which resulted in superior ROIs when compared to the traditional approach.

1 INTRODUCTION

A major Indian steel manufacturer was planning a plant capacity expansion. The capacity expansion involved expansion of the production capacity at different stages of steel making which is shown in Figure 1. Iron ore, coal, coke and limestone are the major raw materials required for production of steel. The inbound raw materials are received and unloaded at a Raw Material Unloading Yard (RMUY). The unloaded raw materials are processed at treatment plants (Coke, Sinter and Pellet Plants) from where they are sent to a blast furnace for iron making. The molten iron is converted into steel at steel converters where molten steel is produced. The molten steel is cast into billets, blooms and slabs in continuous casting machines and the casted materials are then sent to rolling mills for making long and flat products that are sold commercially.

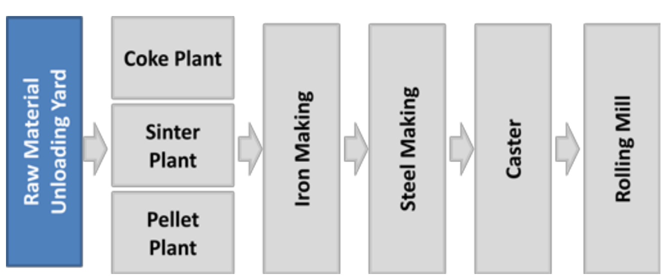

Figure 1: The typical steel making process of a steel plant.

Our study focused on the Raw Material Unloading Yard (RMUY) of the steel plant. At the RMUY, major raw materials such as iron ore, coal, coke and limestone are received from various sources through goods trains called rakes, provided by an external railway agency. The rakes are sent to mechanized unloading stations, where material is unloaded. In this plant, the in-plant movement of rakes is through captive locomotives that run on diesel. The external railway locomotives (that can run only on electrified tracks), deliver the rakes to the yard and leave. Some rakes are divided into smaller wagon sets before being sent to unloading stations. After unloading, the wagon sets are joined together. This process of splitting and joining of rakes is called rake handling. All the rakes after unloading and handling, if needed, are then handed over back to the railway agency.

With the expansion of the steel plant, the demand for raw materials will increase which will increase the number of inbound rakes arriving at RMUY. The increase in the number of rakes arriving at RMUY may cause congestion at the tracks causing bottlenecks for the unloading facilities and limit rake movements within RMUY. The external railway agency providing the rail service, charges for demurrage (delays in return of rakes beyond a certain time limit). Thus, such bottlenecks not only adversely affect the unloading capabilities of the yard, but also increase the demurrage costs. A process flow diagram for the raw material unloading process is provided in Figure 2.

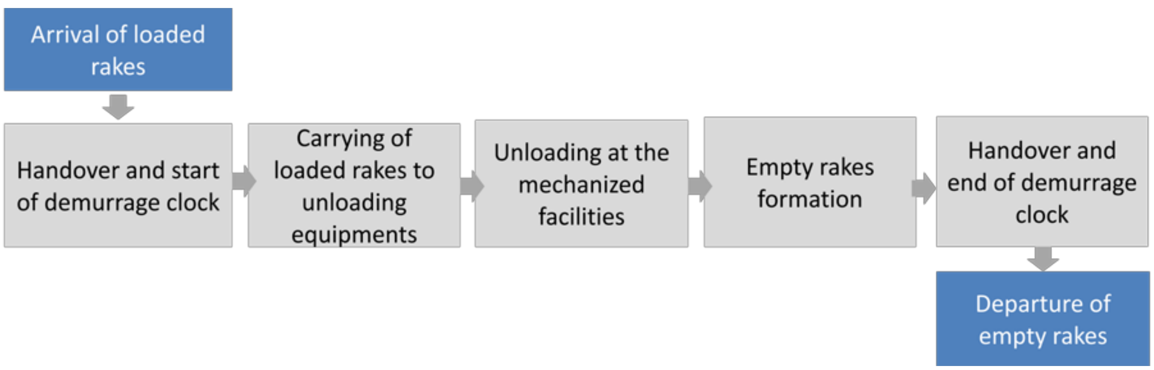

Figure 2: Raw material unloading process

The adequacy of the current facilities for handling the increased arrival of raw materials needed to be investigated and in case of inadequacy, appropriate changes needed to be proposed, so that the system was capable of unloading the annual requirement of raw materials with minimum network congestion.

2 DESCRIPTION OF CURRENT INBOUND SYSTEM

The RMUY comprises of a railway network in which unloading facilities for different raw materials are located at different locations. The existing system and its current rake movement has been shown in Figure 3. For unloading material from the wagons there are two types of unloading facilities: Wagon Tipplers and Track Hoppers. A wagon tippler is a mechanical device which is able to turn a whole open top wagon and tip out its contents. A track hopper is a hopper shaped receiver mounted beside and below railway track, into which side-opening or bottom-opening wagons are discharged.

There are three track hoppers for unloading iron ore rakes namely track hopper 1 (TH1), track hopper 2 (TH2) and track hopper 3 (TH3). There is one tippler for unloading coke rake that is coke tippler. For unloading sinter plant (SP) limestone rakes there is one tippler called flux tippler 1. There is one tippler for unloading calcining plant (CP) limestone rakes that is flux tippler 2. For unloading coal rakes there are five tipplers located in different areas of the yard. There are multiline yards for receipt of loaded rakes from railways (Yard 1), handling and unloading of rakes (Yard 2), formation of empty rakes (Yard 3) and handing over the rake to railways (Yard 4).

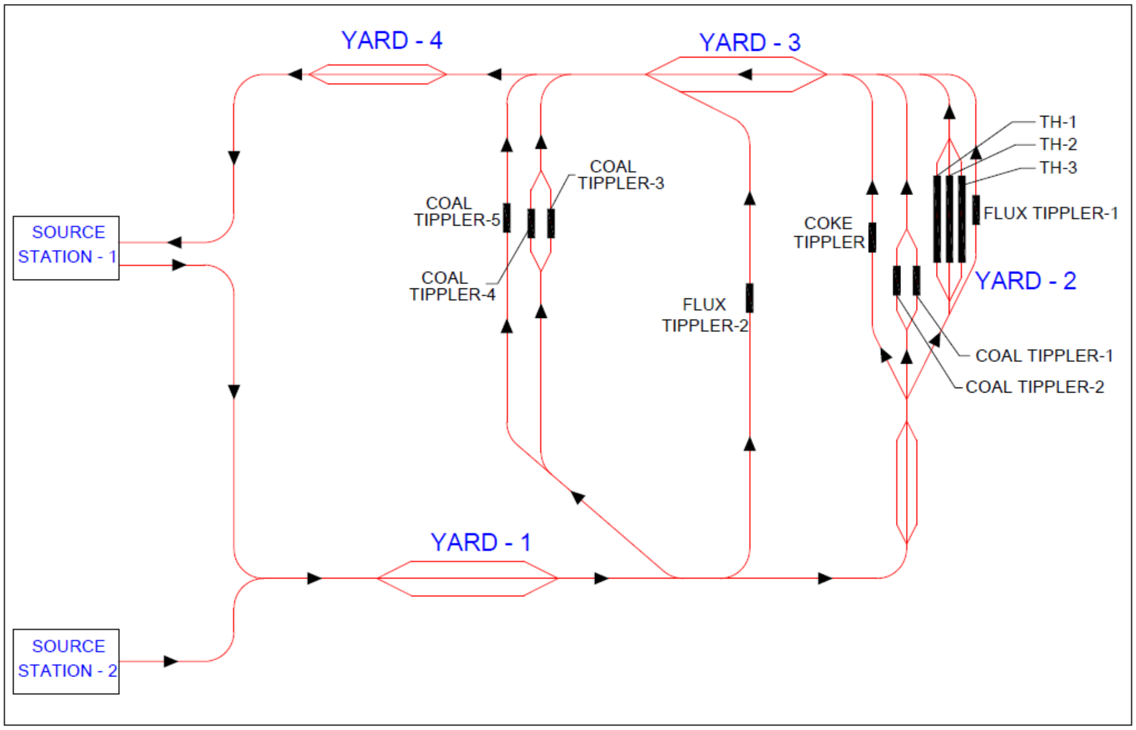

Figure 3: Description of the current system

The inbound rakes coming from the source stations 1 and 2 arrive in Yard 1. The arrival pattern of rakes is extremely variable leading to uneven intervals between rake arrivals. The external locomotive waits for a captive locomotive to get attached to the rake in the rear. Once a locomotive is attached, the external locomotive is released, and another captive locomotive is attached to the front. Two locomotives are required to move the rake from Yard 1 to their respective unloading facilities. A First Come First Serve policy of material unloading is followed at Yard 1. Some of the unloading facilities are not able to accommodate one full rake because of the inadequate length of the tracks. The rakes moving to those facilities are split into two or three smaller sets of wagons. After unloading, all of the empty rakes/wagon sets are moved to Yard 3. All the empty rakes are carried out of the circuit by the locomotives to source station 1 through Yard 4 after the marshalling in Yard 3 and handover formalities.

3 TRADITIONAL APPROACH TO CAPACITY EXPANSION

The total amount of material required to be unloaded for different materials in current situation and after expansion is provided in Table 1. As is seen, the iron ore, which is the major material (56% of total) handled by the RMUY, has an increase of 55% in handling requirement. Other materials have an increase of 23%.

Table 1: Material handling required- current and after expansion.

Material	Currently Handled (mtpa)	Required after expansion (mtpa)	Percentage Increase
Iron Ore	**11.5**	**17.8**	**55%**
Others	**8.9**	**10.9**	**23%**
Coal	4.8	5.6	17%
Coke	1.2	2.2	83%
Limestone	2.9	3.1	7%

The traditional analytical approach applied in design of facilities like RMUY, will focus on increasing facilities proportionate to the required expansion in the capacity of the system. In the given system, based on the traditional approach to capacity expansion, it was worked out(considering the daily unloading requirement of materials and handling capacity of facilities) that more than one track hopper would be required for handling additional iron ore rakes. The analytical approach also suggested that the current unloading facilities for coal, flux and coke handling were adequate for handling the increased capacity as either the increase in inbound material handling capacity was not high(in case of coal and flux) or the equipment was of higher capacity than currently required(in case of coke)

Using the analytical approach, the expansion in iron ore handling capacity would incur an investment of around $11.6 million details of which are provided in Table 2.

Table 2: Cost of capacity expansion in RMUY using traditional approach.

Facility	**Cost**	**Quantity Required**	**Investment Required**
Iron Ore Track Hopper	$ 4 million	2	$ 8 million
Track Systems	$ 1.6 million	2	$ 3.2 million
Total			$ 11.2 million

It was suspected that simply increasing the iron ore handling facility of the system will not be adequate for the RMUY, as the analysis did not take into consideration network congestion which was a possibility because of the increased inbound rakes. Such a network congestion would have increased the duration for which the external railway wagons were in the RMUY, which would have resulted in higher demurrage charges to be paid to the external railway agency. Thus in addition to capital expenditure of $11.2 million involved, further operational expenditures in terms of demurrage costs would have been incurred.

It was also suspected that the existing system had unexploited hidden capacities. If these hidden capacities could be uncovered through changes in operational procedures and policies, a significant increase in the system's handling capability could be achieved. The focus was to ensure that all the unloading facilities were utilized efficiently. This could be possibly done by minimizing the congestion in networks and proper scheduling.

4 HIDDEN CAPACITY ANALYSIS

Simulation has been used for debottlenecking and enhancing logistics capacity of systems previously. Sharda and Bury (2010) used discrete event simulation for a debottlenecking study at a chemical plant and identified bottlenecks and their causes for different production processes. Brito et al (2010) used discrete event simulation and Multi-Criteria Decision Analysis for planning and sizing the logistics and production elements of a steel plant. They concluded that the methodology applied is 'highly efficient' when applied in complex logistic systems.

Considering the complexities of the logistics involved in the plant movement, it was decided to develop a discrete event simulation model for the existing system. The objective of the simulation model can be summarized as:

- Evaluation of adequacy of existing equipments for expansion
- Determination of additional handling capacity
- Minimizing network congestion (Turnaround time)

4.1 Simulation Modeling and Verification

A discrete event simulation model was built using the Promodel Software to simulate the existing system and was validated by conducting an as-is analysis of the system. Rail movement could be conveniently modeled in the software using its feature of network path and entity driven simulation. The results of the simulation (material unloaded at each facility, the turnaround time for rakes etc) matched the data provided by the steel plant.

The model was run with an increased rake arrival corresponding to the plant capacity expansion stage. One year rake arrival data for as-is operational situation was obtained from the plant. For running the model in the to-be scenario, the pattern of the increased arrivals was required. The one year data was fitted into various distributions and best fit distribution was selected with the help of goodness of fit tests.

4.2 Analysis Methodology

To uncover the hidden capacities of the RMUY, the model parameters were investigated for usage and turnaround times. The utilization of track hoppers, wagon tipplers and locomotives were measured and the time taken by rakes at each activity was also mapped. Very high or very low utilization of facilities were analyzed and related rake turnaround times were found. Very high usage of a facility showed high inflow of materials while very low usage of the facility showed that either it was not receiving enough rakes for processing or else the facility had more capacity than required for processing.

The decision table given in Chart 1 shows the relationship of facility usage with rake availability and handling capacity. It provides a structured methodology for finding the cause of bottlenecks in the system, and exploring approaches for debottlenecking, either through changes in scheduling, changes in rake movement routes, or by improving the process efficiency by operational changes or capacity expansion.

	Investigate Rake Availability	***Investigate Handling Capacity of facility***
High usage of facility	Reduce the rake movement by • proper scheduling of the movement • diverting the movement through a different route	Check for process incapability. • reduce process time of the facility • increase the capacity of the facility
Low usage of facility	Check for bottlenecks. • Look for bottlenecks in previous processes by observing the waiting time of rakes at those processes • Associated facilities used in the previous processes may be having a high usage	Check for underutilization. • The capacity of the facilities may be more than requirement • The facility could be utilized for other activities or discarded

Chart 1: Decision Table.

4.3 Results of Simulating the Existing System with Increased Load

On running the simulation model, with an increased load, the system was found to be unable to handle the unloading requirement. This was expected as the existing system was not designed to handle the increased load.

From the results it was found that the utilization of tipplers was low. Iron ore track hoppers had an average usage of 32%. Coal tipplers had a utilization of 30% while flux and coke tipplers showed a utilization of 20%.

Such low utilization pointed towards low inflow of material to the unloading facilities because of bottlenecks in previous processes (See Decision Table, Chart 1). On checking for bottlenecks in the previous processes it was found that rakes had to wait for long times after arrival at Yard 1 before the captive locomotives moved them to the unloading facilities. It pointed towards congestion in Yard 1 area.

The utilization of the tracks in Yard 1 area was high. Moreover the utilization of locomotives was also found to be very high. It was found that the junction connecting Yard 1 and Yard 2 was occupied most of the time, which limited the movement of rakes, thus causing congestion. Thus remedies were to be found to reduce this congestion (see Decision Table, Chart 1).

A combination of approaches was investigated which focused on reducing the traffic in the Yard 1 & Yard 2 areas to release the congestion at the junction. The following operational changes were proposed:

- **Change in route:** To reduce the traffic in the Yard 2 area, which in turn would reduce the congestion in the junction connecting Yard 1 and Yard 2, the route of rakes carrying iron ore (which were majority in numbers) will be modified. These rakes after being unloaded at the track hoppers will use the Yard 1 area for exit instead of Yard 3. This change in route has been shown in Figure 4.
- **Scheduling:** The tracks leading to iron ore tipplers had full rake length, and thus the rakes could have directly moved to the unloading facilities as they were not required to be divided into smaller wagon sets. Thus it would have been beneficial if rakes carrying iron ore did not have to wait in the queue. As they had lower handling times, the first come first serve policy of rake movement will be changed to priority scheduling of rakes, with iron ore rakes having the highest priority.
- **Process improvement:** The tracks leading to iron ore track hoppers will be electrified. Thus the external railway locomotives could take the rakes directly till the beginning of the track hoppers. The placement of wagons in the track hopper could be then done by captive locomotives. The external locomotives then returned the wagons to the Source Station 1 through Yard 1.
- **Increase in capacity:** With the external railway locomotives moving the iron ore containing rakes in the system and returning it back, the captive locomotives will be available more for other processes, thus increasing the effective number of locomotives in the system.

Making these changes would cost $1.6 million which is the cost for electrification of tracks leading to iron ore track hoppers.

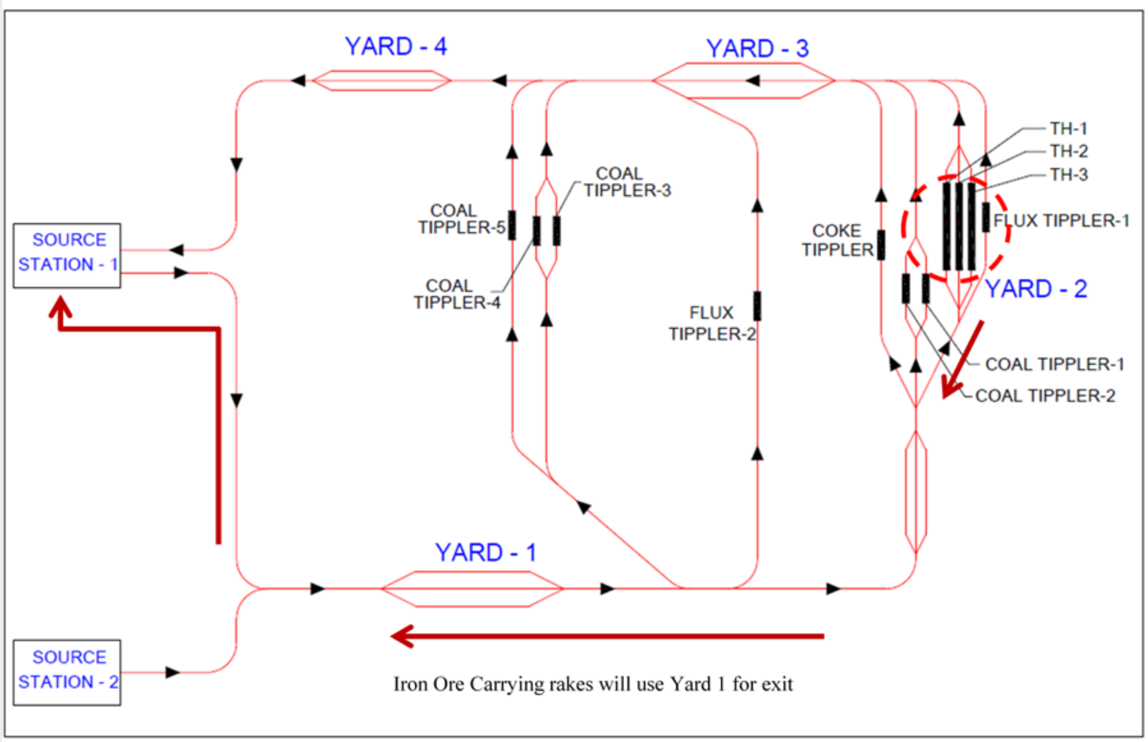

Figure 4: Modifications in the existing system

The material unloading capability of the RMUY with the proposed modifications was simulated. The process and rake movement logic of the simulation model was modified, so that the model could simulate the proposed scenario.

4.4 Results of Simulating the System with Proposed Modifications

From the simulation results it was evident that hidden capacity existed in the system, and the proposed changes led to a significant increase in the handling capacity of iron ore. The system with the proposed modifications was able to satisfy the full requirement of iron ore unloading as shown in Table 3. There was also an incremental increase in the handling capacity of coke and limestone but not sufficient enough for the expansion program. The capacity of coal handled in fact reduced when compared to the capability of the as-is system.

Table 3: Material unloaded at the unloading facilities for the system.

Material	Currently handled (MTPA) [C]	Required after expansion (MTPA) [R]	Unloading capacity with modification (MTPA) [C’]	Capacity delta (MTPA) [δC = C’ – C]
Iron ore	11.5	17.8	18.1	6.6 ↑
Coal	4.8	5.6	3.8	1 ↓
Coke	1.2	2.2	1.4	.2 ↑
Limestone	2.9	3.1	3	.1 ↑

The simulation result also showed that while the usage of iron ore track hoppers and limestone tipplers improved as expected (because unloading facilities were receiving more rakes), the coke and coal handling tipplers still were having very low usage. Coal tipplers and coke tipplers had an average utilization of 26%. Figure 5 shows the utilization of tipplers and track hoppers found on simulating the system with proposed modifications. The causes of their low usage were investigated (see Decision Table, Chart 1) and the wait-times for rake movement in previous processes were explored.

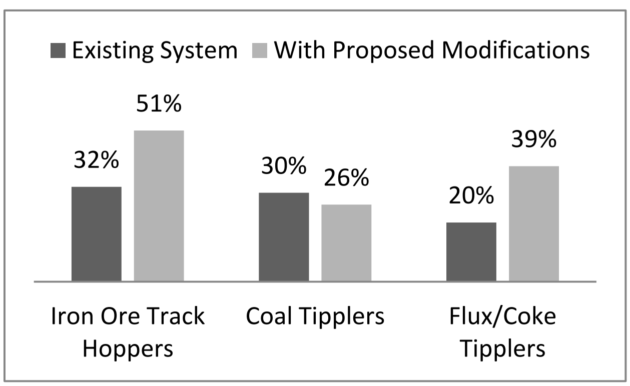

Figure 5: Unloading facility usage with proposed modifications vs previous.

The average rake throughput time for different materials is shown in Table 4. On an average the rakes still had to wait for long time before they can leave Yard 1. As the iron ore rakes were given priority over others, the other rakes had to wait for more number of turns to get locomotives for movement. Moreover there were 5 moderate capacity coal tipplers located at 5 areas scattered in the yard. Thus an incoming rake had to be split into smaller wagon sets and each of the parts then moved to the tipplers, thereby the Yard 2 area getting blocked with multiple movements. This added to additional wait times at Yard 1.

Table 4: Rake Throughput time in system with proposed modifications.

Material	t0 Arrival at Yard 1 to release of railway engine	t1 Release of railway engine to departure from Yard 1	t2 Yard 1 to track hopper/ tippler	t3 Unloading	t4 Unloading comple-tion to handover to Rail-ways	T (t1+t2+t3+ t4)
	(in minutes)					
Iron Ore Lump	202	25	6	251	66	348
Limestone for SP	491	271	18	613	139	1041
Coke	224	31	18	263	98	410
Limestone for CP	1154	29	6	639	106	780
Coal for Coal Tippler 4	365	144	61	828	126	1159
Coking coal (Tippler 1,2,3,5)	348	139	-	-	-	659

The utilization of locomotives was found to be on an average 71%. Increasing the number of locomotives may reduce network congestion but it may be possible that the limited number of tracks is the bottleneck and thus increasing locomotives will have no effect. On increasing the number of locomotives in the simulation model and running the scenarios, it was found that it had no effect on the handling capacity of the system. In fact the handling capacity of the system reduced marginally suggesting that the problem existed with the inadequacy of the available tracks to handle the rakes.

5 PROPOSED SYSTEM DESIGN

Based on the analysis of the scenarios, it was evident that the tracks in the Yard 1 area were not able to handle the incoming rakes. An increase in number of tracks could be a solution to the problem but such a solution was not feasible in the given case as there was a scarcity of land available for expansion. Thus it was decided to change the system design as well as the scheduling of the incoming rakes to their respective unloading sites so that the traffic at Yard 2 could be reduced by diverting some of it away from the Yard 2 area. The following changes were proposed:

- **Modernization and Positioning Changes-** The existing 5 coal tipplers will be discarded and two new high capacity coal tipplers will be installed at a new location such that the rakes can move directly to the new tipplers without going through Yard 2, which was the hub of many unloading facilities in the existing system. Moreover the new tracks could handle one full rake length of coal rake, saving unnecessary handling time. Adding two new coal handling tipplers will cost $7.2 million and additional tracks will require a further $3.2 million.
- **Process Improvement-** These new facilities mentioned above will receive materials through electrified tracks and thus the external railway locomotives would be able to move the rakes directly to the unloading stations inside the plant, further reducing the waiting times.
- **Scheduling-** Both iron ore and coal carrying rakes will have a priority scheduling instead of first come first serve basis policy. With modernization, track electrification and location changes, the waiting time of iron ore and coal carrying rakes could be reduced. This made priority scheduling for coal and iron ore carrying rakes more feasible.
- **Capacity Addition-** With the proposed changes in scheduling, the waiting times for iron ore rakes may increase in Yard 1. As a new hub of coal tipplers was proposed to be developed; it

could be utilized for adding additional unloading facilities for further easing the congestion. Thus one new iron ore track hopper was proposed to be installed in the same area. The existing iron ore track hoppers were not discarded. Adding the iron ore track hopper will cost $4 million and the additional tracks will require an investment of $1.6 million

The previous proposals of electrifying tracks till the beginning of the old iron ore track hoppers, using the external locomotives for in-plant movement and changing the exit route of iron ore carrying rakes will be retained which would incur a cost of $1.6 million. The proposed changes along with the previously proposed scheduling and movement changes were aimed at diverting rake movement through a new route, and also reducing the process time for in-plant movement. Making the total changes would involve a capital investment of $17.2 million.

Figure 6 below shows the layout of the proposed RMUY system. There are four track hoppers for unloading iron ore rakes namely track hopper 1 (TH1), track hopper 2 (TH2), track hopper 3 (TH3) and track hopper 4 (TH4). There is one tippler for unloading coke rake that is coke tippler. There is one tippler for unloading calcining plant (CP) limestone rakes that is wagon tippler 3 (WT3). For unloading sinter plant (SP) limestone rakes there is one tippler called Flux Tippler 1. For unloading coal rakes there are two tipplers namely wagon tippler 1 (WT1) and wagon tippler 2 (WT2). The rakes come from two source stations. The inbound rakes coming from the source stations arrive in Yard 1. This yard has same number of tracks as before. Iron ore rakes go to the unloading facilities. Coke and sinter plant limestone rakes go to Yard 2. Unloading of coke and sinter plant limestone takes place in this yard. The empty iron ore rakes return to Yard 1, from where they go back to the source station. In this design one iron ore facility (TH4), coal and CP limestone unloading facilities are positioned such that it can reduce the congestion in Yard 1 as well as Yard 2. New electrified tracks have been made so that some iron ore, all coal and all CP limestone goes to Yard 4 without going through Yard 2 and Yard 3.

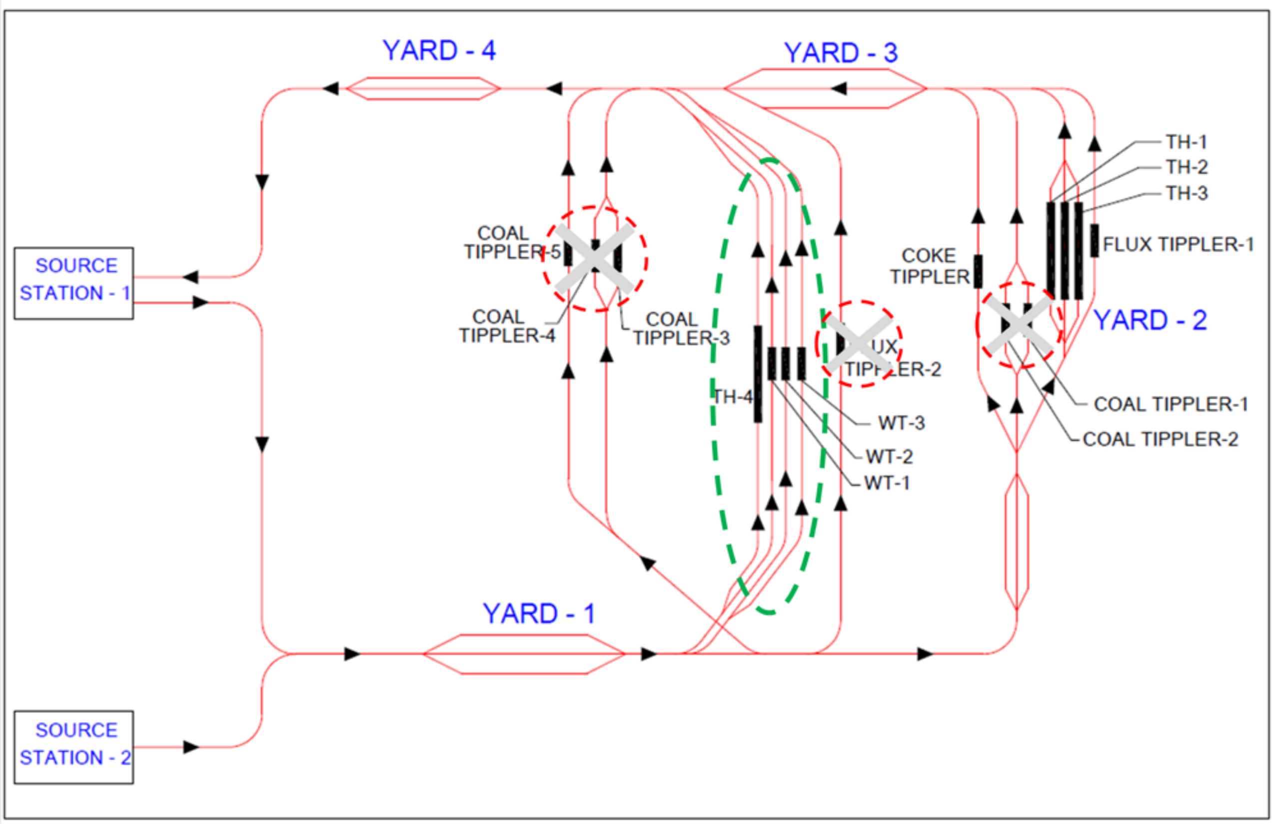

Figure 6: Layout of the proposed RMUY

The empty rakes of SP limestone and coke first go to Yard 3. They wait there and go to Yard 4. The empty rakes wait until they get a green signal to move to the source destination.

As the new system had several changes in layout and routes, a new simulation model was developed to understand the adequacy of the proposed design in handling the unloading capacity.

5.1 Results of Simulating the System with Proposed Design

The simulation model showed that the proposed system was capable of handling the increased inbound raw material rakes required for the capacity expansion. The quantity unloaded on running the simulation for one year matched the requirement as was provided in Table 1- 'Material handling required- Current and After Expansion'. Moreover in this new system design, the wait times at Yard 1 for the rakes decreased as compared to wait times at Yard 1 in the current plant design as shown in Table 5. This was because of the reduction in blockage at Yard 2 and more availability of tracks and locomotives.

Table 5: Rake throughput time in the proposed design

Material	t0 Arrival at Yard 1 to release of railway engine	t1 Release of railway engine to departure from Yard 1	t2 Yard 1 to track hopper/ tippler	t3 Unloading	t4 Unloading completion to handover to Railways	T (t1+t2+t3+t4)
	(in minutes)					
Iron Ore Lump	40	48	6	226	86	366
Limestone for SP	86	219	19	605	113	956
Coke	71	104	18	250	97	469
*New Tipplers of Coal(WT1, WT 2) and Limestone(WT3) receive rakes on priority & complete the unloading in standard times.						

5.2 Benefit Analysis

The proposed design was capable of handling the increased capacity, and importantly, was able to do so with minimum congestion in the yard. This reduction in congestion saved operational costs that would have been incurred in paying the demurrage charges to the external railway agency.

The capital investment required for enhancing the capacities using analytical approach was found to be $11.2 million as shown previously in Table 2. In the simulation model for existing system, the number of iron ore track hoppers was increased by two in accordance to the solution provided by the traditional analytical approach. Two track systems which led to these track hoppers were also added. The results of the simulation showed that such a design would have led to an average of 14.5 hours of demurrage for coal carrying rakes which amounted to incurring operational costs with an inflation adjusted value of $29.9 million ($1.48 million each year for 25 years). In the proposed design the time a rake spent in the system reduced and no demurrage occurred. Implementing the proposed layout changes in the RMUY will incur an investment of $17.6 million as discussed previously and given in Table 6.

Table 6: Cost of capacity expansion in RMUY using hidden capacity analysis through simulation

Facility	Cost	Quantity Required	Investment Required
Iron Ore Track Hopper	$ 4 million	1	$ 4 million
Track Systems for Track Hopper	$ 1.6 million	1	$ 1.6 million
Track Hopper Augmentation	$ 1.6 million	1	$ 1.6 million
Coal Tippler	$ 3.6 million	2	$ 7.2 million
Track Systems for Coal Tipplers	$ 1.6 million	2	$ 3.2 million
Total			$ 17.6 million

As no demurrage is incurred, \$29.9 million of operational costs will be saved by implementing the proposed changes. The total benefit incurred by using the proposed design over the existing system was calculated to be \$23.5 million as shown in Figure 7.

$$\text{Costs saved} = PV(\text{CAPEX saved})_{[\text{Equipments}]} + PV(\text{OPEX saved})_{[\text{Demurrage reduction}]}$$

$$= \sum_{n=1}^{25} \frac{Capex}{(1+r)^n} + \sum_{n=1}^{25} \frac{Demurrage\ Cost\ Saved}{(1+r)^n}$$

Discount Rate(r) = 9%

Capex Data

Iron ore track hopper	= \$4.0 million/unit
Track systems	= \$1.6 million/unit
Track hopper augmentation	= \$1.6 million/unit
Coal tippler	= \$3.6 million/unit
Track systems	= \$1.6 million/unit

Opex Data

Coal capacity per rake	= 3500 tons
Average coal rakes per day	= 4
Demurrage charges	= 0.02 \$/ ton /hr
Demurrage inflation rate	= 7%
Avg. no. of demurrage hrs saved	= 14.5 hrs/rake
Daily Demurrage Cost	= \$4,060
Annual Demurrage Cost	= \$1.48 million

$PV_{\text{Iron ore capex benefits}}$ = **\$04.0 million**

$PV_{\text{Coalcapex benefits}}$ = **-\$10.4 million**

$PV_{\text{Opex benefits}}$ = **\$29.9 million**

$\sum PV_{\text{Benefits}}$ = **\$23.5 million**

Figure 7: Calculating the benefits of using the proposed design

6 CONCLUSION

The paper presents an approach that leads to a few noteworthy conclusions. Traditional approach to capacity addition focuses on increasing capacity without investigating hidden logistics capacity. If these hidden capacities are not properly explored, it may lead to significant operational costs in future. In this particular case of capacity expansion of a raw material handling yard, it was expected that an increase in number of unloading facilities and/or number of locomotives will be sufficient for handling the increased material arrival. But on simulating the existing system with to-be unloading requirements, the tipplers and track hoppers showed very low utilization. Following a structured methodology that focused on investigating turnaround and waiting times, insights into rake availability and facility capabilities were drawn. A fourfold method of changing scheduling, movement routes, improving processes, and incremental capacity increase was undertaken, and significant improvements were achieved. The augmented system was capable of handling a significant increase in iron ore unloading capacity by making some operational changes and extending the track electrification. Further increase in unloading capacity for coal and coke tipplers was attained, by undertaking modernization and discarding old tipplers and adding two new high capacity ones at a different location such that material flow could be seamless in the system. One more iron ore track hopper was added to handle additional rakes of iron ore reducing further congestion. By reducing congestion in tracks, the operational costs in the form of demurrage charges were saved, which led to a saving of \$29.9 million over a period of 25 years. This methodology lead to benefits worth \$23.5 million compared to the traditional analytical approach. The proposed system is currently under implementation by the manufacturer.

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