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OPTIMIZATION APPROACH FOR MULTI-LAYOUT CONTINUOUS CASTED BILLET STORAGE AND INSPECTION WAREHOUSE

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Abstract: *In the present work, we propose an interactive approach for multi-layout electric steelwork shops expedition areas where casted round billets are stored in order to be cooled, inspected and loaded into means of transportation to be sent to the beneficiary. Even though this study was made referencing an electric steelwork shop in southern-Romania, the approach is universally available for multi-layout continuous casting billet warehouses where billets are handled using yard cranes or overhead bridge cranes. From an analytical standpoint, we use Arena Simulation to model the discrete event logistic system where entity flow through the system is described using a Poisson distribution and processes cycle time is described using a Normal (Gaussian) distribution. First of all, our study focuses on the optimal crane configuration or maximal number of billets to be handled to ensure a balance between the crane's cycle and process waiting time. From this end, having as input data the current steel mix and the demands for the length of the cut bars, a proper storage location logistics is explained based on the crane's travelling time and the number of cycles required to unload different configurations of billets. Finally, for proper production scheduling based on expedition priorities, a dimensional analysis model is presented where two total crane travelling distance formulas are derived. Using this model, complete cycle time can be predicted for any storage location. This approach made an overall improvement potential of 10% of the shipped output capacity for our reference case study.*

Key words: *Discrete event logistic system, normal distribution, Poisson distribution, process analyzer, storage location logistics, complete cycle time prediction.*

1. INTRODUCTION

Worldwide steelwork shops cast liquid steel into semi-finished casting products (billets, blooms or slabs) to be sent for further processing like rolling into plates, sheets, strips, coils, billets, bars or rods.

A steelwork shop warehouse can be defined as a diffused manufacturing system with more than two working points (single or multi-casting machines with Inspection and expedition areas) connected by transport and transfer systems like Overhead Bridge Cranes (OHBCs) or Yard Cranes (YCs) that can move vertically and horizontally along the racks, using work in progress (WIP) buffers (different configurations of storage racks organized in a cross isle storage and retrieval way) [1, 2]. The complexity of the system and uncertainty of the processes structures allow us to define a steelwork shop warehouse as Discrete Event Logistic system (DELs) [3]. The operation of such warehouses can be distinguished as manual picking picker-to-parts, where products are handled by manually-operated cranes and the material flow through the system is continuously altered by the functional constraints imposed by the linearity of the processes of the architecture. The casted products material flow through the warehouse can be defined as a discrete material flow based of distinct and countable entities (casted products of different geometric and size configurations), circulating between a creation point (the output of the Continuous Casting Machine - CCM) and a dispose point (batches of entities loaded into means of transportation at the output of the warehouse) with fixed trajectories and deposits at local or system level [4].

Multiple optimization approaches were studied for optimizing general warehouses efficiency. According to the optimization target, we can divide algorithms in path optimization algorithms (storage assignment problem in terms of travel distance and order retrieval time through simulation study) [5], line sequence optimization in terms of sequencing of picking lines within a batch [6] and dispatch or order priority processing algorithms (process time reduction, scheduling orders and identifying deadlines) [7]. All this algorithms represent functional remodeling algorithms, consisting of changing the order of some operations or changing cycle times [8].

Prior to any manufacturing or logistic system, a simulation for the existing material flow is required to identify efficiency problems. A lot of simulation software is available for modeling material flow [9], the purpose being to achieve an optimum configuration for the system, regarding machines placement, order of processes and other factors involved in the architecture [10].

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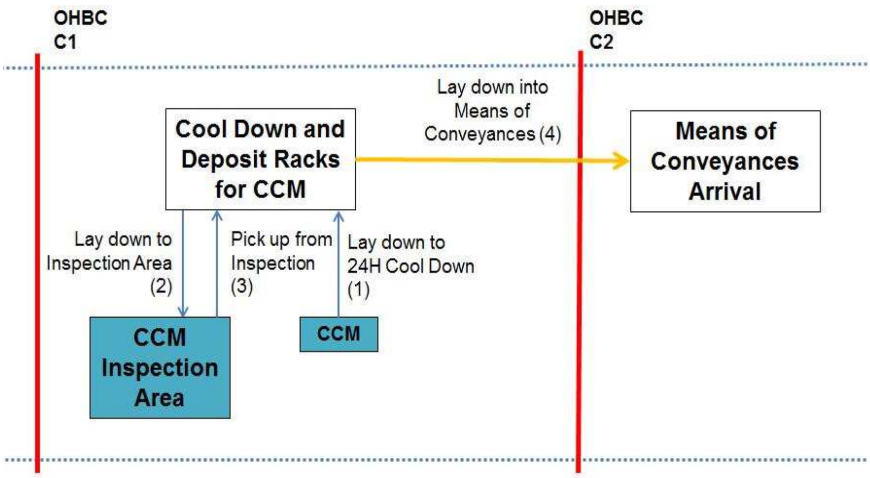

Fig. 1. Single-casting machine with internal shipment area.

Multidimensional analysis represents the capability to output software simulation data into information suited for the analysis of logistic system performances [3]. Using integrated or third-party data analysis tools, output data resulting from single or multiple replications of the simulation model can be organized in the form of one or several response variables in order to derive statistical data.

An optimization approach that can be divided in analytical and multidimensional analysis algorithms is proposed. First, a crane cycle time prediction algorithm using a normal distribution is presented [11]. Next, entity creation is described using a Poisson distribution [12, 13]. Having all this input data, a simulation model to determine the optimal configuration of a crane (handling capacity in relationship with process waiting time) is built. For the given optimal crane configuration, using a second simulation model, a path optimization algorithm is discussed for unloading the full capacity of one storage area. Finally, using a dimensional approach, a complete cycle time prediction theory based on the crane movements and the processes cycle times is explained. The model can be further used for dispatching and ordering priority processing.

2. GENERAL LAYOUT FOR ELECTRIC STEELWORK SHOP EXPEDITION AND STORAGE AREAS

In any steelwork shop, continuously casted products (billets, blooms or slabs) are usually stored and inspected in a common working space called the Expedition area. Here, OHBCs or YCs use magnetic or cable spreaders to handle products. The configuration of this Area (Figs 1 and 2) depends on the number of casting machines: single casting machine with internal shipment loading area or multi-casting machines (Fig. 2) with external shipment loading area. A complete material flow in these areas usually consists of 5 processes:

1) Picking up bars from the caster and laying them down into storage racks for a cooling period;
2) Laying down cooled bars from their storage rack to the Inspection Area;
3) Picking up inspected bars from the Inspection Area and laying them down to intermediate storage racks;
4) Laying down bars from intermediate storage racks to means of transportation to be shipped to the beneficiary.

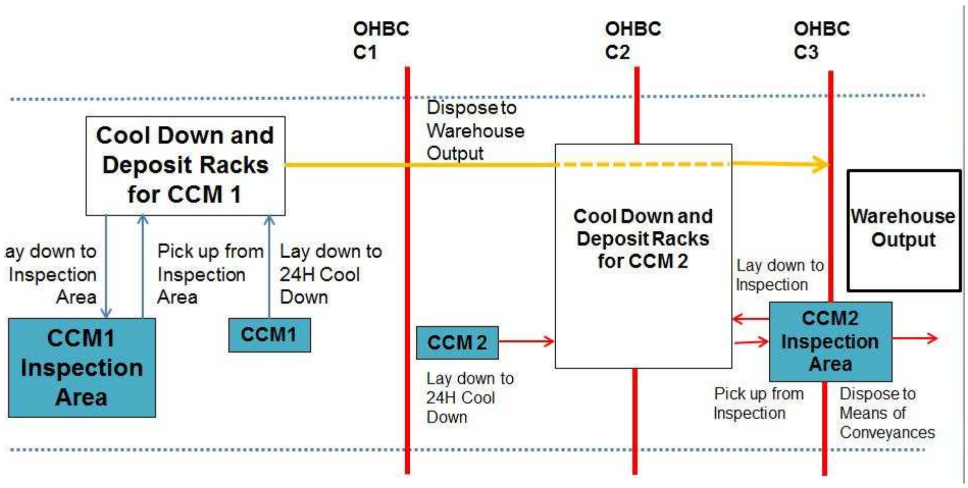

Fig. 2. Multi-casting machine with external shipment area.

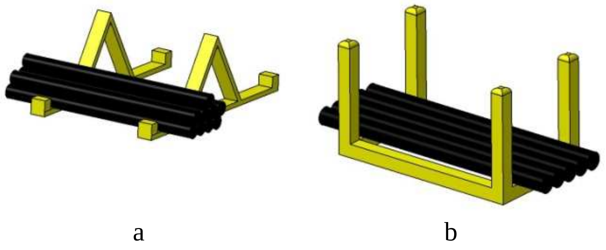

Fig. 3. Types of beam storage racks: *a* – triangular; *b* – rectangular.

Storage and Work In Progress (WIP) buffers are usually under the form of triangular beam storage racks (Fig. 3,*a*) or rectangular beam storage racks (Fig. 3,*b*) positioned in one single area or in multiple areas depending on the configuration of the warehouse.

Both rack configurations are limited by the length between the beams and the maximum allowable storage capacity (in tones).

In our reference case study the main continuously casted products are round section billets of different geometric configurations.

The crane configuration studied is an OHBC (Fig. 4), equipped with two rows of magnetic spreaders supported by two hanger chains. In this configuration, the crane has 4 degrees of mobility:

- Gantry travel (*Tz*);
- Trolley travel (*Ty*);
- Hoisting the spreader up or down (*Tz*);
- Wheeler roll around *Z* axis (*Rz*).

The handling capacity of the crane is limited by the electromagnet's length and the overall handling capacity.

To withstand the heat impact caused by hot billets to the electromagnets and for safety reasons, the crane will wait for the next process in a stationary position found near the center point of the warehouse. From this position, the crane operator has a clear view of the operations, avoids placing the spreader over workers and avoids overheating the electromagnets by the heat generated by recently casted products.

3. COMMON DELAYS AND SYSTEM BOTLENECKS

Being described as a process with high productivity, the material flow rate resulting as output from a casting machine requires a proper handling logistics in order to avoid system bottlenecks. As noticed earlier, the general layout of an Expedition Area can consist of multiple cranes sharing the same runway beam. Each crane is assigned to a specific operation. For example, in a two crane layout (Fig. 1), crane 1 is used for handling billets between the first three processes while the second crane is used for shipment loading. Other configurations (Fig. 2) use multiple cranes to complete only the cooling and inspection processes, while other cranes pick up billets at the output of the storage area for shipment processing.

To avoid casting stops, process 1 has the highest priority. In some scenarios, due to the lack of empty storage racks, the crane operator will have to lay down hot casted bars in the working area of the second crane. In this case, the second crane operator will have to end its task and to pull the crane by the end of the runway to allow the first crane to lay down its load. Such scheduling problems can double the cycle time of one crane causing the loading performance to drop.

Another crane scheduling problem is common for multi-casting machine expedition areas. Considering that CCM2 has casting priority, production planning will have to assure that the cooling and storage capacity for the first machine is large enough as to handle WIP until casting breaks of the priority machine allow the second crane to handle the entire casted capacity of the first machine to the output.

Other performance drops can be caused by incorrect OHBC handling capacity (picking up too many or too less billets) as well as incorrect positioning of the billets in the available storage racks, leading to increased rack-unloading cycle times.

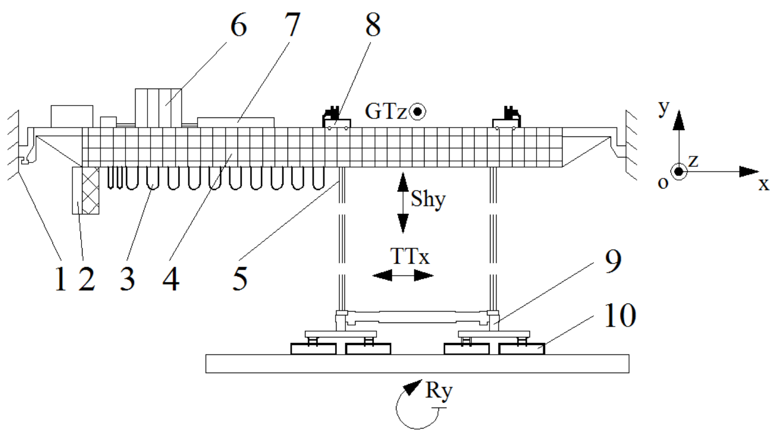

Fig. 4. OHBC configuration (1 – Gantry runway, 2 – cabin, 3 – electromagnet power supply cable, 4 – bridge, 5 – spreader hanger chain, 6 – electromagnet control panel, 7 – backup battery, 8 – wheeler, 9 – spreader, 10 – electromagnet, *GTz* – Gantry travel on *Z* axis, *Shy* = Spreader hoisting on *Y* axis, *TTx* – Trolley travel on *X* axis, *Ry* = roll around *Y* axis).

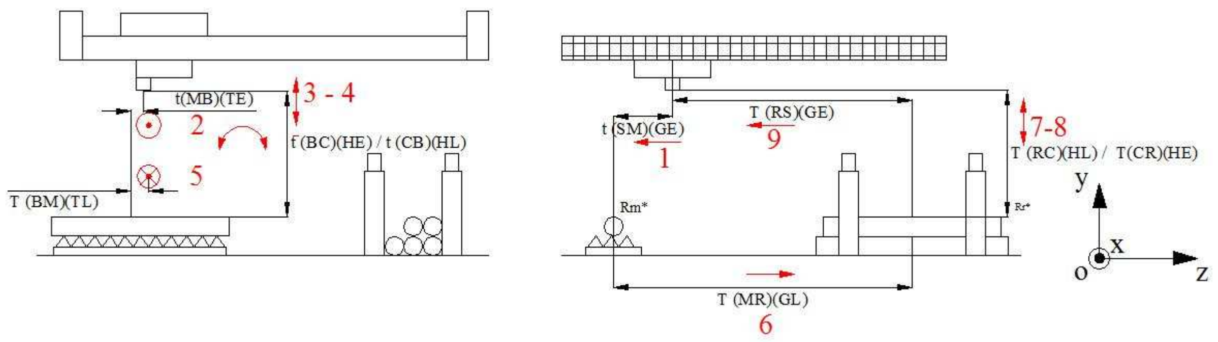

Fig. 5. Main range of movements for one cycle.

4. CYCLE TIME PREDICTION MODEL FOR GANTRY-TRAVELL CRANES

4.1 Cycle time definition

The cycle time of a working machine can be generically defined as the total time required for a machine to start and complete an operation, being a comprehensive way to determine the productivity of a manufacturing or logistic system.

Regarding OHBCs or YCs commonly used in electric steelwork shops warehouses, the cycle time can be divided into elementary movements. Expecting cranes equipped with Automated Storage and Retrieval Systems (AS/RS), gantry traveling cranes are usually manually operated, being hard to describe a cycle time as a constant value due to the uncertainty of the operator's decisions and movements.

In electric steelwork shop warehouses, two different types of handling equipment are usually used: YCs and OHBCs. The operations done by the crane can be divided in receiving operations where casted products are handled between the CCM and storage racks, handling and storage operations were cooled down products are handled to be inspected and stored and delivery operations, were conform casted products are loaded into means of transportation for final shipping.

Extensive cycle time analysis models were made for container terminals. However, similarities and differences between the range of movements and the technological equipment of the cranes were observed. For example, both handling operations use electromagnetic spreaders to handle products but in the case of electric steelwork shop warehouses, only Tchebycev movements (movement described as the sum of two or more movements) can be made due to the existence of an auxiliary *Z* axis roll.

4.2. Measurement chart

Our approach presents an elementary time analysis chart (Fig. 5) where the complete range of movements done by the OHBC in one cycle operation is divided into movements requiring constant and variable time to complete. Also, re-handling operations times are to be considered.

A measurement table (Table 1) is used to analyze one cycle time for the same handling position and operation. For the sake of efficiency, at least 5 on field measurements of the elementary movement times for the same

Table 1

Measurement results

Range of movement	Time m_1	Time m_i	Mean value (μ)	Std. Deviation (σ)
t (SM)(GE)	5	4	4.5	0.5
t (MB)(TE)	4	5	4.5	0.5
T (BC)(HE)	18	12	15	3
T (CB)(HL)	.	.	.	.
T (BM)(TL)	.	.	.	.
T (MR)(GL)	.	.	.	.
T (RC)(HL)	.	.	.	.
T (CR)(HE)	.	.	.	.
T(RS)(GE)	3	5	4	1
*Rm**	85	66	75.5	9.5
*Rr**	79	63	71	8
Cycle time (μ, σ)			174.5	12.8

traveling distances and handling operation should be made.

The following notations are used for:

- Basic handling elements:
  - *T* variable time between cycles;
  - *t* constant time between cycles;
  - R_r variable time required for positioning/rehandling of the billets in the storage rack;
  - R_m variable time required for positioning/ rehandling of the billets from the CCM;
- Type of motion:
  - *G* Gantry travel;
  - *T* Trolley movement;
  - *H* Spreader hoisting movement;
- State of Equipment:
  - *L* Loaded;
  - *E* Empty;
- Starting and ending positions:
  - *S* Stationary point;
  - *B* Boundary of a billet;
  - *C* Position of the spreader that is picking up or releasing a batch of billets;

4.3. Normal distribution description

Having all necessary analysis data, OHBC's cycle time can be described as a normal distribution. The normal (Gaussian) distribution is the most common way

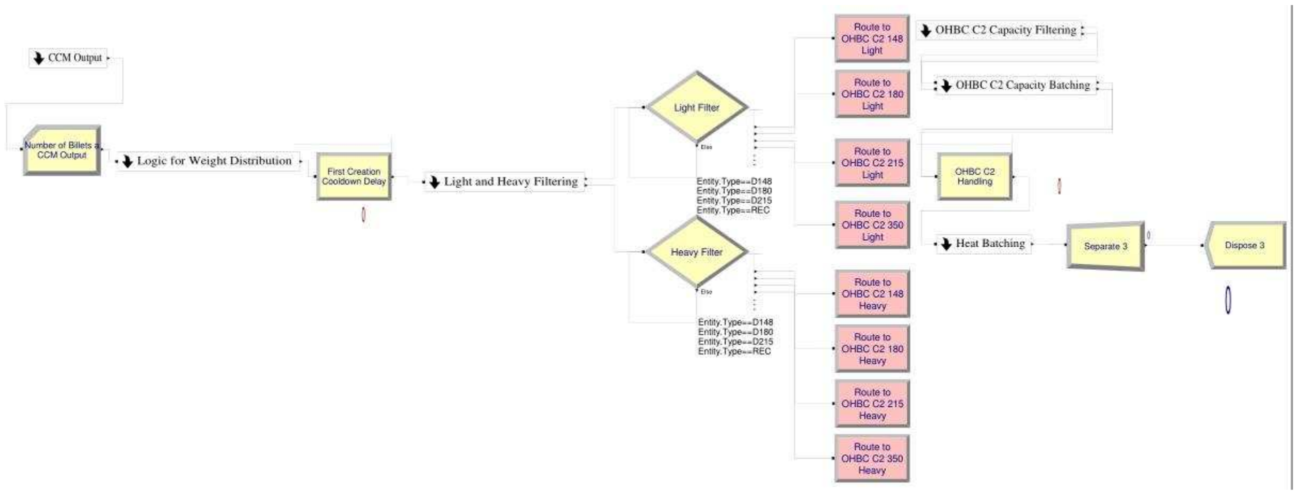

Fig 6. Optimal OHBC configuration simulation model.

used to characterize quantitative variations of original data, summarized using the arithmetic mean and standard deviation or standard error.

The mean value (μ) can be described by the formula:

$$\mu = \frac{1}{n}\sum_{i=1}^{n} x_i \tag{1}$$

and the standard deviation (σ):

$$\sigma = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i - \mu)^2} \ . \tag{2}$$

At first, we described resulting cycle times by a normal distribution. Later, doing a simulation study we concluded that the accuracy of the model was low. To solve this problem, we described each elementary movement as normal distributed independent random variables:

$$f(x,\mu,\sigma) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(x-\mu)^2}{2\sigma^2}} \ . \tag{3}$$

Finally, a sum of independent random variables that are normally distributed is also normally distributed, i.e. if:

$$X \sim N(\mu_X, \sigma_X^2) ;$$
$$Y \sim N(\mu_Y, \sigma_Y^2) ;$$
$$Z = X + Y ; \tag{4}$$
$$Z \sim N(\mu_X + \mu_Y, \sigma_X^2 + \sigma_Y^2) .$$

As a conclusion, 40% of the OHBC's cycle time represents gantry travelling times, while 60% represents rearrange movements.

It is important to notice that measurements were made when the crane was handling the maximum allowable capacity. Acceleration and deceleration of the bridge are not taken into consideration.

5. DISCRETE EVENT SIMULATION MODELS

5.1. Optimal OHBC typology for a given steel mix

To start the DELs simulation and optimization process, all data regarding entity creation, specific process cycle times and resources is required to be derived analytically, statistically or based on field data analysis. The dynamics of DELs on an event-by-event basis is defined in a discrete event simulation model by using the simulation software logic modeling capabilities.

We use Arena Simulation for building different simulation models.

The optimal OHBC configuration simulation model (Fig. 6) defines the logic and material flow of one cooling working cycle (Fig. 7) in a closed loop for the same storage position with a constant OHBC cycle time.

The model consists of 6 submodels where complex logic is defined. One submodel (the CCM output) defines the entity creation statistically, based on time and arrival rate described by a Poisson distribution (Fig. 8). For each entity type, a set of attributes like length or prediction of quality control conformity is defined for each entity created using a condition or decisional module. OHBC and first creation cooling delay processes are defined using constant and normal distributions (described in chapter 3).

The maximum number of billets allowed on the OHBC's magnetic spreader is limited by the maximum

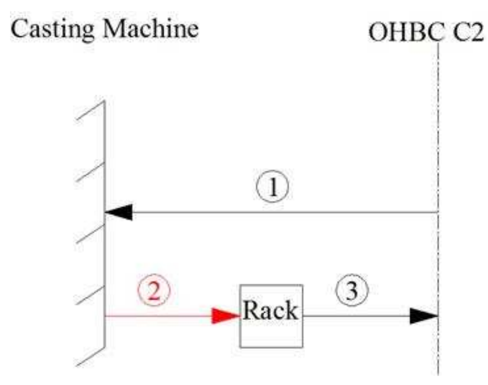

Fig. 7. One cooling cycle.

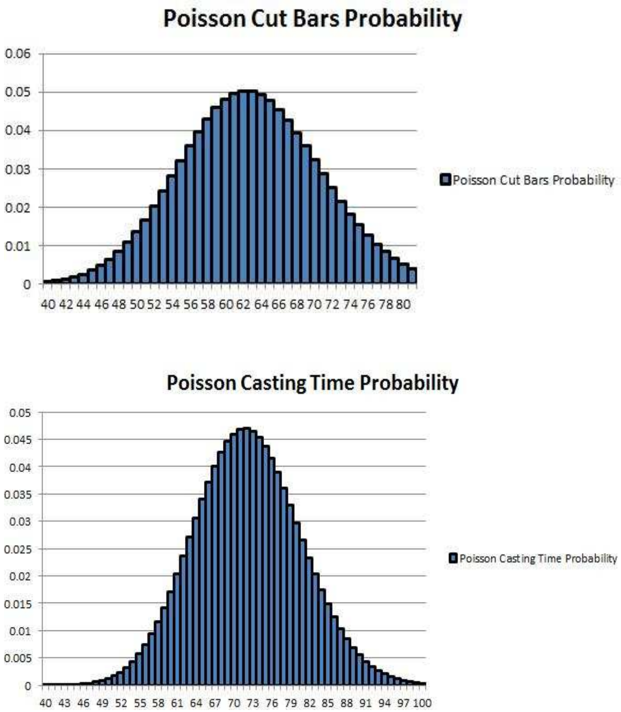

Fig. 8. Poisson cut bars and casting time probability distributions.

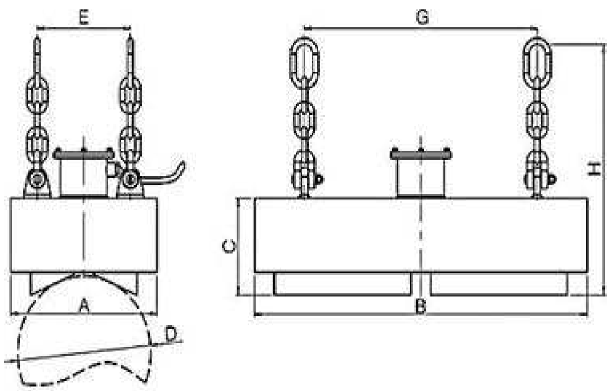

Fig. 9. OHBC magnetic spreader dimensional configuration *A* – maximum allowable handling length [mm], *B* – distance between magnets, *D* – maximum allowable diameter, *E*, *G* – distances between hanger chains, *H* – spreader height.

handling capacity of the crane and the length of the spreader (Fig. 9).

Knowing the average weight of each billet configuration, a simple mathematical formula can be used to estimate the maximum number of billets allowed on the spreader. However, a roundown function must be used as result, in order to obtain integer values representing the allowable capacity.

The programming capabilities of Arena simulation software allow implementing this function in the simulation model (Fig. 10) using ANINT command to round a variable and ABS to describe the absolute value of a number.

Further, an example is provided, where *v*1 is the estimated input capacity, *v*2 the round variable of the estimated input capacity and res the final rounded down output capacity.

```
START

v1 = 1.87
v2 = ANINT(v1)
v2 = 2
counter = v2 - v1
counter = 0.13
IS counter > 0
YES counter = counter - 1
counter= -0,87
Return to question
YES res = v1 - ABS(counter)
Res = 1

END
```

To analyze the performances of different OHBC configurations, variables defining the maximum handling capacity of OHBC and spreader length are initialized at the beginning of the simulation. Based on the roundown function, different capacity response variables will change the handling batch size for each billet type. A counter variable is used to count the number of cycle finished for the given simulation time.

For simulation experiments design, Arena Process Analyzer had been used.

An OHBC configuration typology is presented in Table 2.

For the given steel mix and the cut bars configuration at the output of the CCM, each crane typology is analyzed (Fig. 11).

Theoretically, an OHBC with a bigger handling capacity can improve productivity. In practice, the handling efficiency of a crane is a relationship between the handling capacity and the process waiting time (Fig. 12), or the time required for a given number of entities to exit the casting machine in order to be handled.

5.2. Unloading the full capacity of one storage area

Having as input information the estimated OHBC cycle time and percentages of the travelling and rearrangement movements for one given storage position (described in chapter 3), using a layout map or a predictive model based on on-field measurements of the effective distances for each storage position, a OHBC cycle time for any position can be estimated considering the rearrangement movements and gantry travelling speed as constants.

Table 2

OHBC typology

Overhead crane capacity [tonne]	Maximum handling payload	Spreader maximum allowable length (A) [mm]
12.5	7.5	750
15	10	750
15	10	1000
20	15	1000

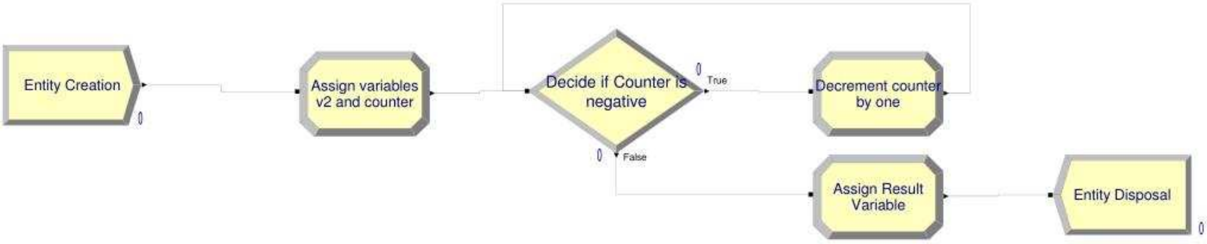

Fig. 10. Roundown function logic in Arena simulation.

	Scenario Properties				Controls		Responses			
	S	Name	Program File	Reps	Magnetic Spreader Maximum Allowable Length	OHBC C2 Handling Capacity in Tonnes	Charge Counter	148mm Heavy Handling Capacity	148mm Light Handling Capacity	180mm Heavy Handling Capacity
1		Scenario 1	17 : Algoritm	1	750.0000	7.5000	1460.000	4.000	5.000	3.000
2		Scenario 2	17 : Algoritm	1	750.0000	10.0000	1468.000	5.000	5.000	4.000
3		Scenario 3	17 : Algoritm	1	1000.0000	10.0000	1462.000	6.000	6.000	4.000
4		Scenario 4	17 : Algoritm	1	1000.0000	15.0000	1463.000	6.000	6.000	5.000

Fig. 11. Arena Process Analyzer for optimal OHBC.

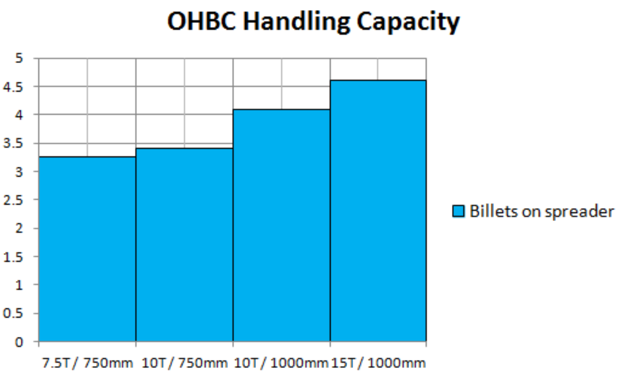

Fig. 12. Process waiting time for each OHBC typology. Minor axis = handling capacity for each spreader configuration (in tones), Major axis = maximum number of entities on spreader.

Table 3

Mean and standard deviation values for different storage racks

Gantry + Trolley Cycle	Mean	Standard Deviation	Rack	Cycles	Type of Charge Loaded
319.99	381.99	60.40	12	15	148 Light
398.41	460.41	72.80	30	11	148 Heavy
393.71	455.71	72.06	27	10	180 Light
315.29	377.29	59.66	9	14	180 Heavy

The mean and standard deviation values time for any traveling position can be determined as in Table 3.

The number of unloading cycles was determined for the crane typology which was selected as optimal in the previous chapter.

Using all this information, a distribution of billets into racks can be done based on the following logic:

- Billets with the shortest unloading cycle are stored in racks with the highest OHBC travelling time
- Billets with the highest unloading cycle are stored in racks with the shortest OHBC travelling time.

The simulation model (Fig. 13) uses hold modules to describe the racks and their unloading order. At the beginning, the hold modules are filled by a creation module. Filters are applied to avoid creating too many or to less entities.

The first entity created will pass through the rack 3 cycle assign module and change the cycle time for the OHBC process (Fig. 14). A counter variable will gradually release each hold module. For each iteration, the OHBC's cycle time shifts according to the OHBC travel time cycle and number of cycles required for rack unloading. Once all racks are unloaded, the simulation will stop and the total simulation time will represent the total unloading time.

Two scenarios for the same simulation model are presented.

At first, the racks are randomly filled based on the decision logic of the OHBC operator. The total unloading time was estimated at 62 hours. Next, the simulation for our distribution of billets logic is performed achieving an estimated 52 hours unloading time representing a 10 hour optimization.

6. DIMENSIONAL ANALYSIS FOR COMPLETE CYCLE TIME PREDICTION

The complete cycle time can be described as the time required for a casted batch of billets to be cooled, inspected and loaded into means of transportation to be sent to the beneficiary. Production planning and shipping priorities require a simple complete cycle prediction tool.

Being inspired from the dimensional chains tolerance analysis, our prediction model divides all the moves made by the OHBC in a full cycle in datum lines referencing OHBC travelling distances between elements of

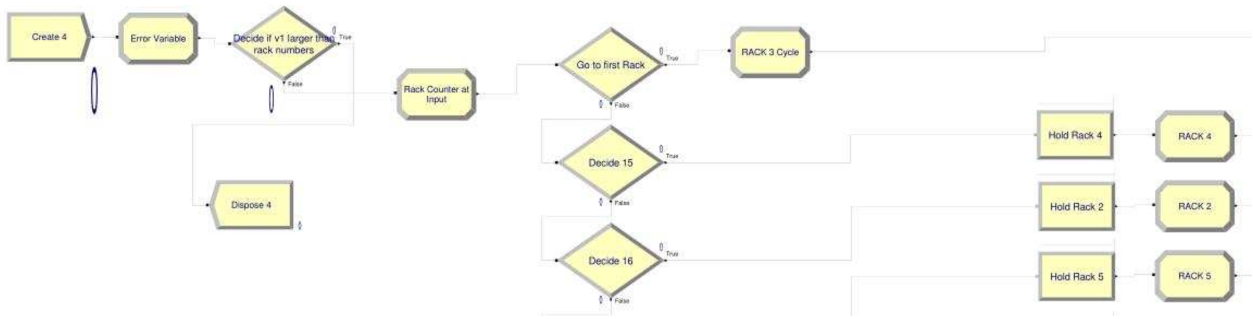

Fig. 13. Rack unloading simulation model.

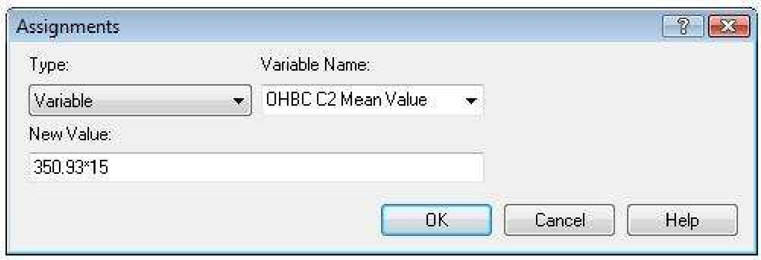

Fig. 14. Cycle time shifting variable.

interest (OHBC stationary point, CCM output, rack position, Warehouse output). Notations are used to simplify the model and determine formulas for delivering the total OHBC travel distance for one cycle.

An example for one area of a multi-casting machines layout (Fig. 15) is presented below.

The formula for the first case is:

$$\sum_{n=1}^{9} n = l+L+(3\cdot 2)+(6\cdot 2)+9= \\ (l+L)+2d+2D+E=a+2b+E. \quad (5)$$

where: $a = L + l$, $D = 3 + 7$ and $E = 9$

and for the second case:

$$\sum_{n=1}^{9} n = l+L+(3\cdot 2)+(6\cdot 2)+9= \\ (l+L)+2d+2D+E=a+2b+E. \quad (6)$$

where $b = d + D$.

As a preliminary conclusion, $2D$ datum line is slightly larger than $2b$, meaning that the smallest cycle time is for the second case.

Knowing the total travel distance of the OHBC for one cycle, the following formula can be used to predict the complete cycle time:

$$Tci = Nc\cdot(Tg\cdot Ts + R)\,. \quad (7)$$

where:

- Tci Total cycle time for rack i;
- Nc Number of cycles required to unload rack i;
- Tg Total gantry travel distance for rack i;
- Ts OHBC travel speed;
- R Re-arrange average time.

It is important to pay attention to the units used or to use conversion formulas for the final result.

An example is presented below:

$$\begin{aligned} &a = 93200+3300;\\ &D=(4400\cdot 9)+(1000\cdot 8)+2000+(\frac{14200}{2});\\ &E=(\frac{14200}{2})+25600;\\ &Tg36=\frac{a+2D+E}{1000}=242.6m;\\ &Tc36=14\cdot(Tg36\cdot 2+62)\cdot 0.000277=2.122h. \end{aligned} \quad (8)$$

7. TECHNOLOGICAL IMPROVEMENTS

Technological improvements consist of reconsidering all the manufacturing system structure. Equipment used is either upgraded or changed with new one and transfer and transport facilities are modified to increase the overall productivity of the logistic system. The use of such techniques asks for a proper cost analysis to be done to compare the initial investment to the productivity increase.

One observation made during on-field data acquisition regarding OHBC cycle times was that 60% of the time of a cycle consists of rearrange movements. Most of these auxiliary movements were caused by the axial sway of the spreader generated at hoisting down movements at slow linear motions. To overcome this fault, different patents of sway reduction devices have been studied.

One feasible solution uses a hydraulic sway feedback device (Fig. 16) consisting of a double-rod hydraulic cylinder mounted to a centered grunion.

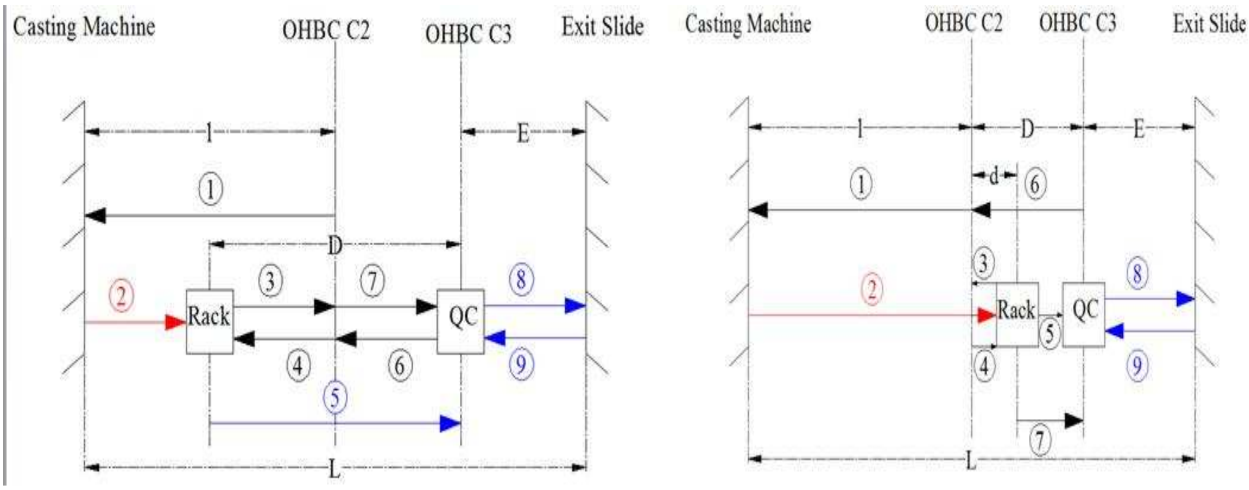

Fig. 15. Dimensional analysis model.

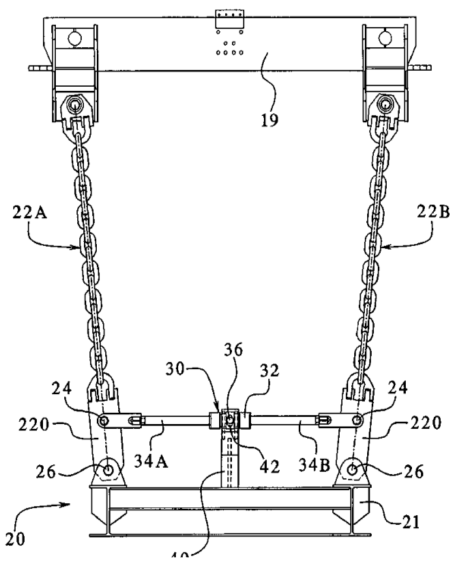

Fig. 16. Hydraulic Sway Reduction Device [14] (19 – supporting beam, 20 – spreader, 21 – corner of the main frame, 22A, B – hanger chains, 24 – rod attachment points, 26 – pivot, 30 – dampener, 30, 32 – double-rod hydraulic cylinder, 34A, B – rod, 36 – pin).

This device works on the principal of hydraulic balance, rods of the pistons extending in opposite directions. The flow resistance of the assembly is limited by two pressure limit valves connected to the end of the cylinder. The trunion provides a floating joint, allowing free vertical movement of the cylinder with respect to the spreader.

It also holds the cylinder to a later direction that also permits some pivotal movement preventing bending stress generated during the sway action to damage the piston.

8. CONCLUSIONS

This paper presents a universal optimization approach for multiple layouts of electric steelwork shop warehouses. First of all, analysis input data is derived statistically, understanding the complexity of the system. Secondly, simulation models are used to describe the material flow, processes and the use of resources. All output data is used to analyze different optimization scenarios. Lastly, a complete cycle time analysis model based on OHBC path and cycle time is presented. Using simulation and analysis methods, an overall productivity increase of 10% can be achieved for our reference case study.

The results of the multidimensional analysis can be further used as input data for dispatch and order priority processing. Another further approach to be considered is the path fallowed by the OHBC crane operator during one cycle. Probabilistic path optimization techniques like the Ant Colony Optimization algorithm can be used to determine the shortest path between cycles and further reduce cycle times. Result of such analysis could be discussed using a multipolar simulation model.

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