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Planning Smelter Logistics: A Process Modeling Approach

Ingo Eick and Detlef Vogelsang
VAW Aluminium-Technologie GmbH
Bonn, Germany

Andrae Behrens
Gesellschaft für Prozeßautomation & Consulting mbH
Chemnitz, Germany

Abstract

A dynamic logistic model, based on High Level Petri Nets, was generated to aid the planning of potroom activities, potroom traffic and logistic equipment needed for a smelter expansion project. This model includes all relevant pot-tending operations, such as anode changing with cavity cleaning and covering, metal tapping, alumina feeding, beam raising, bath tapping, pot stoppage and start-up, gantry transfer and crane maintenance exchange.

The workflow and traffic patterns in the smelter were simulated to analyze equipment utilization and bottlenecks. The rule-driven model incorporated such features as operation scheduling, collision detection as well as the entire material handling process. Pointers for the optimization of the potroom layout, e.g. the consequences of an additional passageway, could therefore be deduced. This discrete event simulation predicts the capacity utilization of logistic equipment, like cranes and service vehicles.

A visualization tool provides a dynamic follow-up to all simulated procedures and traffic activities of the model.

Introduction

If not well organized and suitably equipped, pot operations, such as anode changing, metal and bath tapping, cutting out and restarting pots, can result in backlogs due to bottlenecks in using cranes, forklifts and other logistic equipment. On the other hand, decisions about carrying out an upgrade to overcome such bottlenecks are associated with tremendous costs. Furthermore, due to the complex interdependencies which exist in the use of logistic resources, there is often no clear-cut way of finding the most efficient investment plan. A simulation model is therefore a useful aid to the decision-making process. The main goals of simulating complex logistic systems are to safeguard investment decisions, shorten development cycles and optimize potroom operations. When applying such a simulation model, statements about the dynamic behavior of the system can already be deduced during the planning phase. Based on the information obtained, the optimum variants regarding the static system structures and the dynamic processes in the system can be determined.

This particular simulation was carried out for a smelter expansion project which expanded two potrooms from 60 to 90 pots each. The detailed course of the smelter is shown in Figure 1. It was used for the evaluation of the traffic frequency and identifying vehicle collision conflicts. The original smelter comprised two potrooms with a total of four sections (Section 1, 4, 2, 5). The additional 60 pots were housed in Sections 3 and 6, see diagram. The rodding shop, storage areas, casthouse skimming station and an outside network of roadways were also included in the simulation model.
The expansion resulted in a 50% higher workload for the central units, e.g. the casthouse, skimming station and rodding shop, as well as for the roof filling station for the cranes. A decision about installing additional cranes can therefore be made by taking the use of a dense phase system, optional tapping and tending vehicles and an additional gantry connection into consideration.

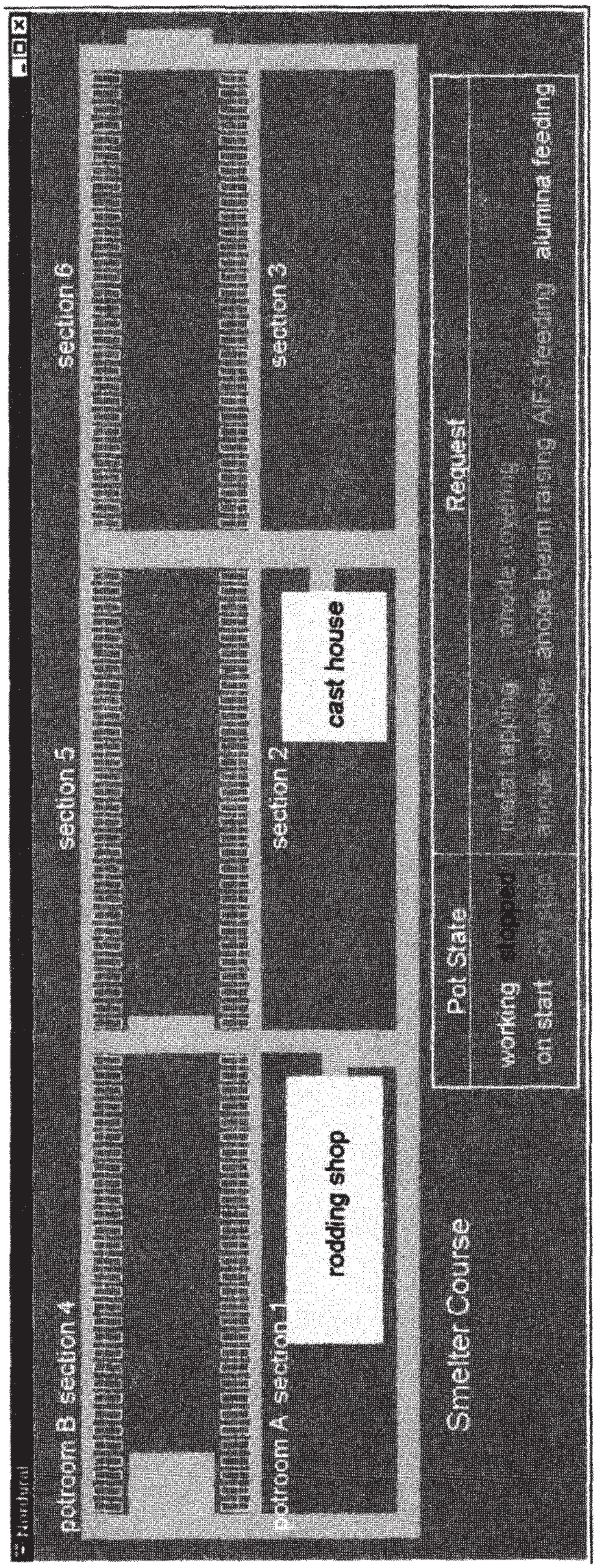

Figure 1: Course of smelter model.

The model shall determine the workloads of the cranes and vehicles. These figures can be used for the verification of the model as well as for comparison with different configuration set-ups. The definition of workload as used in this context is shown in Table I, taking the time-averaged utilization of a crane as an example.

Table I: Workload definition

Maintenance	Possible utilization				
	Actual utilization				Break down
	Workload		Idle	Rest periods	
	Waiting	Active time			
7%	5%	70%	2%	15%	1%
Total workload (i.e. model simulation)			Not included in the model simulation		

In this context, the meanings of *workload* and *utilization* have to be explained. The real workload of a crane, i.e. when it is actually performing a task, is less than the actual utilization. When the crane is in transfer between the roof filling station and back, or during the driver's rest period, the crane cannot be used for any other task. It is therefore "occupied" for this duration. Crane maintenance is also included. in the model and added to the working time. But, as manpower is not taken into account in this simulation model, the driver's rest periods are not part of the modeled total workload.

As a result, the optimized demand of the transport units and equipment is defined, course bottlenecks are visualized and a model for supporting process improvements is built up.

Workflow

A huge logistic model is required to simulate the whole workflow pattern inside the potroom, including the traffic to and from the rodding shop, lining shop, maintenance shop and casthouse.

With regard to the original potroom with a total of 120 pots, 6 different types of material - namely AlF_3, alumina, anodes, bath, butts and metal - had to be taken into account. This material flow is handled by 4 cranes, 4 types of vehicle and other tools, such as jacking frame, pouring spout and lids. The anode rodding shop and casthouse were assumed to have unlimited storage space available.

The resulting daily work schedule comprises the metal tapping of 120 pots, the anode changing of 90 pots and feeding alumina twice to 120 pots; bath tapping and pouring is also scheduled for 20 pots. On a weekly basis, AlF_3 feeding is scheduled for 120 pots, beam raising for 10 pots with 1 pot stoppage and 1 start-up added to the work schedule. Equipment is shared for all these tasks.

Based on the original work schedule, all these tasks had to be enlarged in line with the expansion to 180 pots.

In order to simulate the workflow, all tasks had to be described in detail, down to each individual sub-step. The duration of each sub-step and the materials used had also to be determined, as well as the speed of the vehicles and cranes and gantries under different loads. These descriptions were subsequently condensed to program routines, which became the rules and conditions for the simulation program.

The simulation tool

High-level Petri nets are an ideal tool for these event-driven logistic problems. Therefore the software package POSES++ was chosen [1]. POSES++ is a modeling and simulation environment for discrete event systems with applications in the fields of logistics, communication systems, hardware design and the validation of algorithms.
The simulation system is rule based and derived from predicate-transition-nets (Petri-net), which were established in the last 40 years, [2-4].

The dynamic behavior of a model is governed by the principle of checking all rules in a parallel-acting simulation kernel before fulfilling each step of a task.

When developing a simulation model - which should be close to reality - the model designer has the complicated but challenging task of not only determining the essential states and activities but also identifying their interdependencies in the system to be simulated. He must then describe them by means of net elements and rules, see Table II.

Table II: Basic modeling elements

Rules and activities	Parts of the rules	States	Objects and data
Transitions	Arcs	Predicates	Tokens
Active elements for destroying and generating tokens on concession situations	Connectors between transitions and predicates; the whole set of arcs describe the firing rule of a transition	Buffer for tokens with sorting and access algorithms	Simple counter or complex data structures

To find the solution for each time step of the simulation more than 10,000 transitions had to be checked. This is applied by a so-called weighted matrix formulation. Based on this numerical approach it is possible to build-up a simulation model which is growing only linearly with the number of objects like pots, cranes and vehicles [5].

Smelter model

I) Tasks

The smelter model was generated on the basis of all operational tasks in the potroom. As shown in Table III, different and shared vehicles, additional equipment and materials are necessary for each task.
The description of each task, called a "module", is the source code of the model; it can be adapted to variable conditions by parameterized duration and masses.

Table III: Task list

	Tasks	Vehicles	Equipment	Materials
1	Metal tapping	Truck, PTM, GP, MTV	Crucibles, lids	Metal
2	Anode -, butt transport	LFLT,FLT	Palettes, trays	Anodes, bath, butts
3	Anode changing	PTM		Anodes, bath, butts
4	Anode covering	PTM		ACM
5	Beam raising	GP, PTM, FLT	Jacking frame	
6	Bath tapping	FLT	Bath crucible	Bath
7	Pot maintenance	PTM		
8	Crane filling	PTM,	Filling station	Alumina, ACM, AlF$_3$
9	AlF$_3$ feeding	PTM, GP	Hopper	AlF$_3$
10	Alumina feeding	PTM, GP	Hopper	Alumina
11	Crane maintenance	PTM		
12	Crane transfer	PTM, GP		
13	Pot stoppage	PCM, PTM, truck, LFLT, FLT	Crucibles, palettes	Metal, bath, butts
14	Pot startup	PCM, PTM, truck, LFLT, FLT	Crucibles, palettes	Anodes, metal, bath

ACM = anode cover material, FLT = forklift, GP = construction crane, LFLT = large 6t forklift, MTV = metal-tapping vehicle, PCM = 160t pot displacement crane, PTM = pot-tending crane.

Each task is defined down to its single sub-step, which includes the vehicles and tools used, the assumed duration and masses. All basic data were evaluated by means of measurements and discussions carried out on site.
Normally there are no mileage counters or active-time-counters on cranes and vehicles. Therefore, the database of the ELAS process control system, see [6], was used to determine the statistical average of unit operations. Based on the alarm signals and status messages, the realistic process duration, e.g. for anode changing, tapping and beam raising, was extracted and fed into the logistic model.
On average more than 30 scheduled anodes have to be changed in one section. Burn-offs require an additional anode change and are included into the anode change cycles as well as the resetting of misplaced anodes.
To take all these effects into account - without modeling all these additional work - the total time of a complete anode change cycle is divided by 30 to estimate the average time for a realistic anode change cycle. This time is used to determine the duration of a single anode change. The same procedure was applied to the metal tapping cycle and beam raising.

II) Course

The course of the smelter (Figure 1) contains two potrooms connected by 4 passages - one at the each end and two in between, at 1/3 and 2/3 distance. There is a gantry at the rectifier end (bottom) for crane exchange to the maintenance shop. A storage area for crucibles is located near the rodding shop in the rodding shop passage at 1/3 distance. Another storage area beside the rodding shop is used for the rack. There is a skimming station in front of the casthouse in the casthouse passage at 2/3 distance; skimming has to be carried before the metal transport vehicle enters the casthouse.

There is also a roadway outside which runs parallel to the potrooms and connects all the passages.

The geometry of the potroom, including pots, filling stations and aisles, as well as the vehicles and all accessories which are defined dimensionally exact. Conflicts caused by vehicles passing other vehicles or by crossing roads can be handled by the simulator.

All vehicle speeds are dependent on type, load and location. In addition to this, traffic and interaction rules for the cranes, e.g. to reach the roof filling station, are defined.

In Figure 1, a key shows the different color-coded states of the pots, e.g. working, on stop, on start, etc..

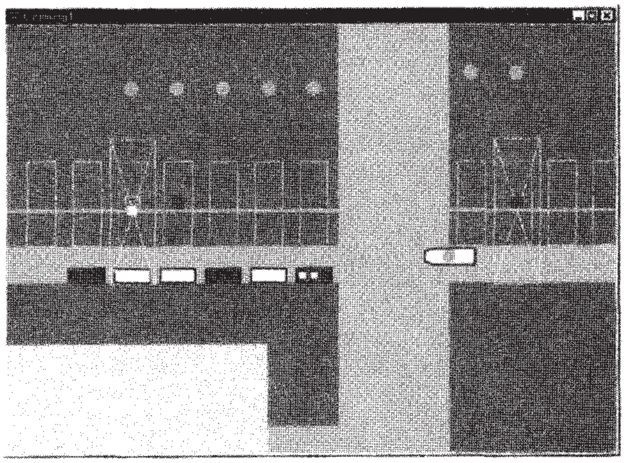

Figure 2: Detailed model view

A more detailed view, as given by the visualization tool, is shown in Figure 2. If a pot requests an operation, a colored signal light goes on, e.g. green for metal tapped and magenta for anode change, as shown in the key for Figure 1. On the right-hand side, a crane has just finished metal tapping and the truck is starting to bring the crucible to the casthouse via the skimming station. When metal tapping is finished, the hood is and the pot-control state changes, the green light goes off and a gray frame remains, indicating the normal operational state of the pot. On the left side, 3 palettes with anodes (green) and butts (red) can be seen in the aisle as well as 3 trays ready for picking up bath material from cavity cleaning. A crane is setting the anode in one pot while the next pot is already prepared for anode changing as indicated by the red square. This figure shows the detailed discretization and visualization of the logistic model.

Validation

In a modern smelter, the pot tending cranes have the heaviest workload. They are the most expensive tools and are restricted to moving backwards and forwards on the overhead rail. Overtaking is impossible. Furthermore, at least one special gantry is needed to remove a crane for maintenance. The workload of these pot-tending cranes was therefore the most important aspect to focus on.

The first aim was to ensure that the simulation model was able to predict the feasibility of the full work schedule in one shift for the existing potrooms.

The next detailed step was to compare the simulation results with the workload of a crane based on the average duration of unit times calculated from the pot control system. These data are displayed in Table IV. General pot operations and rest times had to be added.

Table IV: Nominal workload per crane per day

Task	Pots / day	Unit time [minutes]	Crane workload [%]
Metal tapping	120	9.5	19.8
Anode change	90	17.4	27.2
Alumina feeding	240	2.5	10.4
Beam raising	120 / 17	8.2	1.0
AlF_3 feeding	120 / 7	2.5	0.8
Crane maintenance	4 cranes /14	720	3.6
Total			**62.8**

As a result of running the whole potroom work schedule of 8 shifts or 96 hours in only 30 minutes of computer time, the workload of the cranes is added up for each crane based on the tasks performed. This workload, which depends on the interaction between the cranes and the floor vehicles, is shown in Table V. Different workloads for each crane are given depending on the crane's work schedule and its location in relation to the roof filling station or gantry. Cranes in the end sections of the potrooms have additional periods of waiting due to the longer vehicle traveling times.

Table V: Workloads of cranes from the dynamic model

Task	PTM1	PTM2	PTM3	PTM4	Average
Metal tapping	23.1	23.3	23.5	23.5	**23.4**
Anode change	29.9	30.3	36.8	29.9	**31.7**
Alumina feeding	14.2	10.3	11.8	12.9	**12.3**
Beam raising	1.5	2.4	1.3		**1.7**
AlF_3 Feeding	1.5	1.5		1.5	**1.5**
Crane maintenance		7.5	7.1		**7.3**
Total	**70.2**	**75.4**	**80.5**	**67.8**	**77.8**

The unbalanced total workload distribution of the cranes ranges up to about 15%. This causes anode changing backlogs in disadvantageous areas of the potroom whenever unexpected problems occur with pots or cranes. With regard to cranes with the heaviest workload, the ongoing crane maintenance program is important to ensure pot operation.

Compared to the nominal workload, there is a difference of about 18% due to various interactions with other tasks. For performing intensive tasks, like crane maintenance, beam raising and fluoride feeding, the duration is nearly doubled (see Table IV).

Traffic load on course

Depending on the tapping crucible size, the main traffic load is normally conditioned by the anode change cycle. Bringing anodes and getting butts and bath material from cavity cleaning generates the highest traffic density in the passageway to the rodding shop.

Because the full course is divided into separate paths between each intersection, the traffic frequency can be determined by counting the numbers of vehicles according to their type in the different paths during the simulation run. The resulting traffic frequency is visualized in Figure 3. Each path is therefore colored according to the local traffic frequency.

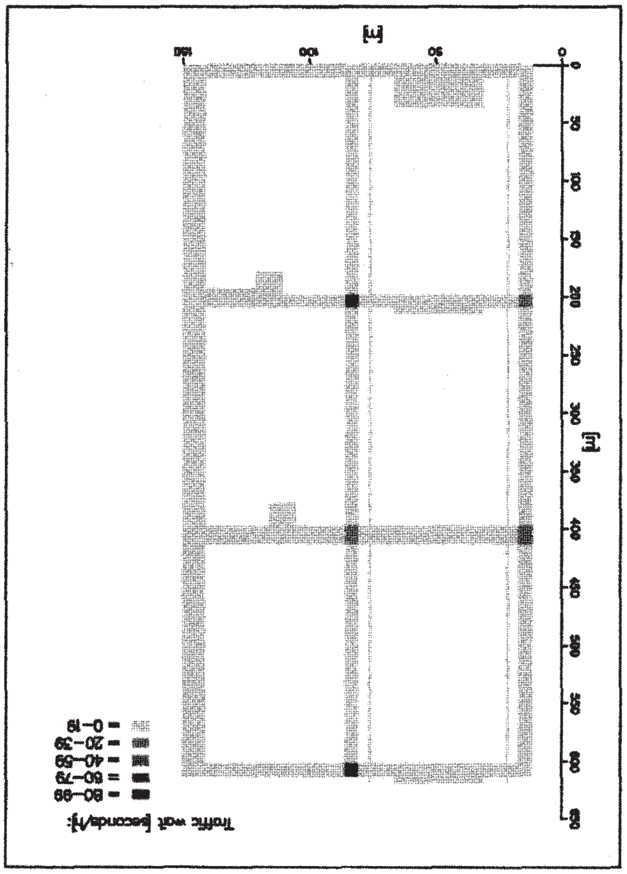

Figure 3: Traffic density on the course [Vehicles per hour].

Following expansion, the highest traffic frequency of 13-15 vehicles/hour is likely to occur at the entrance to the rodding shop. This value, however, is not a critical enough to affect normal smelter operation.

Figure 3 shows the importance of the outside connection between the passages. The aisle in the potroom is often blocked by operations so that the vehicle has to find an alternate way around. If a vehicle wants to enter a blocked aisle or a section where a slower vehicle is moving, it has to wait in the model until this area is free if no other way is available. The resulting waiting times are shown in Figure 4.

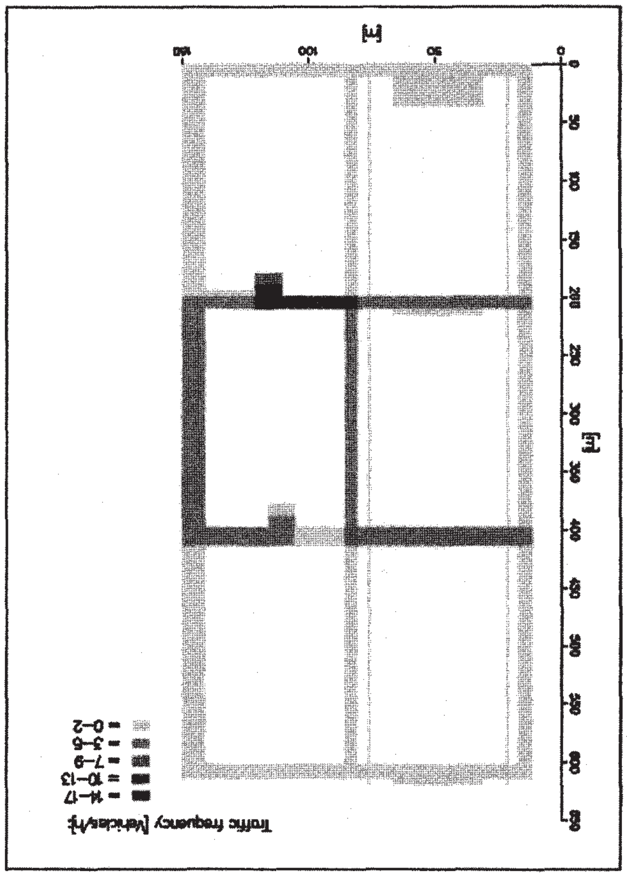

Figure 4: Traffic waiting time on the course.

In this case, no bottlenecks due to vehicles waiting could be seen after the smelter expansion.

At only one intersection did waiting times occur but these were too small to influence normal operations.

But this intersection is the most sensitive point of the course and is containing the general risk of becoming a bottleneck.

Results

To investigate the case of expanding this smelter from 120 to 180 pots, 3 main simulations were carried out:

a) Installation of a dense phase alumina conveying system,
b) Adding 2 PTM cranes,
c) Performing metal tapping by vehicles.

The results show the advantages and disadvantages of each option:

a) Installing a dense phase system without changing the number of pots reduces the high workload of the cranes by 12%. The risk of backlogs in alumina feeding, anode changing or other pot tending activities no longer exists. In addition, the much bigger alumina hopper could now be used for anode covering material.

b) The addition of two further PTM cranes for 180 instead of 120 pots increases the workload due to waiting at the roof filling station or crane exchange for maintenance. This results in an additional workload of about 10%. However, it should be noted that in this study no additional roof-filling station was added. Removing a crane for maintenance with the gantry at one potroom end is, however, extremely time-consuming.

c) The use of metal tapping vehicles uncouples the tapping from the other tasks in the potroom. This allows the overhead cranes to pass over the tapped pots for filling hoppers or to continuously treat sick pots. Despite expanding the smelter by 50%, the total workload of the cranes remains unchanged. The floor load, however, is an important point which has to be taken into account when deciding on this option.

Based on these results and with additional inputs, such as vehicle maintenance, pot tending and general traffic, a totally new configuration was finally decided on.

In addition to the dense phase system, a second gantry was installed at the other potroom end. Assuming one crane per section and additional one for maintenance exchange, 7 cranes in total are required. But, because metal tapping and anode changing are an alternating process and only one of these is done in a section per shift, the PTM and simple tapping cranes are laid out alternately. From shift to shift, the cranes move down through the potroom section by section then turn at the end into the next potroom. With this revolving configuration, each crane is automatically passing the maintenance shop where it is exchanged without additional transfer time. Furthermore, the cranes are restricted to one type of operation which lowers the cost for the additional cranes.

Conclusion

Based on a Petri net technique, the simulation of logistical requirements for the expansion of a smelter demonstrated that the workload of key components, such as cranes and vehicles, can be predicted with reasonable accuracy. The visualization of the traffic flow and pot-tending activities in quick-motion together with the analytical features of post-processing of simulation runs gives a profound insight in limiting resources and bottlenecks. This model is a basic tool for making decisions about capital investment projects, like the expansion of a smelter, and carrying out process optimization.

In addition to this, valuable information about the optimum layout of the smelter course can be gained. By adding personnel resources, this type of simulation model could subsequently be used for optimizing the shift schedules of the potroom personnel, as well as working out a realistic and objective estimate of the manpower needed to run the potrooms.

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