

Real life simulations in target environment as a means to optimize on continuous flow of material transport, evaluate different scenarios and potential impact of disturbances

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ABSTRACT

Future mass mining operations will have the opportunity to optimize on continuous flow of material transport over machine utilization and individual performance. Autonomous load and haul systems have the benefit of being predictable and controllable, which brings the possibility to optimize on a higher abstraction level. Not only will this bring more stability to the sensitive downstream processes, it will also potentially increase the overall productivity while reducing energy consumption. In a complex production environment, the optimal solution can sometimes seem to be counter intuitive, where it could be hard to value instantaneous productivity versus productivity over time.

Change management is necessary to transition from short-term detailed planning to a higher level of assignment abstraction. For example, multi-draw point to multi-dump point loading allows the automation system for the loader and auxiliary equipment to handle disturbances and obstacles such as boulders at the draw point and/or grizzly, deteriorated road conditions, equipment failure, etc.

We have discovered that training and optimization in a realistic simulation in the target environment are essential in this change management process. In such an environment, various mine layouts, production machine performances, and auxiliary equipment can be tested before actual mine development and equipment procurement. This way of working has also been instrumental for closing the gap between the mine operations and the autonomous system development, leveraging on the combined competences from the different disciplines.

This paper will show the potential of the autonomous load and haul systems combined with real life simulations to optimize continuous flow, evaluate different scenarios and potential impact of disturbances.

1 INTRODUCTION

Block caving is a high productivity mining method, ideally suited for automation. The use of autonomous load and haul systems offers significant advantages over manually operated machines.

The general nature of block cave mining emphasizes continuity and is ideally suited for a 'pull' approach starting from the end where the ore processing plants receives ore from, e.g. crushers connected via conveyor systems.

An autonomous load and haul system can maintain an optimal filling level in the ore bin, always ensuring a continuous flow. This can be achieved with a fleet of loaders that easily rotates between tasks in the production area and the service bay.

Connectivity, decent road conditions, dust suppression and a layout optimized for automation is essential to reach an even material flow. Shared areas such as meeting places, service bays, dump places along with curves

along the routes are subject for simulation before development to reach expected material flow.

Autonomous load and haul systems have been around for decades. Integrating tele-remote and autonomous auxiliary machines can contribute significantly to maintain high uptime for the autonomous solution and is also subject for simulations.

2 METHODOLOGY

The data in this paper is based on simulations using a map and routes from log data and experience from various autonomous mines, i.e. as authentic data as possible to represent block cave production.

2.1 Model set-up

Figure 1 is showing the used block cave layout in the simulations.

- Used extraction drives are 1 to 6 and they have prefix D, i.e., D1 to D6.
- Draw points heading west have prefix W and draw points heading East have prefix E.
- Used draw points are 03, 06, 07, 10 and 12.
- Used dump points are DP1 to DP3.

Machines bogging in D1 and D2 are dumping in DP1, machines bogging in D3 and D4 are dumping in DP2 and machines bogging in D5 and D6 are dumping in DP3.

- Machine in D1, M1 is named Mirella
- Machine in D2, M2 is named Mariam

- Machine in D3, M3 is named Elli
- Machine in D4, M4 is named Avin
- Machine in D5, M5 is named Sienna
- Machine in D6, M6 is named Josephine
- Mobile rock breaker, RB is named Jolie

Machines operating in autonomous mode are permitted exclusively within the safety system perimeter, represented by the light blue contour on the map.

2.2 Limitations, simplifications, and assumptions

To establish a benchmark for subsequent simulations, the following constraints have been applied:

- Average mucking time is set to 40 seconds.
- Average bucket weight is set to 15 tonnes.
- Dumping time is based on log data from real autonomous operation with three bucket shakes.
- Short stops due do network disturbances are set to 96 seconds per hour at an average for a system with 6 loaders.
- Short stops from the automation system, e.g. localization errors and dirt on sensors, are set to 110 seconds per hour as an average for a system with 6 loaders.
- The crusher is assumed to have 100% availability.
- Shift length is assumed to be 10 hours.

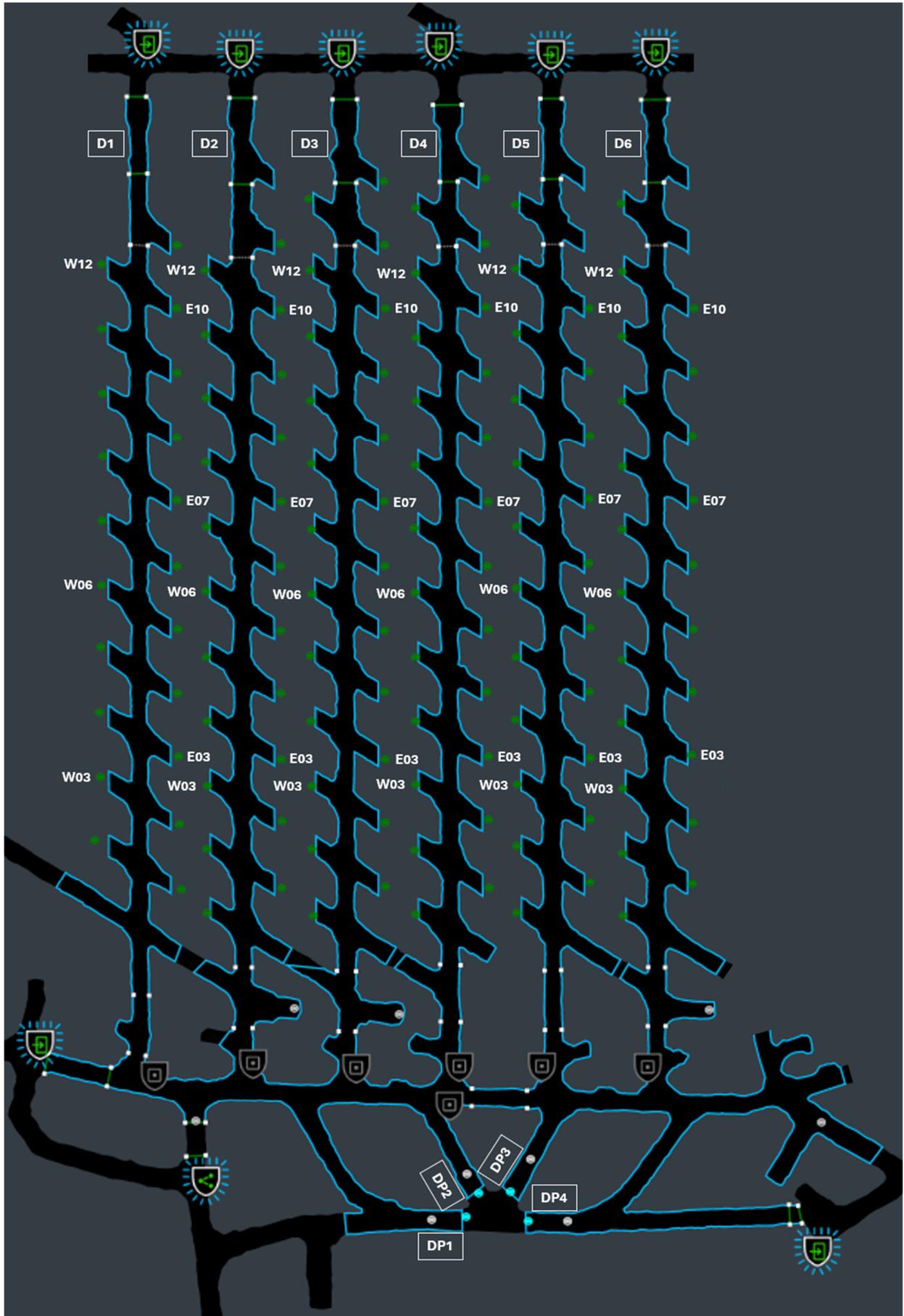


Figure 1 Block cave layout plan view.

3 SIMULATED SCENARIOS

Following scenarios have been simulated:

- Case 1 Baseline production without any disturbances
- Case 2 Production with added short stops based on statistics from various autonomous mines
- Case 3 Production with stop in one draw point handled by reconfiguring the mine safety system allowing for staff to enter the drive
- Case 4 Production with stop in one draw point handled with a tele-remote controlled mobile rock breaker
- Case 5 Production allowing machines to always be turned in the bucket direction when entering shared areas.

Case 3, 4, and 5 are described in detail in subsequent subchapters.

3.1 Case 3

Production with stop in one draw point handled by taking the loader out of production and reconfiguring the mine safety system allowing for staff to enter the drive”

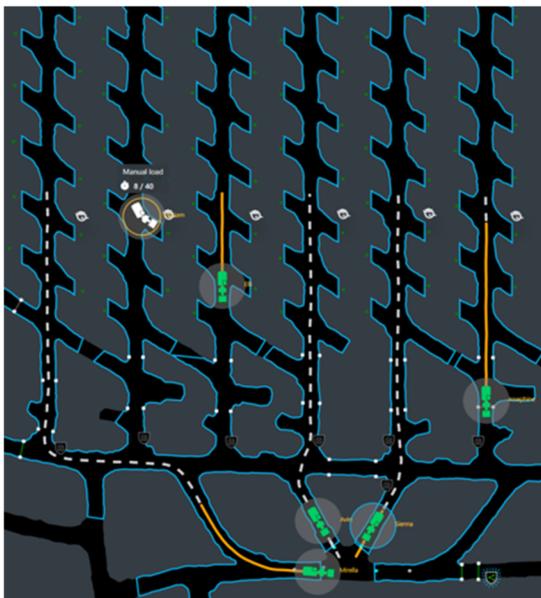


Figure 2 Production ongoing.

Production ongoing in all drives from draw point E03

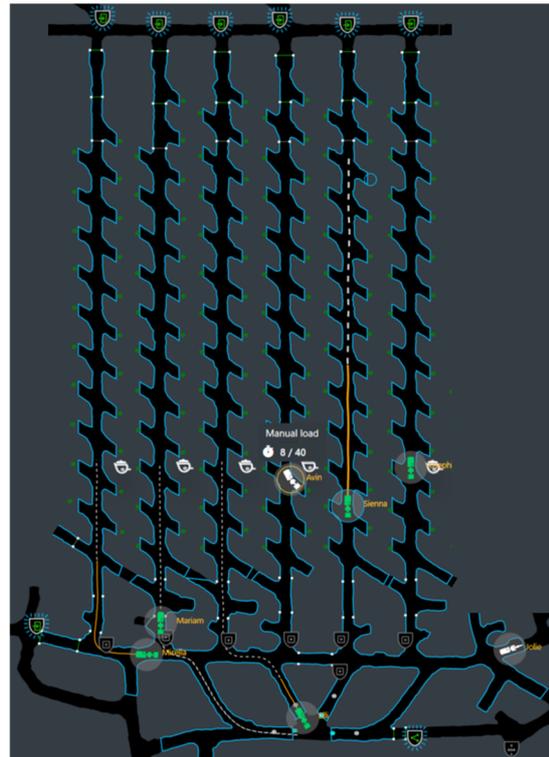


Figure 3. Draw point blocked.

Draw point E03 in drive D5 is blocked by a boulder after one hour of production in the shift. Sienna is assigned to go toward the drive entry.

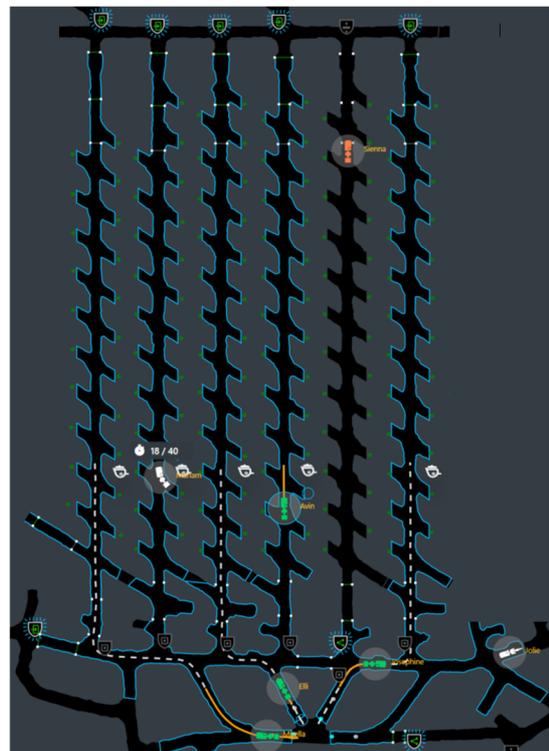


Figure 3 Production area reconfigured.

The production area is reconfigured in 4 minutes to allow for staff to enter drive D5.

Sienna is now in manual mode and the rest of the fleet has resumed production.

Production runs with 5 machines the remaining 8 hours and 56 minutes of the shift. Josefine will run without traffic disturbance from Sienna.

3.2 Case 4

Production with stop in one draw point handled with a teleremote controlled mobile rock breaker.

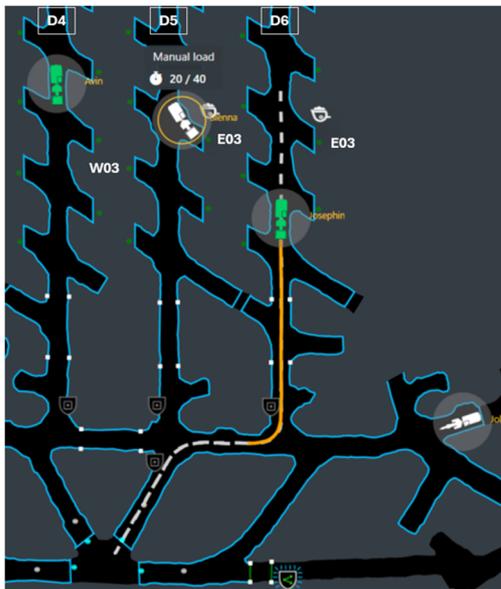


Figure 4 Production ongoing.

Production ongoing in drive D5 and D6 from draw point E03

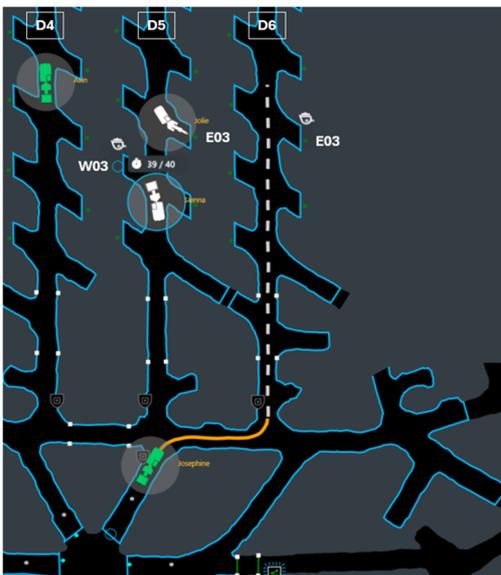


Figure 5 Draw point blocked.

Draw point E03 in drive D5 is blocked by a boulder.

Sienna automatically receives an assignment to continue bogging from W03 in the same drive.

Mobile rock breaker Jolie moves in to break the boulder in draw point E03. The traffic control system prevents Sienna running in autonomous mode to collide with Jolie.

The rock breaking operation is assumed to last 30 minutes. Meanwhile, Sienna is bogging from W03.

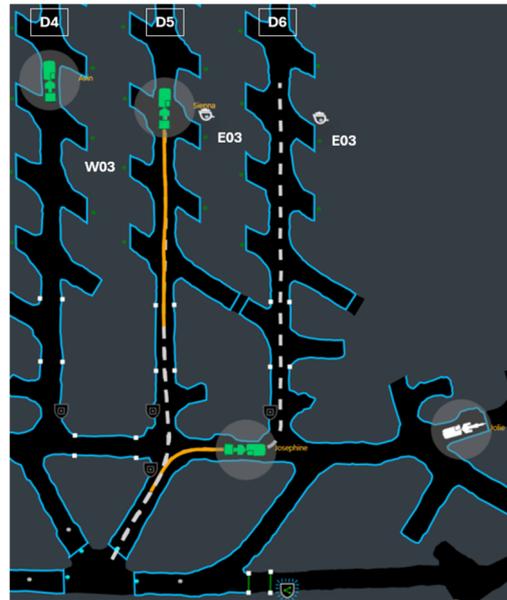


Figure 6 Production restored.

Mobile rock breaker Jolie moves back to its parking place.

Sienna resumes automatically the assignment to bog from E03.

The disturbance takes 40 minutes in total whereof mobile rock breaker Jolie occupies draw point E03 for 30 minutes and moving back and forth 10 minutes. During the period Sienna continues to produce from W03.

3.3 Case 5

Production allowing machines to always be turned in the bucket direction before entering shared areas.”

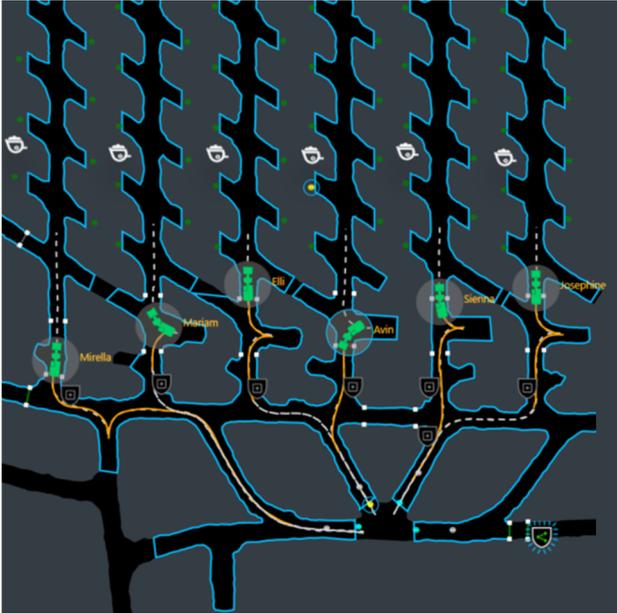


Figure 7 Modified mine layout.

The case required changes in the map as well as new routes to support the turn around when bogging from the west oriented draw points.

The routes were recorded in the simulator and set to represent machine performance as close to reality as possible based on log data from real autonomous operation.

4 SIMULATION RESULTS

The baseline of the study is established through a series of simulation runs, in ideal conditions, from different draw points, aiming to accumulate production statistics. This part of the simulation is critical for setting a benchmark, against which all other cases in the paper can be compared.

The machines are running according to log data from a real autonomous operation. This means that there is variation in speed on straights, in curves and in the area close to the crusher bin. The speed varies dependent on the direction as well, i.e. running unloaded or loaded in the map. Consequently, comparing results from similar extraction drives can be misleading.

The simulations collect both production data and event data, which are valuable for subsequent analysis.

Table 1 shows the summary of following runs in conditions without any disturbance.

- All machines bogging in draw point E03, E7, E10, W03, W06, W12.
- Machines bogging in combination of draw point allowing maximum differentiation of cycle time E03 - E10 and E10 - E0.

Table legend for clarification:

- Runtime: Duration of the simulation in hours
- Tonnes: Total production during the simulation.
- Tonnes/h: Total production during the simulation divided with Runtime.
- Queue Events: Total amount of waiting occurrences for entering shared area during the simulation.
- Q-E/h: Queue Events divided with Runtime.
- Queue Time: Total amount of waiting time for entering shared area during the simulation.
- Q-T/h: Queue Time divided with Runtime.

Table 1 Production in ideal conditions based on log data from real autonomous operations.

			Drive 1	Drive 2	Drive 3	Drive 4	Drive 5	Drive 6
			Mirella	Mariam	Elli	Avin	Sienna	Josephine
E03		Tonnes	4350	4365	5220	5235	5235	5220
Runtime (h)	15,5	Tonnes/h	280,6	281,6	336,8	337,7	337,7	336,8
		Queue Events	404	405	410	681	346	5
		Q-E/h	26,1	26,1	26,5	43,9	22,3	0,3
		Queue Time (min)	71,2	186,0	64,0	251,6	303,1	4,0
		Q-T/h (min/h)	4,6	12,0	4,1	16,2	19,6	0,3
E10		Tonnes	1830	1830	2010	2025	2025	2010
Runtime (h)	8,1	Tonnes/h	225,9	225,9	248,1	250,0	250,0	248,1
		Queue Events	24	159	157	169	135	4
		Q-E/h	3,0	19,6	19,4	20,9	16,7	0,5
		Queue Time (min)	10	63,7	46,2	98,7	127,5	1,4
		Q-T/h (min/h)	1,2	7,9	5,7	12,2	15,7	0,2
W03		Tonnes	1560	1575	1560	1575	2025	2010
Runtime (h)	7,6	Tonnes/h	205,3	207,2	205,3	207,2	266,4	264,5
		Queue Events	104	104	225	225	149	150
		Q-E/h	13,7	13,7	29,6	29,6	19,6	19,7
		Queue Time (min)	106,7	156	146,1	190	130	86,5
		Q-T/h (min/h)	14,0	20,5	19,2	25,0	17,1	11,4
W12		Tonnes	1545	1545	1560	1545	1725	1710
Runtime (h)	8	Tonnes/h	193,1	193,1	195,0	193,1	215,6	213,8
		Queue Events	2	103	209	224	134	11
		Q-E/h	0,3	12,9	26,1	28,0	16,8	1,4
		Queue Time (min)	2,5	80,9	57	109,7	82,1	2,5
		Q-T/h (min/h)	0,3	10,1	7,1	13,7	10,3	0,3
E07		Tonnes	2200	2200	2610	2610	2610	2595
Runtime (h)	9	Tonnes/h	244,4	244,4	290,0	290,0	290,0	288,3
		Queue Events	43	199	171	217	175	3
		Q-E/h	4,8	22,1	19,0	24,1	19,4	0,3
		Queue Time (min)	8,5	87,9	36,6	112,3	143,2	1,7
		Q-T/h (min/h)	0,9	9,8	4,1	12,5	15,9	0,2
W06		Tonnes	1845	1845	1845	1860	2370	2355
Runtime (h)	9	Tonnes/h	205,0	205,0	205,0	206,7	263,3	261,7
		Queue Events	123	123	270	263	175	176
		Q-E/h	13,7	13,7	30,0	29,2	19,4	19,6
		Queue Time (min)	87,4	144,2	136,5	187	110,2	48,5
		Q-T/h (min/h)	9,7	16,0	15,2	20,8	12,2	5,4
Mix E3 - E10			E3	E10	E3	E10	E3	E10
		Tonnes	2505	2490	3090	3075	4695	2355
Runtime (h)	10,5	Tonnes/h	238,6	237,1	294,3	292,9	447,1	224,3
	9,5	Queue Events	198	61	328	88	263	208
		Q-E/h	20,8	6,4	34,5	9,3	27,7	21,9
		Queue Time (min)	133,5	26,1	128,6	19,7	56,9	90,6
		Q-T/h (min/h)	14,1	2,7	13,5	2,1	6,0	9,5
Mix E10 - E3			E10	E3	E10	E3	E10	E3
		Tonnes	1890	1890	1875	3645	2775	2790
Runtime (h)	9,1	Tonnes/h	207,7	207,7	206,0	400,5	304,9	306,6
		Queue Events	110	183	178	286	70	244
		Q-E/h	12,1	20,1	19,6	31,4	7,7	26,8
		Queue Time (min)	55	212,7	131,5	62,3	17,7	100,9
		Q-T/h (min/h)	6,0	23,4	14,5	6,8	1,9	11,1

4.1 Base line production without any disturbances

This data from the simulation serves as a benchmark for comparing other cases discussed in the paper. Two sets of data summaries are presented: one for all six machines, and another for only the four machines located in the east. This distinction is made because the two machines in the west have different approach distances.

Drive 1-6 15349 tonnes in the crusher bin over 10 hours.

Drive 3-6 10846 tonnes in the crusher bin over 10 hours.

4.2 Production with added short stops based on statistics from various autonomous mines

This data is based on injecting stops in the simulations according to the assumptions in chapter 2.2.

Results from the two groups of disturbances are separately presented, i.e. connectivity failures and automation system failures.

In the simulation, the short stops are static, meaning they are introduced regularly with a fixed duration. However, these stops vary in both length and frequency, leading to varying degrees of production losses.

Drive 1-6 14473 tonnes in the crusher bin over 10 hours, whereof:

- 408 tonnes loss due to connectivity failures.
- 468 tonnes loss due to automation system disturbances.

Drive 3-6 10226 tonnes in the crusher bin over 10 hours whereof:

- 288 tonnes loss due to connectivity failures.
- 331 tonnes loss due to automation system failures.

4.3 Production with stop in one draw point handled by reconfiguring the mine safety system allowing for staff to enter the drive

This part of the simulations serves as base for discussion around strategies for oversize handling, road maintenance, etc.

The results are obvious, and the value from simulations is the concrete figure between the two cases. The difference will differ depending on where in the mine a drawpoint is blocked.

Taking the loader out of production and reconfiguring the mine safety system allowing for staff to enter the drive results in following production losses:

Drive 1-6:

- 16061 tonnes in the crusher bin over 10 hours
- 3039 tonnes loss due to the stop in D5

Drive 3-6:

- 10473 tonnes in the crusher bin over 10 hours
- 3002 tonnes loss due to the stop in D5

4.4 Production with stop in one draw point handled with a tele-remote controlled mobile rock breaker

Handling the situation with a tele-remote mobile rock breaker available inside the automation area safety system perimeter results in minor production losses:

Drive 1-6

- 18990 tonnes in the crusher bin over 10 hours
- 110 tonnes loss due to the stop in D5

Drive 3-6

- 13365 tonnes in the crusher bin over 10 hours
- 110 tonnes loss due to the stop in D5

4.5 Production in conditions allowing machines to always be turned in the bucket direction when entering shared areas

This simulation serves as base for discussion of layout optimization, ahead of development, in a real time simulator.

The benefits of this approach are rooted not only in the data but also in the visual experience, which allows experts in production and mine development to discuss the advantages and disadvantages of various layouts.

Moreover, when presenting alternative solutions to a problem, real-time simulations can facilitate change management by grounding new ideas and providing a platform for future staff training.

The raw data from the simulations is gathered in Table 2 and are compared with base line data in

Table 1):

- 9434 tonnes in the crusher bin over 10 hours. Machine turned in bucket direction (Table 2).
- 11794 tonnes in the crusher bin over 10 hours. Improvement 2360 tonnes.

Summary from simulations from draw point W06 indicate an expected lower improvement since the distance to the shared area is longer and the disadvantage of turning around the machine before entering the shared area is smaller due to lower traffic congestion:

Baseline production data from W06 (

Table 1.

Summary from simulations from draw point W03 indicate a significant improvement:

Baseline production data from W03 (

Table 1):

- 9367 tonnes in the crusher bin over 10 hours. Machine turned (Table 2).
- 10775 tonnes in the crusher bin over 10 hours. Improvement 1408 tonnes.

Table 2 Production with machines facing in the bucket direction when entering shared areas

Machine turned around			Drive 1	Drive 2	Drive 3	Drive 4	Drive 5	Drive 6
W03		Tonnes			2355	2355	2370	2355
Runtime (h)	8	Tonnes/h			294,4	294,4	296,3	294,4
		Queue Events			164	169	160	129
		Q-E/h			20,5	21,1	20,0	16,1
		Queue Time (min)			46,2	119,4	143,4	20,6
		Q-T/h (min/h)			5,8	14,9	17,9	2,6
W06		Tonnes			1620	1620	1605	1620
Runtime (h)	6	Tonnes/h			270,0	270,0	267,5	270,0
		Queue Events			108	208	107	1
		Q-E/h			18,0	34,7	17,8	0,2
		Queue Time (min)			20,8	70,7	67	0,2
		Q-T/h (min/h)			3,5	11,8	11,2	0,0

5 DISCUSSION

Starting with the production simulations as described in Chapter 2, without any disturbances, i.e. Case 1, an initial and obvious insight becomes immediately apparent, which is to spend as little time as possible in shared drives.

As simulated, machines bogging in western draw points enter shared areas with the engine first, while machines bogging in eastern draw points enter shared areas with the bucket first and can proceed directly to the crusher bin giving following differences in productivity.

Average tonnes/h per machine in drive D3 - D6:

- West draw points 225 tonnes/h.
- East draw points 292 tonnes/h.

Simulations in Case 5, production in conditions allowing machines to always be turned in the bucket direction before entering shared areas, indicate a significant improvement and should be investigated further.

The tonnage figures could be used in analysis when developing the layout and planning infra structure, e.g. connectivity.

Production in real conditions suffer always from various disturbances and it is obvious that machines standing still cannot feed the crusher as expected. The interesting figure in this case is the concrete figure of lost tonnage:

- Drive D1 - D6 88 tonnes / hour in lost production.

- Drive D3 - D6 66 tonnes / hour in lost production.

The tonnage figures could be used in analysis when considering investing in alternative connectivity standards as well as improving conditions, e.g. road conditions, dust suppression, to minimize stress on the automation system.

Production in real conditions suffer also from boulders and other obstacles preventing planned production. The simulations conducted using tele remote controlled rock breaker situated in the automation area shows concretely the advantage of including auxiliary autonomous ore tele remote controlled machines in the automation area.

Comparing Case 3, taking machine and drive out of production, with case 4, using a tele remotely controlled mobile rock breaker, to deal with obstacle in a draw point indicates a huge advantage, closer to 3000 tonnes of production and a better plan adherence.

The tonnage figure varies with addressed draw point and the mine safety procedures and could be used in analysis when considering autonomous auxiliary machinery investments.

The conclusion so far has focused on material flow to the crusher. Quick analysis of the event counters indicates an overall average 18 queue events / hour and machine. This is a lot of start and stops of a machine weighting 65 – 70 tonnes. This comes with a cost in fuel consumption, road and machine wear and ventilation that is likely to be visible in the mine operational expense.

6 FUTURE WORK

Many of the findings in the simulations in this paper are intuitive, but the added benefit is that it gives a reliable and quantified figure on the improvements. In addition, less obvious and new findings was also discovered and gave input to further work and improvements of the loader automation system.

Future evolvement of this paper could focus on improving the simulations in Case 1, production in conditions as commissioned without any disturbances, by:

- Vary mucking time to trigger the dynamics in the shared areas.
- Vary stops over time to trigger the dynamics in the shared areas.
- Vary combinations of draw points, mixing east and west, as well as distance from shared area.

Furthermore, the following can also be investigated:

- Modifications in the mine layout allowing machines to run faster in corners.
- Modifications in the control system allowing machines to share draw points and dump points.
- Modifications in the control system and simulator allowing “speeding up time.