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Integrating materials supply in strategic mine planning of underground coal mines

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Abstract

In July 2005 the Australian Coal Industry's Research Program (ACARP) commissioned Gary Gibson to identify constraints that would prevent development production rates from achieving full capacity. A "TOP 5" constraint was "The logistics of supply transport distribution and handling of roof support consumables is an issue at older extensive mines immediately while the achievement of higher development rates will compound this issue at most mines." Then in 2020, Walker, Harvey, Baafi, Kiridena, and Porter were commissioned by ACARP to investigate Australian best practice and progress made since Gibson's 2005 report. This report was titled: - "Benchmarking study in underground coal mining logistics." It found that even though logistics continue to be recognised as a critical constraint across many operations particularly at a tactical / day to day level, no strategic thought had been given to logistics in underground coal mines, rather it was always assumed that logistics could keep up with any future planned design and productivity. This subsequently meant that without estimating the impact of any logistical constraint in a life of mine plan, the risk of overvaluing a mining operation is high.

This thesis attempts to rectify this shortfall and has developed a system to strategically identify logistics bottlenecks and the impacts that mine planning parameters might have on these at any point in time throughout a life of mine plan. By identifying any logistics constraints as early as possible, the best opportunity to rectify the problem at the least expense is realised. At the very worst if a logistics constraint was unsolvable then it could be understood, planned for, and reflected in the mine's ongoing financial valuations. The system developed in this thesis, using a suite of unique algorithms, is designed to "bolt onto" existing mine plans in the XPAC mine scheduling software package, and identify at a strategic level the number of material delivery loads required to maintain planned productivity for a mining operation. Once an event was identified the system then drills down using FlexSim discrete event simulation to a tactical level to confirm the predicted impact and understand if a solution can be transferred back as a long-term solution. Most importantly the system developed in this thesis was designed to communicate to multiple non-technical stakeholders through simple graphical outputs if there is a risk to planned production levels due to a logistics constraint.

The system was developed for two generic mine designs, the first being a shaft where the mine progresses away from the shaft, then returns and progresses away again. The second was reflective of mining from a sub-crop or outcrop using an adit or box cut where the mine progresses away in a single direction. Experiments were conducted using the model to understand the impact on logistics from variations to the mine design, productivity, geotechnical regime, extraction sequence, the introduction of infrastructure such as shafts closer to the production faces, dedicated travel inbye and outbye travel roads, variability of delivery speeds, use of dedicated delivery windows and sizes of the delivery payload. If a logistics constraint could not be solved, the system was also able to cap production levels to quantify the shortfall between a constrained and unconstrained mine plan.

Whilst each variable had an impact on logistics, the most relief was found by developing a new mining domain closer to the base of the supply shaft / portal just prior to logistics becoming a production constraint. Another major relief mechanism was the introduction of a shaft/portal closer to operating faces which

granted, is intuitive but can now be quantified. Payload and speed of delivery was also found to provide relief, but when studied closely using FlexSim, it was found that this relief was maximised when there was a much higher proportion of travel time compared to loading plus unloading time which is reflective of a large mine. In contrast, a small mine with a much smaller proportion of travel time compared to loading plus unloading time, needed to focus on optimising the time taken to load and unload rather than speed of delivery and payload.

Lastly the system was applied to a real-world Australian coal mine with actual logistics tracking data input for both calibration and prediction testing. It confirmed that the system was indeed a “bolt on” system and could predict the number of delivery load-haul-dump (LHD) units operating at any point in time within the mine’s life.

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Certification

I, David Kevin Conrick Walker, declare that this thesis is submitted in fulfilment of the requirements for the conferral of the degree Doctor of Philosophy, from the University of Wollongong, is wholly my own work unless otherwise referenced or acknowledged. This document has not been submitted for qualifications at any other academic institution.

David Kevin Conrick Walker

22nd January 2023

List of Names or Abbreviations

Adit: Entry to a mine from an outcropping coal seam usually in the side of a hill or mountain.

AMPLA: A Production and Maintenance Management information system. Can track rate and utilisation, delay allocations and time.

Blue Sky: An overly aggressive mine plan that does not give enough weight to potential constraints.

Cage: Houses personnel or transport whilst travelling up and down a shaft.

CAPEX: Capital Expenditure

CCS / Coal Clearance System Roadway: A dedicated conveyor roadway which transports the coal from the face to the surface.

Conveyor extension: The advancement of the conveyor system to remain close to the production face. In gateroads is typically done with a panel advance.

Cut and Cover: A graded excavation (cut) that exposes a geotechnically sound portal entry point to a mine over which then a false roof is constructed back up to the original topographical surface. The false roof is then backfilled (cover) with spoil to create an artificial tunnel.

Development inventory in advance: How far development units are ahead of the longwall.

Delivery Machine: Delivers materials to the production unit. Typically, a multi capability low height front end loader with or without a trailer attached to increase payload. Interchanged with the terms **Supply machine**, **LHD** or **Loader**.

Development Unit: A Continuous Miner or other form of tunnelling machine used to develop the Mains, Gates, and Install Roads to support the longwall operation.

Dolly Car: A steep dip rail mounted transport system wound up and down on a cable in a drift used for conveying personnel (using carriages) or materials (using flat tops rail cars)

Dolly Car

Drift: Grade entry to a mine from the surface usually through multiple rock units to the coal seam. This may be a steep grade (1:6) where a combination of rope winding on rail tracks are used for typically deeper mines or shallower grades (1:8-1:10) where rubber tyred vehicles may pass. Also known as a “decline”.

Drop hole: A larger diameter typically 450-600 mm borehole connecting the surface to the seam to reduce outbye machine movements and reduce haulage time to critical locations. Typically used for supplying ballast and concrete into the mine.

Explosion Protected: Where an enclosed apparatus ignites a flammable atmosphere, the explosion cannot propagate outside of the apparatus to ignite a flammable atmosphere by cooling the flame path as it travels from inside to outside the apparatus. These are used for any electrical apparatus on equipment that could be subject to a flammable atmosphere that is not intrinsically safe. Also known as a flameproof apparatus.

Face: The location where coal is being cut/won either by a continuous miner or longwall shearer.

First Workings: Cutting of a roadway on advance. In a longwall mine it would be considered the development of roadways and cut throughs in mains and gateroads.

Gates / Gateroads: Roadways which develop out to a longwall face. The Maingate is also known as a Headgate in North America and is the virgin side of the longwall adjacent to the next consecutive longwall.

The **Maingate** holds the main transport road and longwall conveyor and except for homotropal ventilation supplies most of the intake air.

The **Tailgate** is the previous maingate of the previous longwall or the very first gateroads driven that is not adjacent to the next consecutive longwall.

Inbye: For the purposes of this thesis, the direction of looking from the portal towards the production face.

Install roads: Widened roadways which are the start line where longwall machinery is installed prior to longwall block extraction.

Intake: Fresh air roadways transporting air to the production face.

LHD: Load Haul Dump rubber tyred loader. Interchanged with the terms **Supply machine**, **Delivery Machine** or **Loader**.

Light Sections: A section of road controlled by traffic signals where clear line cannot be maintained such as around corners that could be at risk of a collision.

Line: Cut through number

Line of Oxidation: The line of intersection between the base of weathering and the seam floor. Typically, the position of mine portals for cut and cover and box cut operations. Also known as a sub-crop.

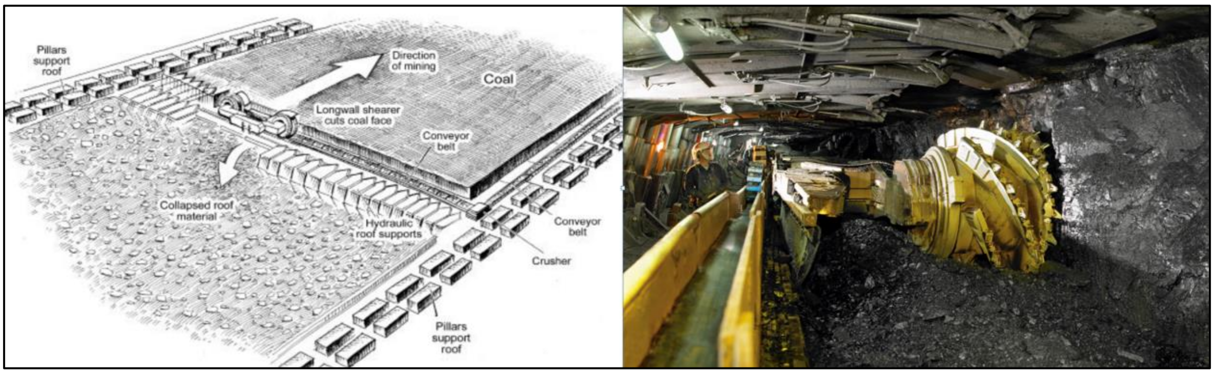
LoA / LoM: Life of asset / Life of mine (interchangeable) this is the total years for a mine plan out to end of mine life.

Logistics Breaking Strain: Introduced term. The term where the deliveries required to maintain production cannot be achieved and therefore productivity is capped, and the mine plan is deemed invalid.

Logistics Management Team: The department in a mine responsible for the supply of materials to a production district.

Logistics Strain: Introduced term. The required number of delivery vehicles operating within an underground mine. Logistics strain is directly proportional to number of deliveries per production panel and distance of the production panel to the portal. Interchanged with the term “Loads on road”.

Longwall: A longwall is a bulk seam extraction unit bound by a block of coal typically 200-450 m wide and up to 5000 m long which takes slices or shears of 800 mm to 1000 mm at a time along the width as it progresses along the length of the coal block. As the shearer mines each slice of coal along the width, supports or shields behind the shearer advance a slice width with every shear cycle to provide temporary support to the production face whilst behind the shields, the strata are allowed to collapse behind into what is known as the *goaf*.



Longwall Extraction

Longwall Float: This is how far development roadways are ahead of the longwall. It can be measured either by time or geography. For example, 6 months of longwall float would mean that development has completed a longwall block 6 months prior to extraction, or ½ a longwall block of longwall float means that when longwall number x has started, development has completed ½ of longwall x+1. Interchangeable with **development inventory** and **development float** or **float**.

Maingate: See Gates / Gateroads.

Mains: Multiple headings consisting of intake, coal clearance and return roadways which connect the surface to succeeding gateroads / longwalls.

M&M Shaft/Drift/Adit: Personnel and materials mine access almost always a fresh air intake and where delivery units from the surface would travel to reach the coal seam.

Mine Design: The physical layout or drawing of the mine.

Mine Plan: The combination of the mine design, reserve, schedule, and financial model. A mine plan can be a single deterministic plan (typically budget and forecast level) or a stochastic plan consisting of multiple deterministic plans to give a most probable plan (LoA).

Mtpa: Million tonnes per annum.

OPEX: Operating Cost Expenditure

Outbye: For the purposes of this thesis, the direction of looking from the production face back to the portal. It is the opposite of inbye.

Outbye Coordinator: Typically, is the head of the logistics management team. Is typically responsible for all support works operating from pit bottom to the start of the production district. Australian, English term.

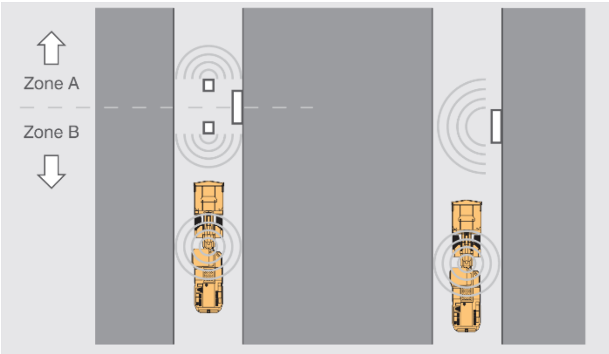
Panel: A zone bound by the production face to typically 400 m outbye. It is overseen by a supervisor known as an ERZ controller in Queensland (QLD) or Deputy in New South Wales (NSW) who have attained statutory certification (level 3 in New South Wales) in supervision and control of a coal mine.

Panel Advance: Moving the entire production district to the next pillar inbye. Includes conveyor extension, movement of electrical reticulation, a fan move and the movement of the production district boundary.

Perfect storm: Circumstances or occurrences when combined can make overall outcome worse. It is a term frequently used to describe challenging events within the Australian industrial landscape including the underground coal mining industry.

PED Tracker: System to track personnel and equipment underground and report this back to the Management Information systems such as SAP/Pulse etc back at the surface.

LHD PED Tracking system



Personnel Transport / Driftrunner / PJB: Personnel bus approved for transport from surface to the face and within the production district. A "Ute" is a variant of a Driftrunner / PJB but with a flat tray for transportation of items and tools in and around a production district.

Pit Bottom: The immediate mains district in and around the bottom of a decline or shaft.

Pod: A container used to transport various equipment and consumables underground. These are fit for purpose-built trailers.

Portal: The surface entrance of the mine. This could include drift, shaft, and adit entry styles.

Production District:

The NSW Coal Mines (Underground) Regulation 1999 defines a production district as:-

(1) The production districts provided for in a mine inspection system must be all the areas in the mine within which there is a place, or places, where coal or stone is mined (other than places at which coal or stone is mined for repairing or enlarging roadways).
(2) Subject to subclauses (3) and (4), a production district must, at least, include all places within 100 metres of a place where mining occurs and in the same ventilation split as that place.
(3) The start of a production district must not be in a hazardous zone.
(4) In determining the extent of a production district, the ability of the mining official in charge of it to effectively carry out required inspections and oversee the safety and health of persons in it must be considered.

(5) A mine inspection system may provide that a place that would otherwise be a production district may be treated as not being a production district during any period of not less than one shift when coal or stone is not intended to be mined in it.

(6) The start of a production district in a roadway through which people normally travel must be clearly and durably marked to the effect that it is the start of the district".

The NSW Work Health and Safety (Mines and Petroleum Sites) Regulation 2014 redefines a Production District more broadly under the term Production Area as: -

(b) a production area is identified in respect of each area of the mine at which coal or mineral is extracted that includes—

(i) in the case of an underground coal mine—the site of that extraction, any part of the mine within 100 metres of the site and, if the production area would be wholly within a hazardous zone, such other parts of the mine as are necessary to ensure that the production area starts outbye of the hazardous zone

Production Face: The physical location where coal or stone is to be cut immediately or in the future within a production district by either a longwall shearer or continuous miner.

Production Unit: A development unit or longwall unit.

Rehanding: To flip the longwall so that the maingate and tailgate drives are reversed, and the Beam Stage Loader and conveyor roadway are on the other side of the longwall. Usually occurs when changing from one domain to another or where the longwall changes to the opposite side of mains roadways. Simply to rehand or the act of rehanding reverses the direction of flow of the armoured face conveyor and the management of the associated implications to allow for this change.

Return: Dirty air roadways transporting air back from the production face to the surface.

ROM: Run of mine – the tonnage and composition of coal as it leaves the mine portal and goes to either a bin or stockpile ready for rail load out (bypass) or ready for the Coal Handling Preparation Plant (CHPP).

RTV: Rubber tyred vehicles. The majority of these are Load Haul Dump/LHDs (with or without trailers) and Personnel transport. All colloquially known as "**machines**".

Second Workings: Is the extraction of solid blocks of coal after first workings have taken place. Pillar extraction is an example of second workings.

Shunting: One machine must drive into a cut through to avoid a collision with a machine either travelling in the opposite direction based upon right of way of that mine site, or if a faster machine comes up behind a slower machine, the slower machine may drive into a cut through to let the faster one pass. Shunting creates an operating delay.

Stopping: A ventilation control device which is a wall constructed underground to prevent air from short circuiting between intakes and returns to make sure the required air goes to where it is needed.

Strategic Planning: Long term macroscopic planning. It has greater capacity to identify and rectify problems without impacting productivity. Estimates operational value.

Supplies: Interchangeable with "materials" and includes all consumable items that support the development of a coal mine at the face.

Supply Node: A logistics storage area within proximity to production faces where heavy delivery LHDs would transfer deliveries to production district delivery LHDs. Nominally a node would be located outside but very close to a production district ventilation split, to not be limited by its ventilation capacity bound by legislation (NSW-Government, 1999) and (NSW-Government, 2014) and would typically be around each production panels "Zero line".

Tactical Planning: Short term day-to-day planning. Would be considered microscopic / detailed planning. There is very little opportunity to rectify an undiagnosed strategic problem without considerable expense and complexity in the tactical timeframe. The Tactical Plan outworks the Strategic Plan on a day-to-day basis.

Tailgate: See Gates / Gateroads.

Travel Road: The main personnel and logistics transport roadway. These can be split into different types of travel roads:

1. Heavy transport travel road: A dedicated heavy haulage transport route designed to separate higher speed personnel transport from lower speed materials transport. Rarely seen due to lack of roadways in a high production mine.
2. Inbye travel road: Transport Road to the face.
3. Outbye travel road: Transport Road from the face.
4. **Ventilation split:** Intake and return airways from Mains headings.

Ventilation Split: An airway system for a production district comprising of intake and return airways. For example, 220 m^3/s total intake air quantity may travel down mains intake airways and then split into a longwall (80 m^3/s), two gateroads (50 m^3/s each) and mains development (40 m^3/s) production districts including leakage. Ventilation quantity in an individual split governs the number of diesel machines that can operate there. This can greatly influence the rate of delivery, particularly within production districts.

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Chapter 1

INTRODUCTION

As underground coal mines continue to expand away from their surface infrastructure bases, the criticality of good supply chain management increases. To de-risk outcomes and provide higher levels of certainty and to provide a cushion from the impact of unfavourable foreign exchange rates and commodity prices, a mine may increase its total "Run of Mine" or ROM production to reduce cash cost per tonne. The mine then must increase its rate of extraction which will in turn stretch its logistics supply chain to maintain the updated productivity. Whether or not the mine increases its productivity, it will move away from its portals and in doing so also stretches the logistics supply chain over time. Both these events, speed of extraction and mine progression impose strain upon the logistics supply chain over time.

Development metres, or lack of them, continues to plague modern longwall coal mining operations in the world today (Norwest-Corporation 2008) and therefore significant value potential is not achieved (Kizil, et al. 2011). The more development and longwall production the higher the rate of consumption of items such as stone dust, pipes, conveyor extensions, primary and secondary support, and consumables to name a few. Therefore, achieving higher development metres means greater and more precise logistical support, more machine movements underground and can lead to significantly more strain on an operation and diseconomies of scale. Apart from gut and typically lengthy manual calculations a strategic mine planner has no real idea how his or her design needs to be logistically supported. Usually, a planner will have a development rate limit (metres per week, metres per annum based upon geological / geotechnical constraints per continuous miner and then will apply more continuous miners to achieve the necessary total development per annum to support the desired production rate. On paper this sustains net present value (NPV) and thus feasibility, but in execution, is the mine truly capable of handling the additional logistical movement and, thus, achieving promised shareholder value?

There is an old saying in the underground coal mining industry, that if the reserve has not been touched until today there is usually a reason why. Nonetheless mining companies trying to paint a perpetually rosy picture to shareholders optimistically pursue deposits that are not as "blue sky" as the limited exploration borehole information allows us to believe. Historically it was not unusual to find a deposit where the geology and geotechnical conditions were so benign that longwall after longwall would be positioned adjacent to each other mining down-dip in a repeatable system that only increased the distance between the centroid of mining operations and the position of surface infrastructure by 300-400 m per annum. Currently with the most easily accessible and therefore more favourably economic mining areas being depleted, focus now turns to less favourable resource areas that are not well understood, technically complex areas to sustain raw material output, we are seeing less than ideal conditions for coal mining, which is a combination of: -

1. The increased presence of gas within the seam and within the surrounding strata creating a large reservoir for emissions into return airways.
2. Environmental constraints imposed on mines that limit longwall subsidence. This may be reflected in narrow longwall panels or no longwall operations at all.

3. The presence of geological anomalies and an unfavourable geotechnical stress regime slowing the rate of advancement of development mining.
4. Proximity of old flooded workings with high inrush potential.

These conditions have mining companies making strategic decisions between persevering with adjacent longwalls in states of low production or developing mains headings in search of a more favourable mining domain that is less impacted. It is no longer atypical to see an underground coal mine which originally was planned for a life of mine of 30 years or more, adjacent longwalls in a single mining domain to be broken up into several domains 2-5 longwalls at a time and then drive mains headings away to the next domain of 2-5 longwalls.

Mines are now faced with a new problem, the historical slight stretch of moving from one longwall to the next adjacent resulting in an increase in logistics supply chain distance of 300-400 m per annum is now more significant, with a step change of kilometres every few years being presented as the reality as new mining domains are needed to be accessed to continue production. Increasing machine movements reflect these periodic step changes in centroidal distance between the production faces and the surface infrastructure feeding supplies and manning. Both capital and operating costs rise due to this increase as the mine seeks to provide a stretched lifeline to its production face through longer work hours for manning and more manning to operate more machines in the logistical supply chain.

Mines therefore, continue to expand and radiate away from their existing surface infrastructure. The immediate response to maintaining equilibrium between the supply chain and the production face is to increase machine movements. Increasing underground machine movements or the intensity of supply chain movements has historically been the panacea for “underground logistics strain”. However, increasing the intensity of operations will inevitably lead to diseconomies of scale where no matter how many resources are assigned to logistical supply, the rate of production face advancement is impeded by the rate of supply.

The simplest way to slacken the logistical supply chain is to simply move the surface infrastructure closer to the productive faces and sinking new shafts or drifts. Geographical and budgetary constraints may exclude this option, and, thus, the only other conventional options to relieve logistics strain are to increase supply speed of delivery or increase payload of each delivery.

1.1 Underground Coal Mining Logistics

Underground coal mining logistics is typically regarded as all activities undertaken to support production (Hanslovan & Visovsky, 1984). These activities may be done utilising either underground rail networks in the case of older mines or through rubber tyred vehicle (RTV) roadways. Underground coal mining logistics for the purposes of this thesis is limited to the areas between the portal access of the mine and the production faces and includes: -

- The transportation of the workforce to the production districts or other areas where support of such production is required.
- The transportation of materials to all necessary areas either using purpose-built machines, load-haul-dump (LHD) units and trailer configurations or flat top rail networks. This typically includes:

- Conveyor componentry, including structure, belts, rollers and idlers, and drive-head construction materials.
- Primary and secondary support material.
- Longwall equipment between change-outs.
- Longwall consumables for the duration of extraction within a block.
- Ventilation control device construction materials.
- Other production support machinery.
- Pipework for transport of water.
- Electrical reticulation and cabling and supporting infrastructure such as switch rooms, transformers, and district circuit breakers.
- The supply of road construction materials (gravel or concrete).
- The supply of concrete for critical roadways or other infrastructure requiring it.
- The removal of rubbish and human effluent.

- The supply of electricity compressed air and fresh water through pipelines.
- The removal of dirty water and drained gas from the areas of mining to the surface for disposal.

Underground coal mining logistics may also include multiple methods of transport from the portal to a face. Some mines require transport underground using steep winders or vertical shafts which add additional points of transfer in the transportation of goods to production or production support areas, other mines use RTVs from the portal to the production face which are for either adit entry or shallow depth.

As timely delivery of materials to the production face is critical in increasing machine direct cutting hours and hence productivity, this thesis is limited to the transportation of supplies from a portal to production districts and will not be considering water, transport of flammable and noxious gas, electrical reticulation, or surface movements of machinery. This is because the flow of material loads inbye to a production face like personnel transport is in batch delivery mode and frequency of such loads vary with the conditions faced and the greater risk that as a mine expands the rate of such delivery cannot be met meaning a downgrade in productivity and total mine value.

1.1.1 Logistics Strain

The term logistics strain is used throughout this thesis. It is difficult to find a definition for logistics strain *per se* but the term is readily interchanged with the term supply chain strain, supply chain risk or more simply supply risk. Brindley (2004) defines supply chain risk as a subset of business risk and comprises of risks associated with logistics activities in the flow of information and material. More specifically Business-Queensland (n.d.) a subsidiary of the Queensland Government defines supply risk as supply disruptions or shortages "caused by any interruptions to the flow of product, whether raw material or parts, within your supply chain" or as defined by (Trkman & McCormack, 2009) supply disruption likelihood.

Considering these definitions, logistics strain for the purposes of this thesis, is a spectrum rather than a singular event, between the low-complexity free flowing supply of material and personnel to ongoing production interruption due to material and personnel supply shortages to maintain the level of productivity that could be undertaken if such a constraint did not exist. Logistics strain is measured by how many materials delivery LHDs are travelling on the road, called "loads on road" at any given time. The higher the "loads on road" the higher the likelihood of delay as machines have higher rates of interaction with each other particularly in shared transport routes that exist along mains headings. However, larger mines can sustain more loads on road, more transport routes can do the same and therefore what one mine can sustain may not be possible for another with a different deposit size at a different stage of its mine life.

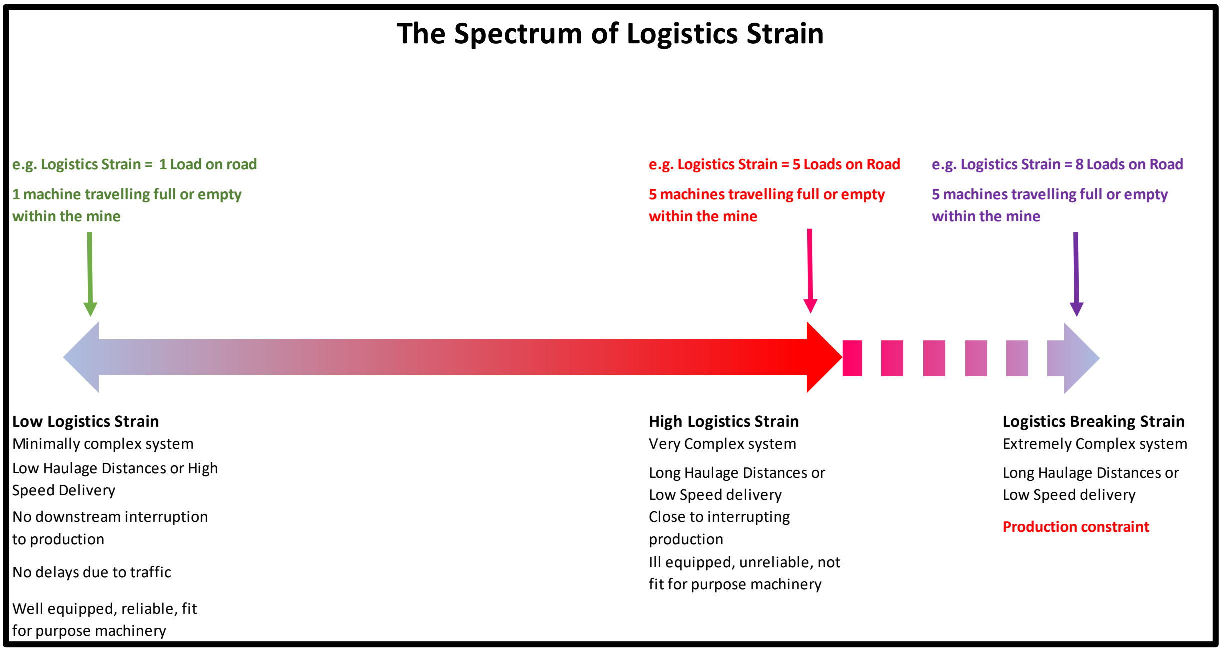

Figure 1-1: Illustration highlighting the logistics strain spectrum

Figure 1-1 outlines the spectrum of logistics strain that are encountered within a coal mine. Not all defining events may be present, for example a mine may well have low logistics strain even with unreliable slow machinery due to very low haulage distances. Likewise, even with very high speed, a mine may experience very high logistics strain or logistics breaking strain due to the mines size and vehicular interactions leading to delay.

High logistics strain would be barely keeping up with production, but there is no production constraint. There would likely be multiple machines in transit, many traffic jams with slower machines causing holdups or machines having to stop and shunt as other machines pass in the opposite direction. Of course, logistics strain may be alleviated by identifying and subsequently removing or delaying bottlenecks, such as purchasing more reliable transport or concreting roadways to increase speed of delivery, but strain will continue to rise typically as the mine expands. However, if during the mine life, the mine only experiences high logistics strain there will be no shortfall in production. For a mine to never cross over the threshold of production constraint also known as logistics breaking strain is to continue to defer the progress of logistics strain through effective planning and innovation over time.

At the other end of the spectrum is low logistics strain. Low logistics strain is barely noticeable, and it would be inconceivable that production would be interrupted. This is a dangerous phase because this is the point typically in the early stages in a mining operation where planning can be undertaken to debottleneck and future-proof logistical operations between a portal and the production district assuming that upstream bottlenecks, (surface supply), and downstream bottlenecks, (face supply), have been optimised and criticality for total production supply is removed. The main risk here is as the mine expands, identification of logistical bottlenecks is not prioritised or even identified as they are not seen as a priority in the present circumstances.

Proactive identification of bottlenecks in the early phases of the life of mine and subsequent changes are usually much cheaper than reactive retrofitting of solutions later once a problem is encountered and is why this thesis is being undertaken.

1.2 Operational Context

There is currently no mechanism for mine management and strategic mine planners to identify potential future logistical supply chain bottlenecks within a mine plan and address them proactively (Walker et al. 2020). A mine plan is a combination of the physical design, machine paths or sequence, and productivities for a particular mining operation. The general assumption is that any mine plan can be supported logistically at a strategic level and that the tactical level can deal with any unforeseen challenges on a day-to-day basis. The impact of this assumption will depend on the size of the operation itself. Consider a large geographical footprint highly productive operation compared to a smaller less productive mine. The geographically larger and higher producing mine will likely experience higher logistics strain compared to the smaller operation. If a logistics bottleneck is missed because the planning does not consider it, the larger mine will be first to encroach the logistics breaking strain threshold. By only tactically identifying any logistics breaking strain, the mine may delay the inevitable productivity decrease for a short period of time but will likely create a new long-term shortfall in productive capacity compared to the original mine plan or an expensive recovery to reactively address the bottleneck created by logistics. Both of these actions devalue the operation compared to the mine plan.

Consider a large underground coal mine. Consumables / supplies and personnel enter and exit through an adit, drift or through a shaft. Over time the active mine working will migrate away from these portals. With an adit through a sub-crop or outcrop the mine will always move away from the portal entrance. A centralised drift or shaft may migrate away from the shaft only to return closer to the shaft again after several years to commence a new domain in a new direction.

1.2.1 Centralised Shaft or Drift

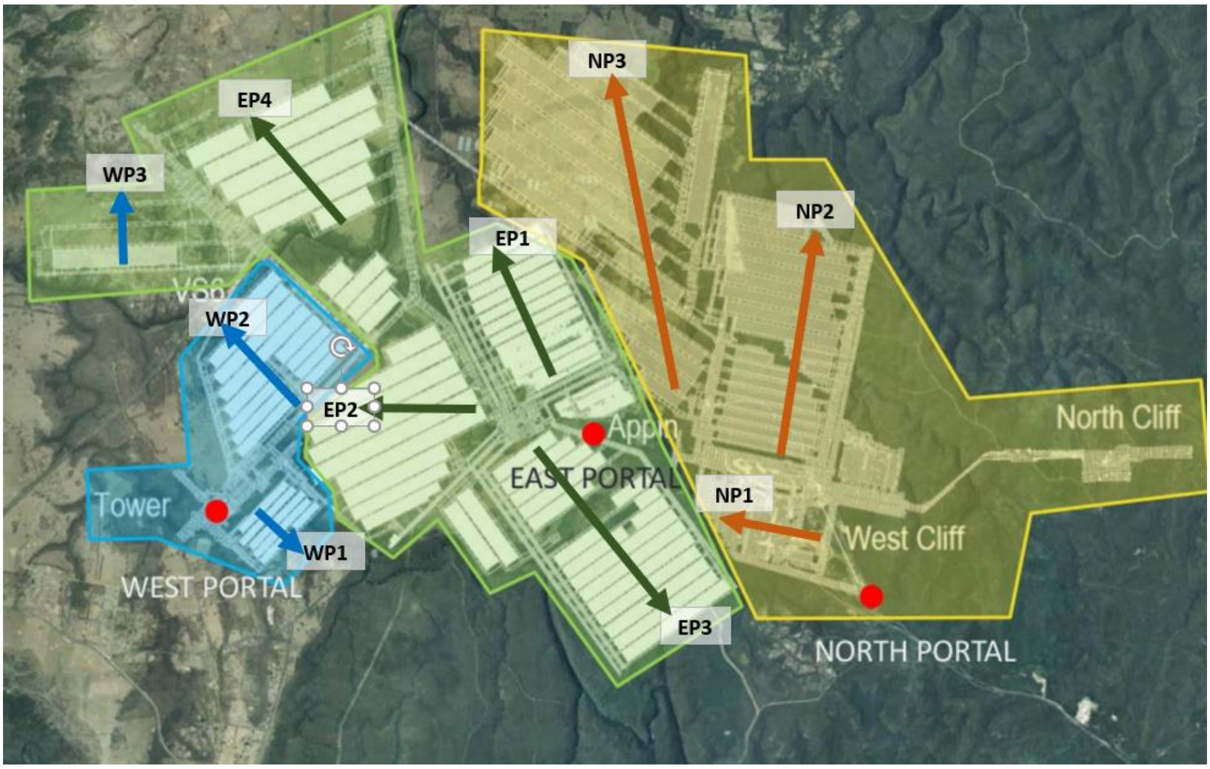

Figure 1-2: Shaft and cross measure drift portals (in red) for a large coal mining complex Appin Mine highlighting the migration away and return to the portals for active operations. (Underlay Map Source: Young (2017))

As can be seen in Figure 1-2, operations with a shaft or cross measure drift operations can be seen to migrate away from the surface access portals as domains EP1, NP1 and WP1 migrate away from the East Portal, North Portal, and West Portal, respectively. At the completion of these domains, the logistics maintaining this supply chain of personnel and consumables are at their farthest point, then relaxation can occur of the supply chain if the next active workings commence closer to the shaft or drift portal as per EP2 from EP1, EP3 from EP2, and NP3 from NP2. Therefore, in a shaft or drift portal context if there were no other limitations to extraction then the active mine workings would radiate out somewhat like Figure 1-3:

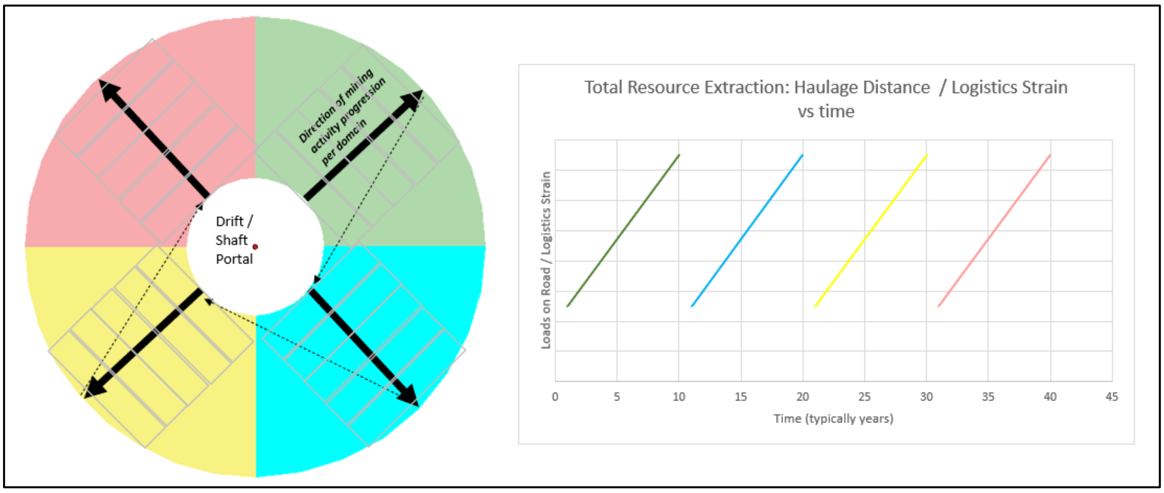

Figure 1-3: The relationship between domain changes for a centralised shaft or portal for production activity progression and haulage distance / logistics strain.

Figure 1-3 is a simplified example of an unrestricted resource with homogenous quality and conditions. What can be seen is four mining domains. Each domain has progressive production panels (e.g., longwall panels) radiating away from the central shaft or drift. As the longwalls continue to progress outwards, longwall tonnes per development metre decrease until the operation will reach a crossover point beyond the panel operating cost minima which is where the cost of continuing to radiate out in that domain is more expensive than developing the next domain much closer to the shaft / drift. This is the trigger point to progress to the next domain and so on.

Figure 1-3 forms the basis of any strategic mine plan when analysing the priority of extraction between domains. Obviously in reality mining conditions are not unrestricted nor are conditions and quality in coal ever homogenous. This relationship remains valid between a centralised shaft / drift and the fluctuation logistics strain of the operation. It is also important to point out that the logistics strain of the operation is not dissimilar to the highest ventilation load of an underground mine which is never the last longwall panel in a domain. Rather it is the most inbye location of a production district where all mining activities are still wholly within that domain. After this time development of a new domain commences where at least productive activity is closer to the shaft / drift and therefore reducing total logistics strain.

1.2.2 Adit / Box Cut / Cut and Cover Mine

Unlike the centralised shaft / drift operation, adit operations will continually move away from the surface portal. Usually, operations that use such entry systems cannot be centralised because they are using an adit entry (Dendrobium, South Bulli operations) or a box cut at the mine resource line of oxidation. Both portals' entries in this circumstance can only radiate away from the portal not around it. Narrabri North Mine is an example of such an operation in which the Life of Mine plan radiates away from the mine portal (Figure 1-4).

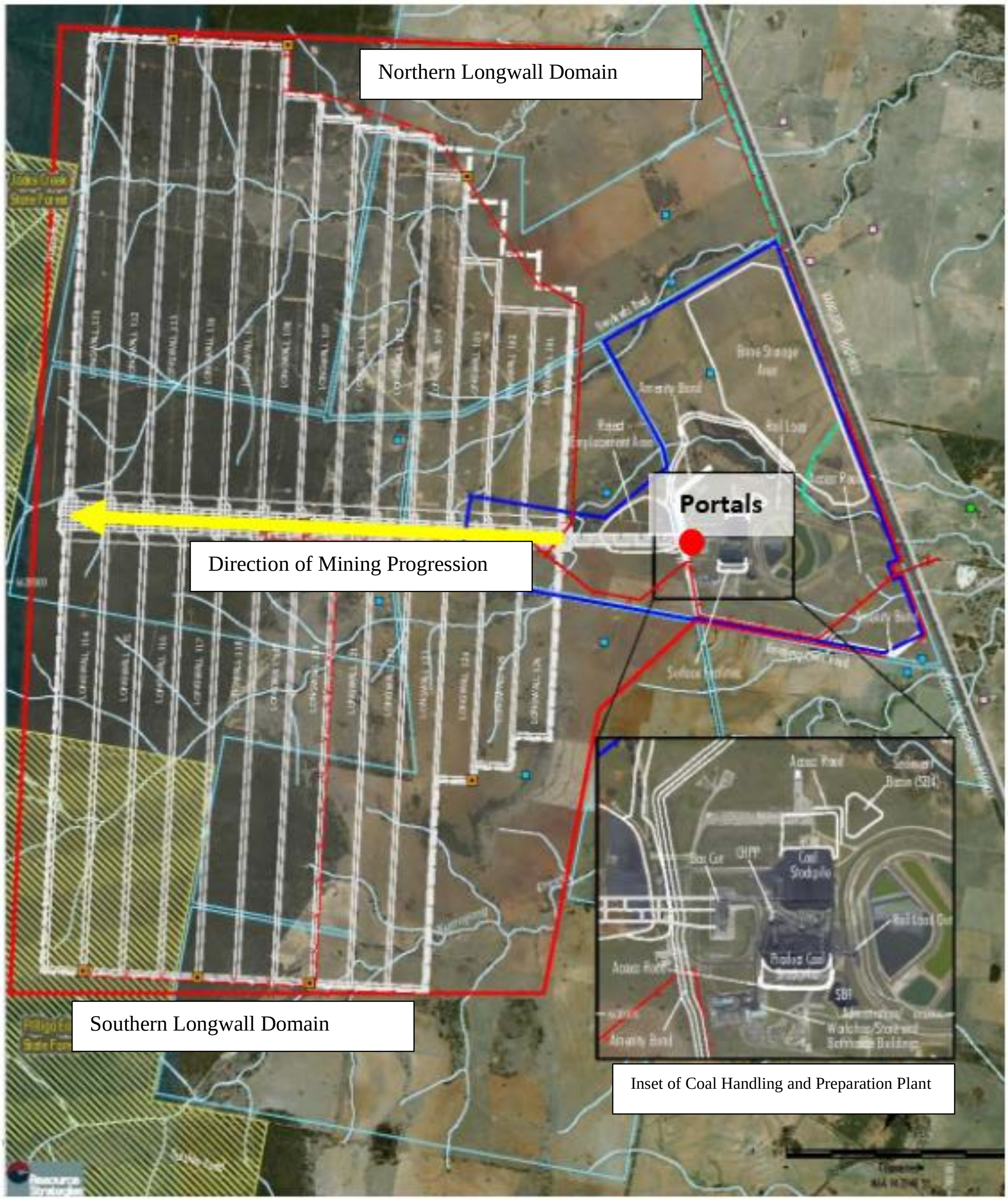

Figure 1-4: Narrabri North Mine plan showing pit progression away from the surface portals. (Underlay Map Source:RW-Corkery (n.d.))

As can be seen in this case the logistics strain (again as with mine ventilation) increases for the life of the mine. It will only be relieved if either a new box cut with new entry portals are developed (e.g., a whole new mine adjacent on the line of oxidation) or if a new set of portals inbye are established and surface access to the operation is enabled from this point.

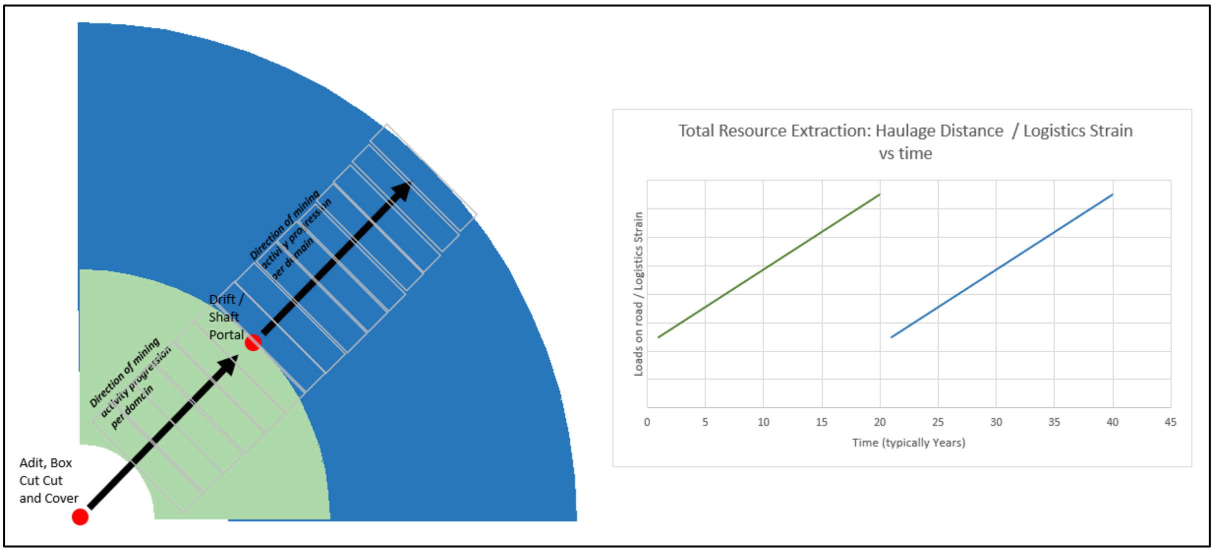

Figure 1-5: The relationship between domain changes for an adit / box cut / cut and cover portal access for production activity progression and haulage distance / logistics strain.

In the case of Figure 1-5 the operation can only relieve logistics strain by continuing to develop drift or shaft portals to continue to service the pit progression away from the original portals. Note in this circumstance the shafts and drifts are not centralised allowing radiation of activities away from the shafts / drift and will typically only service the operation as it continues in a generally singular direction.

Unfortunately, not all operations can sink a new shaft at a new optimal site, particularly as the "licence to operate" due to public perception and political will, can prevent such activities from going ahead in a timely manner. For example, the Dendrobium expansion project was rejected and is now before the courts under appeal (NSW-Government, 2021). Such circumstances include sensitive protected ecosystems, water catchments, archaeological sites, limited surface access, rare fauna, and flora, all of which can prevent a shaft or drift being built to alleviate logistics strain and therefore operations must continue to be serviced by distant surface portals.

Such an example is Dendrobium Mine. It continues to be serviced by a singular small drift/adit sometimes with only a single travel road to move all material and personnel. The Dendrobium Mine is shown in Figure 1-6:-

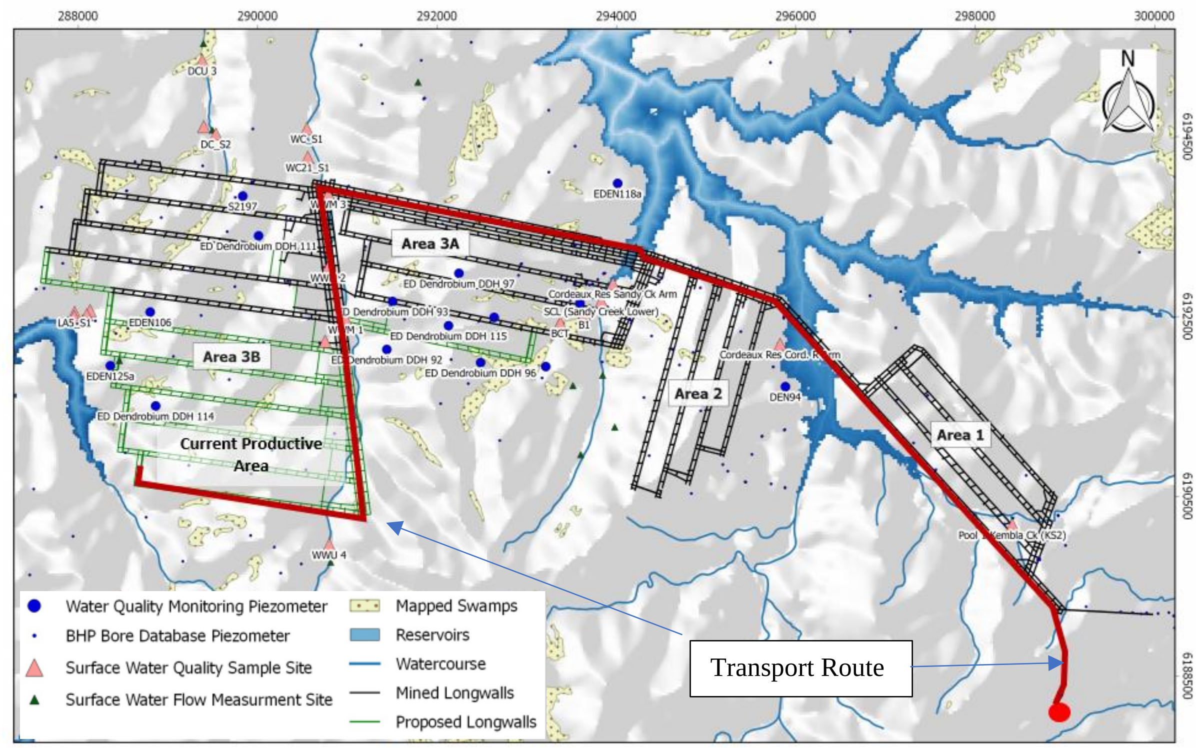

Figure 1-6: Dendrobium Mine showing portal access (in red) and the distance all supplies must travel to reach productive places. (Underlay Map Source:(Skorulis 2015)

In Dendrobium Mine's case the distance from the portal to the most inbye longwall face within the latest productive domain is 17.4 km. This is because there is no ability to install a new shaft or drift closer to the current productive area. Therefore, the logistics continue to be put under increasing strain as the mine continues to expand away from the portals.

Interestingly this is now also the case with Appin mine shown in Figure 1-3 previously. Even with multiple portal entries both productive domains WP3 and EP4 are now migrating away in the same direction meaning that any new shaft installation if approval is granted will emulate more of the adit / box cut / cut and cover migration away from portals as shown in Figure 1-5.

1.2.3 Logistics Breaking Strain

Circumstances may therefore, prevent relief to Logistics strain by sinking shafts or drifts closer to productive activities as a mine expands. Logistics strain will continue to increase with the expansion until there is a point where the productive activities bottleneck transfers to logistics and the rate of production begins to deteriorate due to either materials supply not being able to keep up or personnel not being able to arrive quickly enough to operate the machinery at the utilisation required. For the purposes of this thesis such an event is known as the Logistics Breaking Strain.

Logistics breaking strain can occur intermittently. In certain circumstances the amount of supplies and the number of personnel travelling to and from the productive area may need to increase due to geotechnical changes requiring more supplies and specialist personnel needing to be delivered, then once through this phase logistics strain returns to normal. Consider logistics strain over a timeline as shown in Figure 1-7:-

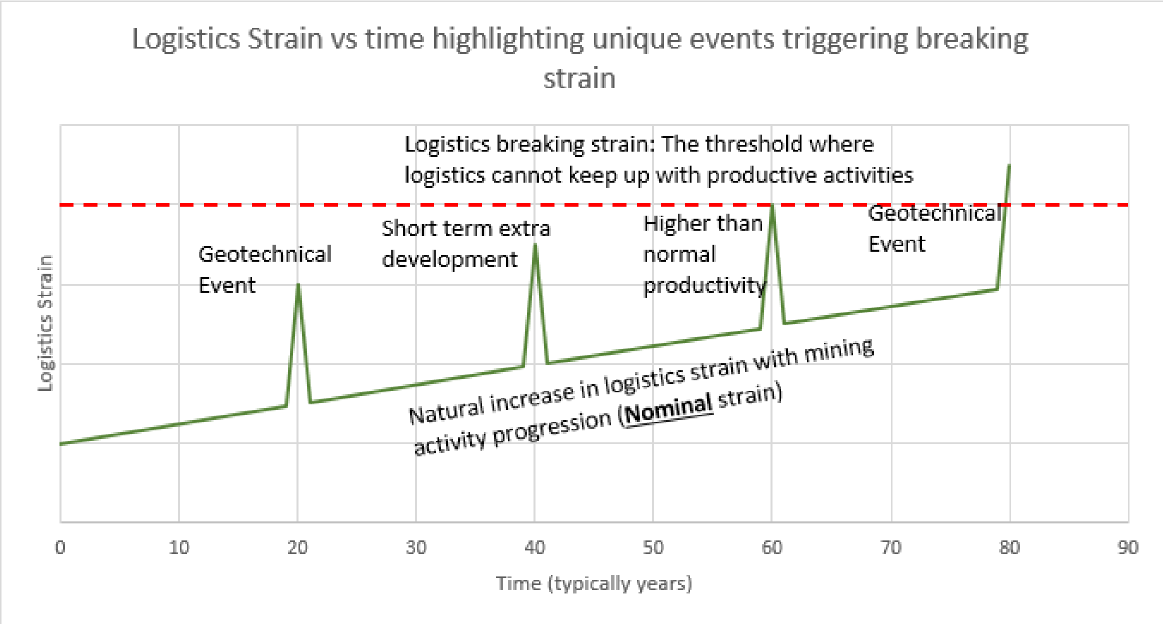

Figure 1-7: A simplistic example of unique events increase logistics strain for a small period before returning to normal.

In Figure 1-7 strain is increasing over time as the distance away from the portals increases. For the purposes of this thesis this will be called the nominal strain increase which is the natural increase in logistics strain as the mine progresses with all other things being equal. For the purposes of a simplistic example, the nominal strain vs time gradient is linearly increasing to explain the effects of unique events. Circumstances may see the logistics strain reduce for a time due to a reduction in the need for supplies delivery, the removal of productive units, or the redeployment of individual productive units to a relatively closer position with respect to the portal. Tactical retrospective planning will likely address the short-term peaks. However, ***nominal strain*** must be addressed at the strategic level with significant lead time to address logistics breaking strain or at the very worst understand the degradation in production and value to the operation.

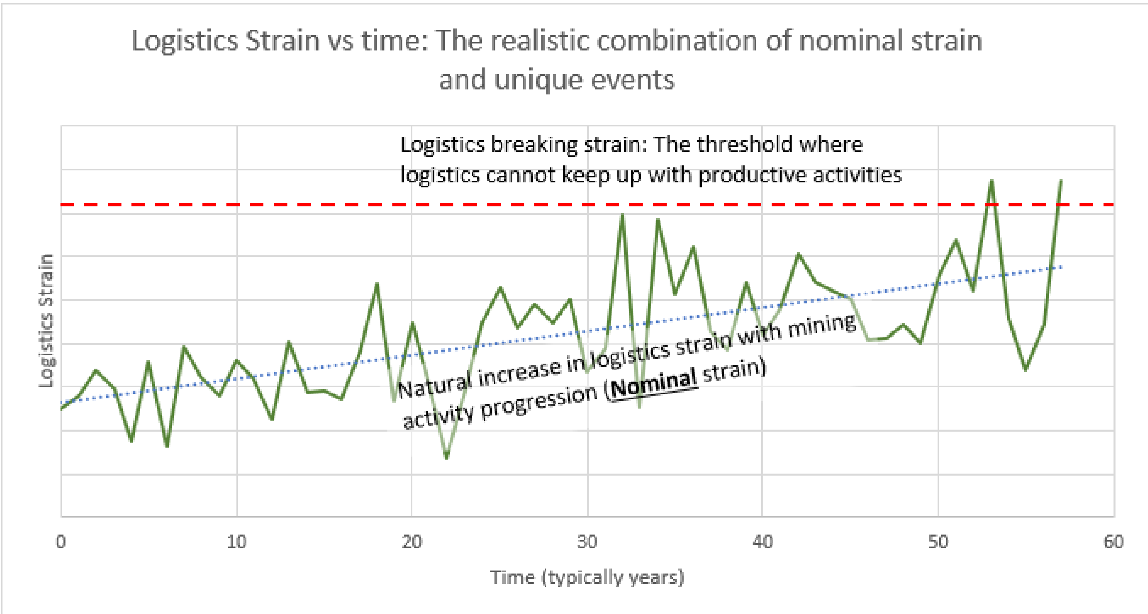

Figure 1-8: A feasibly realistic logistics strain over time graph.

The closer that logistics strain gets to the logistics breaking strain threshold the higher the chance that an event can occur on top of nominal strain that will trigger a breaking strain event and in turn a divergence from budgeted productivities. Total logistics strain is therefore a combination of nominal strain which is at a strategic timeframe as a mine expands away from its portal and unique events at a tactical timeframe such as productivity, the geotechnical regime, mobilisation/demobilisation of production units and can be expressed at any given instant in time as: -

1.2.4 More Units, More Problems

The natural way to fix a fall in productivity particularly in development is to increase the amount of development units. However, if the operations do not know that logistics breaking strain has been encountered, significant diseconomies of scale will likely occur. More development units will require more personnel in transit, more supplies to differing areas of the mine and more distractions of the operational oversight to manage to the point where a reduction in units increases or at least matches productivity. If the operation is blind to logistics breaking strain being the reason for declining productivity, then the operation will eventually reach a point of untenability by driving operating and sustaining capital costs up to address phantom bottlenecks, when all that may be required is a “hard reset” of the operation and a rebuild until productivity losses are experienced.

1.2.5 Perfect Storms

Multiple unique events may occur at any stage which accelerate the mine towards logistics breaking strain. For example, there may be a circumstance where all productive units may require significantly more supplies at once whilst at the same time there has been a significant drop in delivery productivity due to for example machinery breakdowns.

In ventilation and gas management, longwall emission is managed by a Peak to Mean ratio (Kissell et al., 1974). There is a typical background gas emission of gas but on certain days there might be additional emission of gas. The ventilation system is not designed to manage only the background emission but is designed to be able to manage the peak estimated emission. The same should also be said that a logistics system should be designed for the peak or “perfect foreseeable storm” by keeping a buffer between the logistics breaking strain threshold and the nominal strain. However, such a buffer will result in an additional operational cost profile, for example, the implementation of more roadways, increased frequency of maintenance for higher speeds, higher payload capability, and higher ventilation to allow more units inside ventilation splits.

1.3 The Research Question

Given the above context, the key research question that is asked in this thesis is: -

"Can a system be developed in any longwall operation's mine plan, to estimate the logistics strain and predict any occurrence of logistics breaking strain or risk thereof.?" Other secondary research questions include: -

1. Can this system be easily implemented into the traditional mine planning process?
   1.1. Traditionally the mine plan is the combination of mine design and productivity. Can the mine plan be expanded to include mine design, productivity, and logistics?
2. Can the system estimate total logistics strain? This includes: -
   2.1. Nominal logistics strain, including changes to baseline productivity, development inventory in advance, mine design, mine reserve extraction sequencing, the mobilisation and demobilisation of production units, the implementation of infrastructure that supports the logistics system closer to the production districts, the impact of delivery speed, or splitting the delivery system by utilising underground warehousing hubs closer to the production districts.
   2.2. Variable logistics strain including the impacts of variable primary support, day-to-day changes to the geotechnical regime, or changes in day-to-day productivity.

If so, can each variable be isolated on a case-by-case to understand the incremental impact of each?

3. In the event of logistics breaking strain occurring which cannot be fixed, can this system be used to cap production to the logistics breaking strain threshold.
4. Can the system being used in a real-world life of mine plan be calibrated with historical data to give an estimate of logistics strain over time?

1.4 Aim

Currently, there is very little strategic consideration or tracking of machine movements undertaken in relation to logistics from a life of mine planning perspective and any modelling typically ignores any bottlenecking risks that may arise. There is also no substantial evidence of research into correlation between rates of longwall production, development advance and machine movements underground. It is therefore imperative that identification of logistics breaking strain events be identified at the strategic level so that they can be "planned out" early to decrease the risk of logistics breaking strain being encountered until the natural progression of the mine without shaft or decline relief render it unavoidable. Mine designers can identify critical logistical problems that may occur in the future based upon the mine layout and the rates of both longwall and development rates which in turn allows for advanced planning for mitigating logistics breaking strain.

The purpose of this thesis is to develop a new system for early estimation of logistics strain at any point in the life of mine plan and identify if there may be any occurrence of logistics breaking strain within the whole life of mine plan to: -

1. Estimate logistics strain due to migration away from and return to a portal.
2. Estimate the logistics strain due to migration away from a portal in a general direction.
3. Explain the unique events that contribute to logistics strain.

4. Predict the mechanisms for how logistics strain reaches breaking strain.
5. Explaining the impact on logistics strain by adding more delivery LHDs to the system (more units – more problems).
6. Predict "perfect storms" that create considerable short-term strain on the mine's logistics management system.

1.5 Objectives

This thesis seeks to create an understanding and further develop action plans outlined in the next sub-section to address materials logistics in strategic mine planning.

1.5.1 <u>Understand the status of maturity of logistics planning within Australian Coal Mining operations to date.</u>
This requires going to actual Australian Coal Mine sites with a broad range of productivities and complexities and through inspection and stakeholder interviews:

- Understand the logistical constraints of individual operations.
- How logistics are managed at those operations.
- What is good practice and what is poor practice at these operations.
- Understand what role (if any) logistics plays in the strategic life of mine plan for an operation.

1.5.2 <u>Predict the future logistics management for a generic life of mine plan identifying supply bottlenecks in strategic mine planning using scheduling and simulation.</u>
This will require the development of a logistics simulation based on the relationship of longwall extraction rates, development rates, and speed of supply vehicles to point of delivery over time. This will then predict over time logistics strain and any encroachment of logistics breaking strain and therefore allow mitigative steps to be enacted before this logistics breaking strain impacts productivity.

The outcome of this thesis will allow the strategic mine planner to conduct sensitivities using the "Life of Mine logistical supply chain model" to understand the impact of a spectrum of development and longwall productivities.

1.5.3 <u>Quantify the impact of strategies employed in reducing logistics strain and preventing or at the very least deferring an incidence of Logistics Breaking strain.</u>
Underground coal mines can be serviced through multiple access points using multiple access modes (i.e., shafts, drifts and drop holes) utilising the network of roadways to develop alternative transport routes. Therefore, there could be several viable solutions to the underground coal logistical supply chain problem.

As part of the overall solution framework used in developing alternative solutions, a case-by-case build which isolates the change in logistics strain for one variable at a time using variations to key value drivers as shown in Table 1-1 has been utilised.

1.5.4 <u>Validating the overall system by validating the Strategic Model using the Tactical Model</u>
The strategic component of the logistics system must be able to be fed into the tactical level to firstly validate the logistics strain prediction at that time. This is done through comparing the number of LHDs (a term interchangeably used with Loader in this thesis) required using FlexSim (tactical) for any given day for the Life of Mine strategic model in XPAC. FlexSim can calculate based on speed, delays, and distance within any given

day to then predict what the minimum amount of delivery LHDs are required to be operating at once and that can be checked against the prediction made in XPAC.

Table 1-1: Key value drivers used in system experimentation

Value Driver	Description
Mine Design	Understand the impact of logistics strain by either radiating away and returning closer to the portal or migrating away in a general direction.
Productivity	Sensitivity of higher and lower production rates and understanding the impact of development float. Sensitivity of changes to the productivity or the planned delivery time window per day of the delivery LHD either in speed or payload capacity.
Mobilisation	Changes to the number of productive units operating within the mine.
Paths	Changes to logistics strain by changing the sequence of deposit extraction.
Mining Conditions	The impact of geotechnical regimes on the frequency of deliveries.
Additional Infrastructure	The installation of additional inbye portals/shafts to service the operation and/or the use of dedicated delivery transport routes with one-way traffic.
Capping to Logistics Breaking Strain	Having a designated maximum number of machines that can operate at any given time underground, for example ventilation constraints and changing productivities to not exceed that maximum.

Some solutions cannot be discovered at a strategic level inside XPAC, rather there are tactical solutions inside FlexSim that can be explored and applied back at a strategic level. For example, the true implication of delays on two-way roadways, where supply vehicles must shunt for each other when they are travelling in either direction in comparison to a dedicated one-way road travelling in and out which eliminates the need to shunt.

1.5.5 Apply the new embedded logistics system into a real-world life of mine model

Whilst testing a generic situation it is important to understand the key scheduling driver impact on logistics strain, if it cannot be applied easily to a real-world model then this thesis has no net benefit to industry. The system was tested on an existing life of mine plan in a mine designated here as "NSW02". Gathering of delivery data versus actual development rate enabled a realistic check of logistics strain predictions and enabled a prediction into the future of the suitability of its existing mine logistics system and if any measures needed to be taken. Historical deliveries allow validation of the system and calibration of future predictions of logistics strain whilst also highlighting the need for better logistics tracking into the future.

The application of this model needed to be proven that it could be "bolt on" so that it did not affect the integrity of the life of mine schedule. If this could occur, this means that historical or existing mine schedules could be retrospectively examined for logistics strain without ruining the integrity of the schedule which in turn minimises time spent by the mine planner and the risk of incorrect results by having to replicate the historical life of mine plan.

1.6 Chapter Conclusion

As mines continue to get larger and expand further away from portals at a faster pace, a new system that predicts logistics constraints is increasingly important. This is particularly so, with more constraints on the licence to operate, which may not allow arbitrary sinking of shafts to alleviate logistics strain. An early warning logistics system gives the mine an opportunity with sufficient lead time to explore ways to mitigate an event that is likely to reduce or cap productivity and increasing the reliability of the mine plan and its subsequent estimated valuation presented. The system must be able to be retrospectively applied as a bolt on to existing schedules and be rapid in application and prediction and it must be proven in the field with a real-world life of mine schedule. The system developed within this thesis had been designed to be this and enables early focus on a constraint that has been historically overlooked during mine planning.

Chapter 2

BACKGROUND AND RESEARCH JUSTIFICATION

2.1 Introduction

In July 2005, the Australian Coal Industry's Research Program (ACARP) commissioned Gary Gibson to identify constraints that would prevent development production rates from achieving full capacity. Gibson (2005) identified the following major constraints:

1. Primary roof and rib support.
2. The stop-start nature of shuttle cars where haulage distances are greater than 70 m.
3. Advancement of mine services and conveyor systems particularly in super unit /dual continuous miner configuration within a panel.
4. Advancement of ventilation ducting when not using concertina ventilation ducting mounted on a monorail.
5. The logistics of supply transport distribution and handling of roof support consumables is an issue at older extensive mines immediately while the achievement of higher development rates will compound this issue at most mines.
6. The rudimentary technology for the installation of long tendons as primary support.
7. The actual physical demands of the development face working environment.
8. The development of breakaways for cut-throughs, niches and cut-outs slowed up development considerably.

Since this time there has been a high degree of variability across Australian coal mining operations to address these constraints. Most of the research has been to address the production district constraints which are all the listed constraints above except for constraint 5 concerned with logistics limitations. Gibson (2005) rightly indicated that older operations with extensive underground workings required considerable labour-intensive logistical support to be able to maintain production levels at the status quo; but any step change increasing development would require a significant overhaul in the traditional logistical supply system for existing extensive mines. He also pointed out that whilst newer operations may not in the near-term experience production delays due to logistics bottlenecks there was a risk as these mines progressed that these bottlenecks would arise. There is no evidence that strategic planning in underground coal mines considers logistical supply chain bottlenecks as one progresses through the life of mine. It would be considerably cheaper if the life of mine planning engineer was able to identify the logistical bottlenecks and modify the mine plan accordingly to remove those bottlenecks or at least highlight the potential for a reduction in productivity rates at certain times within the mine's life.

This literature review discusses the use of simulation applications within the coal mining industry, current mine planning practices, existing logistical supply chain methods, the application of the theory of constraints (TOC) (McMullen Jr, 1998), LEAN business practices (Thangarajoo & Smith, 2015), and supply chain management (SCM)(Habib, 2011; Zeng et al., 2021), the use of robotic and unmanned supply methods all applicable and within the context of the underground coal mining industry. Above all this literature review is just for those objectives of this thesis while highlighting the shortfall of research done within the strategic life of mine space for logistical supply chain management in an underground coal mine.

2.2 Background

For a retreating longwall mining operation, roadway development is required to drive access tunnels to provide ventilation, machinery access and a supply route for electrical and water reticulation and other services. In Australia development drivage is a significant cost to the mining operation and therefore minimising this cost is imperative to managing unit cost of production (Kizil, et al., 2011). Development inventory is defined as how far in advance development roadways are ahead of the longwall production unit. Gow (1998) stated that lack of development inventory was a major problem faced by modern longwall coal mining operations in the world and it continues to be today. The larger the development inventory and the more roadways ahead of the longwall, the faster the longwall can go, the lower the development inventory the higher the risk of longwall discontinuity (Kizil, et al., 2011) which is due to the nature of a predominant fixed cost regime in underground mining and can rapidly bankrupt a mining operation.

A typical longwall mine operating at 3-5 Mtpa requires 9-15 km of development roadways to be driven each year (Lewis & Gibson, 2008). As longwall production rates improve the single largest constraint to higher production coal mines is roadway development (Rao et al., 2010; Smith & Hagan, 2012 & Norwest-Corporation, 2008).

If development cannot maintain inventory in advance a longwall discontinuity will occur at significant cost to the mining operation(Kizil, et al., 2011). This lag in maintaining productivity parity with longwall productivity has in turn meant development has had to compensate by installing more development units into the mine. This is supported by Gibson (2005) who found that a typical response to lower development metres was to increase the number of development units rather than examine how to get more productivity and utilisation out of the existing installed development units. Aside from an increase in unit costs and loss of competitive advantage, increasing development units means more strain on the supply chain with higher personnel and material flow in and out of the mine. Muguira (1998) argues that supply infrastructure may not be sufficient to support the additional development units required to bring development rates back to plan. In essence saying that without addressing the constraint of material supply to the continuous miners, more continuous miners will just each receive a proportional reduction in productivity.

Gibson (2005) stated that continuous improvement techniques were undertaken by Mining Management and site Mining Engineers but are typically focussed on the tactical short-term problems and rarely delve into solving the life of mine strategic problem of driving down costs. At the strategic level when suitably qualified mine planners are available with the expertise required to introduce strategic solutions, they will typically nominate an aspirational development rate or introduce more development units without any consideration to the supply chain required to sustain the solution put forward.

Underground coal mining logistics is typically regarded as all activities undertaken to support production within the mine with most mining logistics activities included in the following categories (Hanslovan & Visovsky, 1984):-

1. Personnel, equipment, and materials transport.
2. Coal clearance (transport).
3. Electrical and water distribution.
4. Ventilation.

Personnel and materials transport and materials supply are the primary contributors to logistics strain. Australian labour is expensive and in 2020 ranked 9th in the world with an average wage of USD $55,206 per annum based on purchasing power parity (OECD, 2020) and was ranked highest in minimum wage also in 2020 (World-Population-Review, 2022). Therefore, in Australian underground coal mines it is vital for global competitiveness and that people and materials supply are at the lowest possible cost. Personnel, equipment, and materials transport is the primary focus of this thesis and interestingly categories 2-4 also are reliant on category 1 and therefore supply chain movements are critical for modern coal mines (McKendry et al., 2009).

2.2.1 Supply Chain Equipment

Rubber tired vehicles, also known as RTVs which include LHDs, are now the prevalent personnel and material transport method in modern coal mines both within Australia (Cai, 2017b) and abroad (Guo et al., 2013). In mines where RTV access is not available from surface to face, rail transport in the case of declines or shaft access both transfer in and most transfer to RTVs to travel from pit bottom to the production face or other areas of work cases except for some older mines with rail networks (Lowrie 2002).

2.2.1.1 Personnel Transport

The Driftrunner is an explosion protected diesel powered personnel transport seating up to 12 persons (Hines 2019). Weighing 6 tonnes, it has a top speed of 25-35 kph depending on load and grade of the roadway.

Figure 2-1: Driftrunner personnel transport (left) (Source: Valley Longwall Equipment (2022)) and Driftrunner Hiab/Ute Variant (Right) (Source: Impact Mining Equipment (2022))

Variants include the 4-person capacity Driftrunner utility used for a combination of personnel and supply transport.

Smith (1999) highlighted the successful introduction of modified non-explosion protected (EP) Landcruisers into both Moranbah North and Crinum mines and found the following advantages:

- Higher speeds.
- Lower emissions.
- Higher manoeuvrability.

- Lower operating costs.
- Ride safety and noise reduction.
- Better lighting.

The biggest concern for this machine is that it cannot go into the hazardous zone as it is non-EP, thus, there needs to be hard barriers to prevent these machines driving to the production face or into returns. The system according to ex-employees of Moranbah North noted it was an excellent system with significantly faster travel times around the mine but was expensive to set up when automatic shutdown was required. This was consistent with Smith (1999) who stated that sensors are being used to shut down any non-flameproof transport machinery as it crosses a hazardous zone boundary. Non-EP Landcruiser type transport are yet to be introduced to New South Wales coal mines.

2.2.1.2 *Supply Machine / LHD Units*

LHDs in coal mines are the primary means for delivery of bulk supplies to the production district and have the capacity to tow two trailers in a train arrangement (subject to a mine site risk assessment). Coal mine LHDs are typically either four-cylinder or six-cylinder machines. The Work Health and Safety (mines and petroleum sites) Regulation (2014) limits the entry of diesel machines based upon ventilation where the criterion states a maximum of 3.5 m^3/s or 0.06 m^3/s per rated power capacity of a diesel machine . Therefore a Joy LT650 with a rated engine power of 164kw requires 10 m^3/s. Ventilation at the production face can be lower than this due to ventilation infrastructure constraints which may mean transfer of supplies to a smaller kw rated LHD. This was typically the case at Dendrobium Mine NSW between 2004 and 2008 where a six-cylinder 130 machine would deliver supplies to the production district entry but could not take it further inbye due to ventilation constraints and so a four-cylinder LHD (Eimco 913) would then take it to the face.

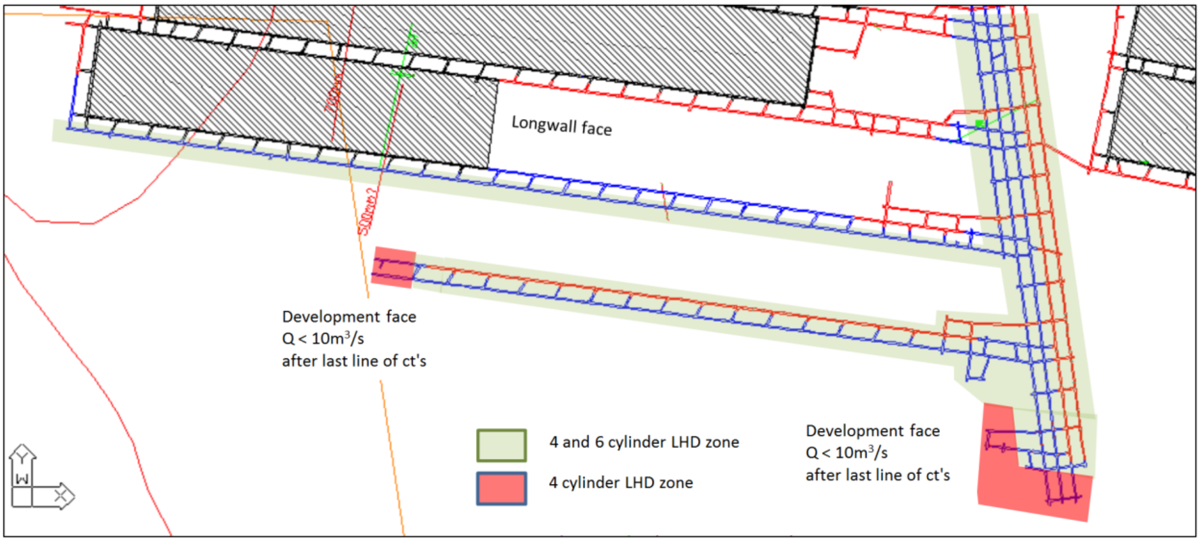

Figure 2-2: Longwall mining operation showing the LHD limits based on typical motor rated capacity due to typical ventilation constraints beyond the last line of cut through's (CT's).

Figure 2-3: Eimco LHD (Source: Orient Pacific Drilling Supplies (2017))

Figure 2-4: Typical implements and pods that LHDs carry in and about a coal mine (Source: Macquarie Manufacturing (2016b))

The aim of this thesis is to develop a supply chain computer model. This will link a mine design and its respective planned production rate, for both development and longwall, and then predict supply chain movements based on transport routes in and around the mine. The predicted supply movements will then indicate if it will be a production inhibitor, the ability of the mine plan to address it, and therefore reflect its realism.

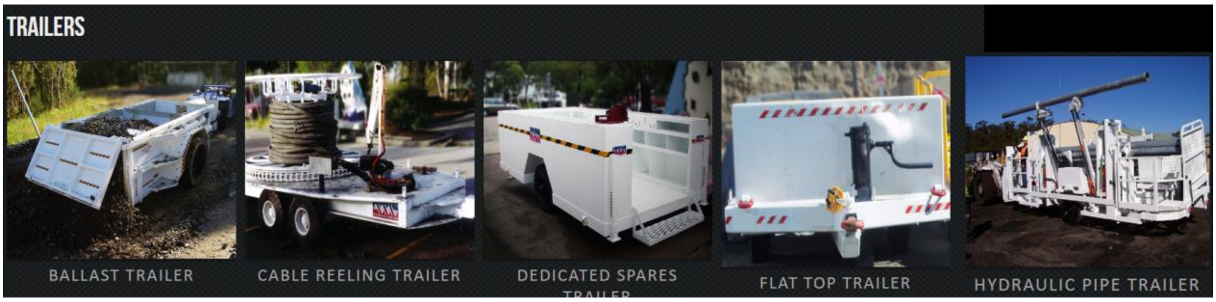

Figure 2-5: Typical trailers towed by LHD in and about the mine. (Source Macquarie Manufacturing 2016a Macquarie Manufacturing 2016b)

2.2.1.3 Autonomous Logistics Support

There is a growing opportunity to study the use of autonomous self-driving vehicles in materials supply (Jaiganesh et al., 2014). This is evident in the mega factory LEGO in Denmark (Figure 2-6) and with Amazon's USD $775 m acquisition of Kiva systems to streamline warehousing systems by using autonomous robotics.

Figure 2-6: Lego autonomous logistics support robot (Source: Canter (2014))

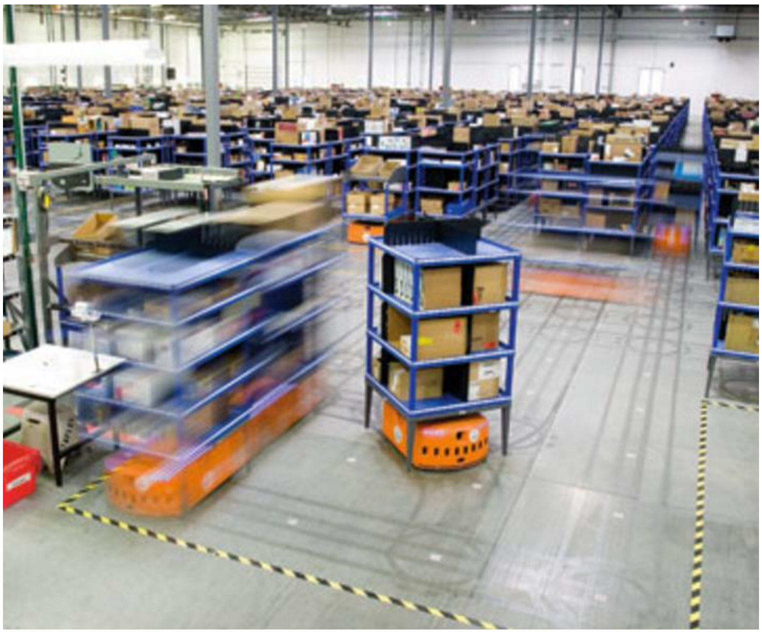

Figure 2-7: Amazon Kiva robots (Source: Kirsner (2012))

Rio Tinto (2017) used 71 autonomous haulage trucks which move 20% of total ore and waste material across its Pilbara operations. Rio Tinto's Nammuldi, Hope Downs 4 and Yandicoogina, operations move all their iron ore using autonomous trucking. Compared to a manned fleet autonomous trucks are 14% more productive and 13% cheaper to run.

Figure 2-8: Rio Tinto Pilbara operations autonomous trucks (Source: Rio Tinto, 2017 (Rio Tinto 2017))

So accurate was the system that enormous wheel ruts were being generated in the haul roads because each truck was going over the exact track of road, and thus an error factor was introduced to mitigate this.

Autonomous supply delivery is entirely feasible in an underground coal mine. Simple repeatable components of the logistics supply system could be transferred to autonomous underground haulage if powering these machines lies within the legislative requirements and the inherent coal mining industry biases are overcome. It has the capacity to have predictable systematic delivery of supplies whilst reducing manning complexity in a mining operation. As satellite global positioning system (GPS) does not exist in underground coal mines a quasi – GPS through positioning sensors installed along the roof with an error factor to prevent wheel ruts much the same as Rio Tinto the bulk of materials haulage could be taken from "surface to supply node". The supply node / storage area location for manned pickup would be nominated by those in charge of the mines supply logistics (typically the outbye, development and/or longwall coordinator(s)) but would be envisaged to be as far inbye as possible to reduce the time spent in manned supply units.

2.2.1.4 Monorail

Monorail systems are predominantly used within the production district of a coal mine and are used for the delivery of services to continuous miners and longwalls. Figure 2-9 illustrates the installation of a monorail system in a development panel. Smith and Hagan (2012) stated that Mandalong Mine had attributed the following improvements in the development panel to a monorail installation: -

- A decrease in production delays of 25%.
- A decrease in panel extension delays by 32%.
- A decrease in safety incidents of 37%.

Whilst monorail systems are used at production faces, they could be adapted to be used for autonomous high speed supply delivery to reduce RTV traffic and in conjunction with autonomous self-advancing monorail ((Meers & Van Duin 2012)) which in turn would reduce delays associated with human material handling during face advancement. This would likely be a surface to delivery node location where there was a sufficient area for storage and then transferring from the node to the production face using RTVs. This would require significant setup for existing mines to retrofit such a system and to ensure that appropriate assessment takes place to minimise RTV / monorail interaction.

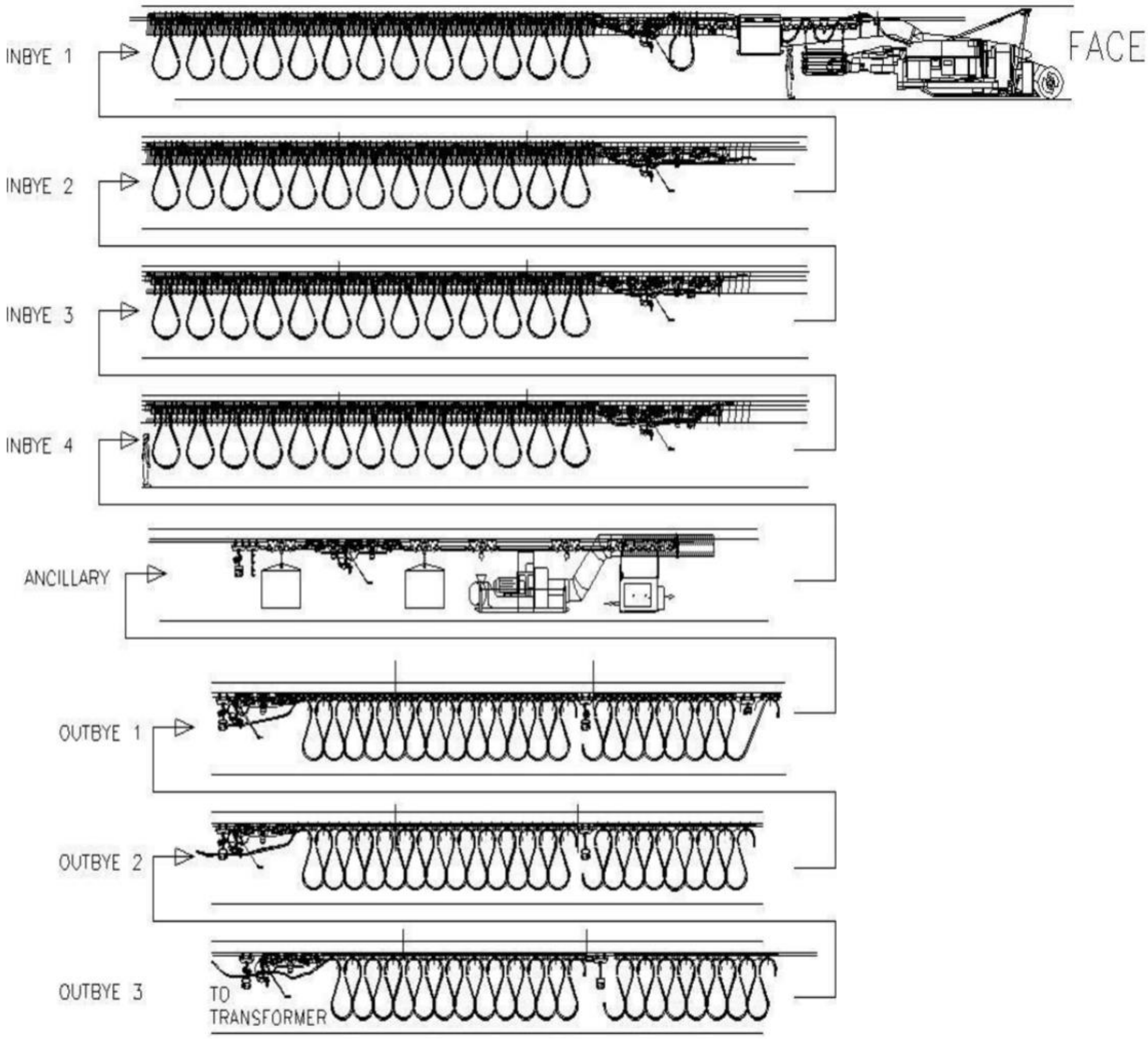

Figure 2-9: A schematic diagram of a development monorail. (Source: Coppins (2008))

2.3 Database Searches

Database searches were conducted across Google Scholar, Scopus and Web of Science using various terms, with very few results for coal mining logistics. The results are shown in Table 2-1. There is very little specifically about coal mining logistics. With more specific search terms such as "Underground coal mining logistics" these are discussed in the next sentences. The remaining instances of research as the search terms became less specific using the term "coal Logistics" were predominantly about downstream logistics from the coal face to the customer or movement of coal outside of the mining environment such as power stations. Underground logistics research was typically associated with civil infrastructure and city planning. As the search moved to even more generic terms, using "Mining logistics" the instances of research were predominantly about general supply chain management, data mining or transport generally between a supplier and customer.

Table 2-1: Search results for mine logistics research

Keywords, Topic, Title	Google Scholar	Scopus	Web of Science (all databases)	Comment
Underground coal logistics	0	0	0	
Coal mining bottleneck	0	0	0	
Strategic mine Logistics	0	0	0	
Longwall mining logistics	1	0	0	Within production zone interactions.
Underground coal mining logistics	3	2	0	Within production zone interations.
Underground mining Logistics	6	0	0	Includes 2 books >30 years old on actual logistics methods and equipment used. Includes upstream (supply to face) and downstream (clearance of coal/ore to the
Coal mining logistics	25	3	1	Downstream logistics from face to consumer.
Underground logistics	552	69	44	Primarily Urban planning and Traffic Management
Coal logistics	948	68	50	Downstream logistics including power plant supply management.
Mining logistics	808	30	11	General supply chain management, Data Mining, downstream transportation and Ancient Egypt building construction.

2.4 Evidence of research in underground coal mining logistics

The most prominent research undertaken in underground coal mining logistics focusing on machine movement so far has been by authors such as Cai (2015), Baafi et al. (2015), Baafi et al. (2019) and Cai et al. (2011, 2012a, 2012b, 2013, 2014). Their work over the years has been primarily focussed on inbye *within* the production district and the optimisation through simulation of these activities. Their work would be considered ground-breaking in optimisation of the face from the commencement of the production district to the coal face and would be considered complementary to the research undertaken in this thesis which is focussed on the portal to the start of the production district.

2.4.1 Evidence Logistics Study Through Underground Simulation

2.4.1.1 Simulation of Roadway Development

Prior to his contribution to the research on increasing development rates using simulation, Cai (2015) demonstrated the application of simulation software for continuous miner development panels. Cai's work demonstrated the ability to identify bottlenecks within a production district, and it is also capable of cycling through pillars for an entire development panel so that changes can be observed based upon changes to pillar length and changes to primary support regime per pillar cycle. From a tactical perspective Cai's work allowed development superintendents in charge of optimising pillar cycle to identify development face bottlenecks between cutting cycle primary support, ancillary delay, and shuttle car clearance rates and it is very effective in demonstrating potential immediate productivity gains from modifications to these factors. Cai's work was limited to a development production district of a coal mine; however, it did not have the capacity to identify supply chain bottlenecks from a mine portal to the entry of a production district. It also did not identify, as the continuous miner advanced linearly along a panel, as to whether the increasing travel time between a portal and a production district of the outbye logistics supply chain was able to maintain adequate supplies for the advance rate of the continuous miner.

Figure 2-10 is a flowchart which demonstrates how an entire development panel progresses, advancing from pillar to pillar using simulation software. On the left side of the flowchart is the logic of how a continuous miner and its ancillary equipment proceed to advance intra-panel. The variables that affect progression include factors such as advancement of the continuous miner versus the distance the shuttle car must move from the boot and primary pillar support type and ancillary delay. Once intra-panel tasks are completed, the logic moves to the right-hand side of the flowchart where a panel advance delay is encountered before resetting to the left-hand side of the flowchart for the next pillar cycle. There is no consideration for material supply from a portal to a production district on this flowchart as the system assumes that all outbye supply can keep up with the continuous miner advancement.

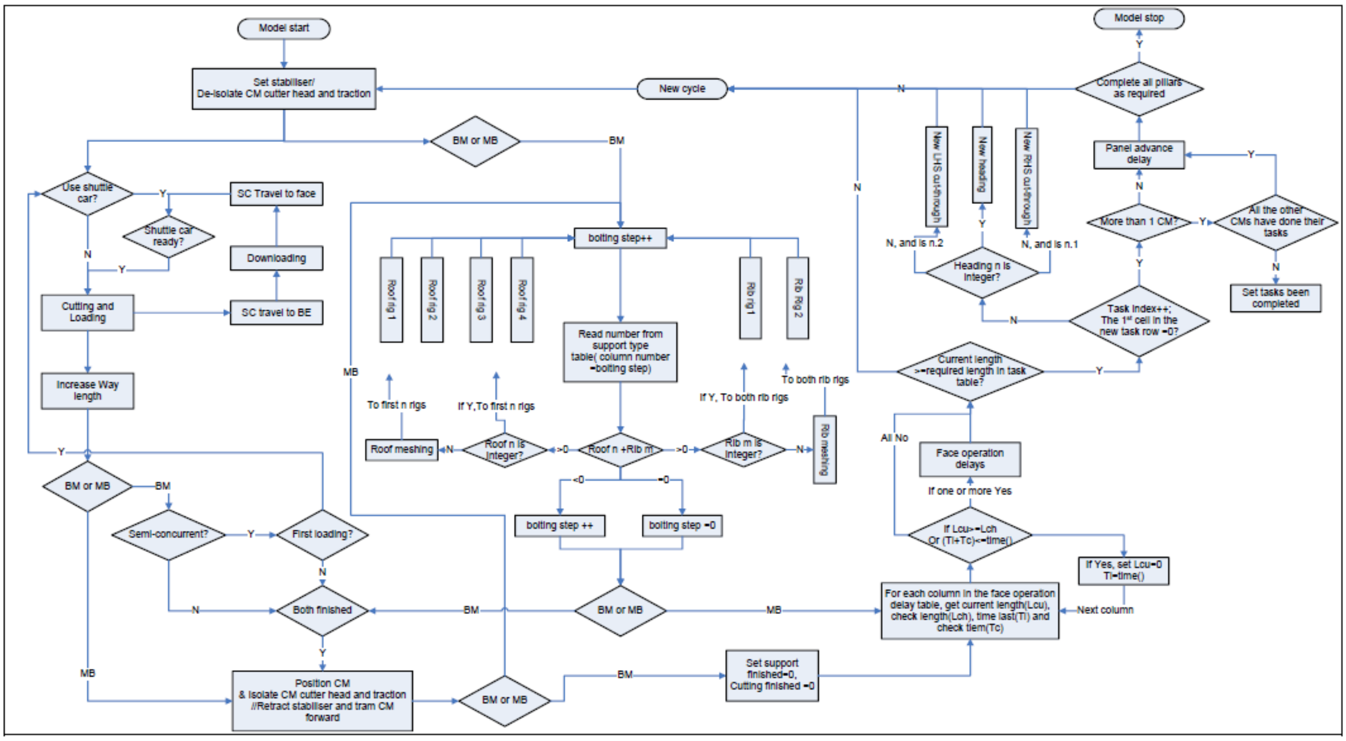

Figure 2-10: Integrated flow chart of the FlexSim roadway development model (source: Cai (2015))

2.4.1.2 Longwall Simulation

Cai et al. (2012a) constructed a discrete simulation model for longwall mining space using FlexSim software. The base model was originally built only to understand unconstrained bottlenecks by only changing the speed of each longwall component such as the speed of the shearer or the speed of the supports as it operated 365 days a year for 24-hours meeting identification of bottlenecking was difficult. The model was then enhanced to be able to account for delays that are experienced on a longwall face and history matched to real-world data. This allows the mining engineer to study the effects on the following: -

- Total productivity of longwall length.
- Longwall width.
- Production rate of unidirectional versus bidirectional cutting.
- Shearer speed.
- Armoured face conveyor (AFC) capacity.
- Coal clearance capacity.
- Speed of shield setting.
- Process delay and web depth on total productivity whilst also accounting for bottom line longwall utilisation.

As can be seen in Figure 2-11, bottlenecks can be introduced between the operation of the AFC and the shearer for example if the AFC is overloaded, the shearer must shut down. Much like the work done with simulation in the development production district, the longwall simulator is also limited to the longwall production district and does not consider outbye logistical support between a portal and a longwall production district and therefore cannot identify strategic supply bottlenecks as the mine continues to advance in the long-term.

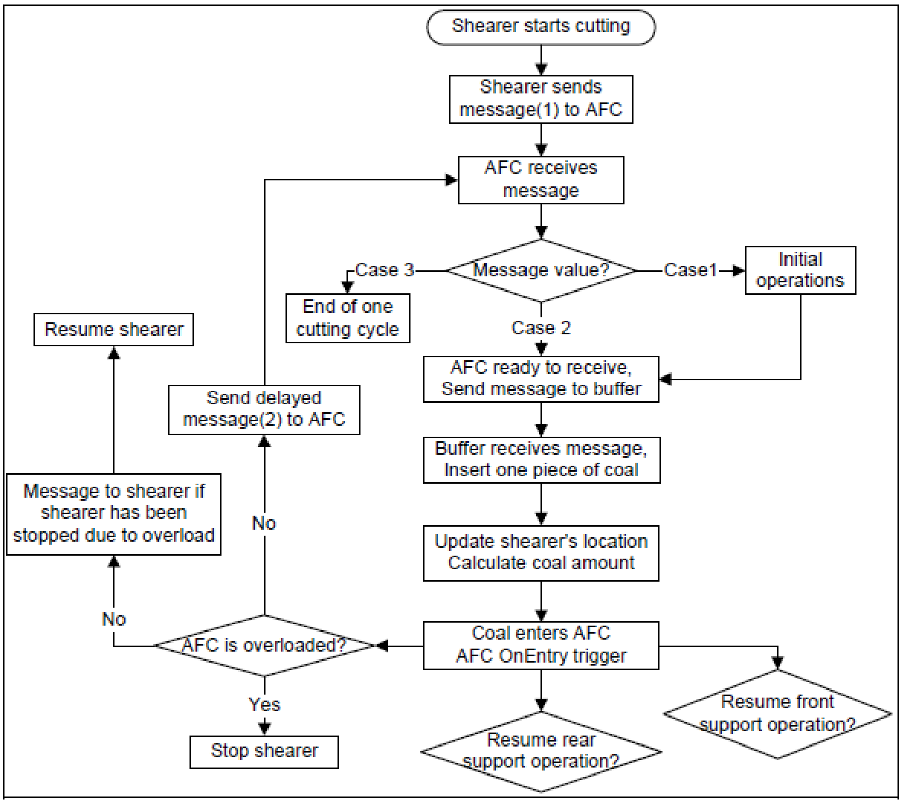

Figure 2-11: Flowchart logic between AFC and longwall shearer within simulator (source: Cai (2015))

2.4.1.3 Simulation to Optimise Development Productivity

Using simulation a 30% increase in development performance could be realised by increasing the speed of the shuttle car (Baafi et al., 2019). This suggests that the major inbye bottleneck particularly over long pillar lengths is coal haulage back to the boot end and return to the face. If such a bottleneck was able to be practically and safely removed by increasing speed, given the risk to high pedestrian traffic in and around the production district, it would be vital that the outbye logistics system studied in this thesis was able to accommodate such an increase in development rate.

2.4.1.4 Simulation of Material Supply

Not to be confused with Cai (D), Cai (L) in (2017a) again using simulation examined the effect of material supply on a single development unit's productivity. Cai (L) introduced various delays to represent materials supply delays, with small delays being from the production district storage area to the continuous miner and large rolling delays to represent upstream logistics delays that cannot keep up with the demand for supplies from the production district. He found that material supply from the production district storage area to the face has only a minor impact on development rate, reducing development rate by between 3.33% and 8.33%. However, he did note that if there were frequently large delivery delays that would be due to primarily systemic outbye materials supply bottlenecks in not keeping up with development demand the following was found:

- A material delivery delay of two hours for every 40 m of development would lead to a 15% reduction in development productivity.
- A material delivery delay of two hours for every 12 hours of operations would result in a 22% reduction in development productivity.

Such large regular delays can only be attributed to outbye logistics bottlenecks. In fact, if the above delays are realised, logistics breaking strain has occurred and from an upstream supply perspective, the impact of face material supply is minimal compared to material supply delays from the portal to the production district. This justifies why early strategic identification and mitigation of any outbye supply chain bottleneck is vital to maximise value of the operation throughout its life.

2.4.2 Life of Mine (LoM) Optimisation

Originally LoM plans typically had a single suite of productivities, a single suite of machine paths and a single geological model all which culminated together to form a single deterministic NPV to multiple schedules done very quickly to find the highest NPV. LoM Optimisers such as Blasor developed by BHP Billiton (Zuckerberg et al., 2007) (Rocchi et al., 2011) and GeoVia Whittle ™ (GEOVIA, 2022) aim to maximise NPV through high speed processing of automated mining schedules using a set of rules for variables such as productivity, production caps, processing and costs. Optimisers typically deal with the large input variables, but in doing so miss critical inputs like logistical supply bottlenecks.

Life of mine simulation includes the variability of the orebody itself (Dimitrakopoulos et al., 2002) and then adding to this the optimisation of waste emplacement. If we look closer at the issue of geological uncertainty by pit, optimisation evolution seems to be limited to only its application predominantly for the variability of size and grade of the orebody (Vallejo & Dimitrakopoulos, 2019). Orebody size and variability of grade was also discussed by mathematical and linear programming Rimélé et al., (2018). This included pit optimisers that expanded the scope to include optimal in-pit waste treatment within LoM simulations. However, these have been typically open cut pit optimiser centric and are known to treat production rate simplistically that require frequent intervention by the planning engineer (Levinson & Dimitrakopoulos, 2019).

Most recently simultaneous stochastic models (Levinson & Dimitrakopoulos 2019) address variability in productivity, grade, waste emplacement, inventory and processing. The impacts from a conventional LoM plan can be seen in Figure 2-12. In plan-view for period 10 the conventional schedule is predominantly mining to the west whereas the simultaneous stochastic model is predominantly mining to the east as the stochastic model attempts to review higher value ore earlier in the LoM schedule.

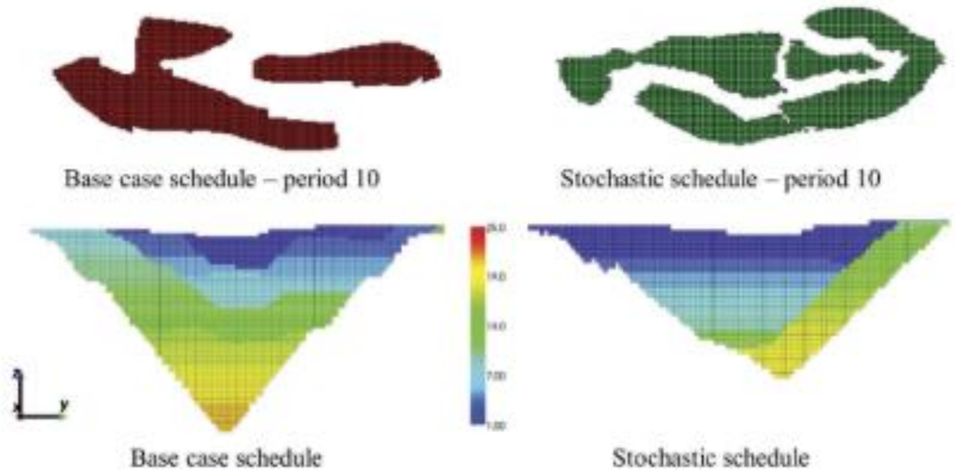

Figure 2-12: The difference between a traditional LoM schedule (Levinson & Dimitrakopoulos, 2019)

The application of LoM optimisation into the underground coal mining industry was discussed by Rocchi et al. (2011). There was a comparison between the use of deterministic XPAC scheduling compared with the BHP Billiton Blasor optimiser. "Shoe horning" of an open cut centric optimiser required it to be turned into an underground optimiser by removing all overburden and therefore targeting only the constraints associated with the orebody itself. Blasor also needed to be modified to ensure that the sequence of underground mining was adhered to. As Blasor would search for the greatest value as early as possible, new open cut pits could be opened at any time meaning in an underground coal mine new longwall blocks that add the most value individually could be spread across the entire resource and realistically these would not be possible given the need to maintain longwall continuity. Therefore, a modification to Blasor was made which essentially optimised groups of longwalls known as domains. With these modifications, it was found that XPAC even with multiple scenarios was limited in its approach to finding an optimised LoM plan compared to Blasor although the claim was not substantiated by replicating the Blasor schedule in XPAC. The constraints Blasor was capable of applying in Rocchi et al., (2011) varied from production rate, mining cost, blending and included downstream coal clearance and processing constraints but critically with respect to this thesis did not include any form of upstream underground supply logistical constraint, and therefore it did not identify any future supply bottlenecks either dynamic or static that any such optimal LoM plan may have.

Pit optimiser tools have therefore been used to optimise large value drivers that are typically encountered in the open cut environment, for which they were originally built. Ore grade and orebody size, productivity, waste emplacement for optimisation of hauls can all be addressed which for a comparatively unconstrained open cut environment mean that the system works very well. What is obvious is what would not be considered a major constraint within an open cut environment such as a supply bottleneck, in an underground mine reduces the development rate that in turn increases the risk to longwall continuity, nullifying any NPV optimisation gains if not addressed. It can be concluded that without considering underground centric bottlenecks such as logistical supply bottlenecks, the maximum NPV determined by a pit optimiser will always be higher than what is realised.

2.5 Broader Logistics Research

Simchi-Levi et al. (2008) describe the efficient integration of manufacturers and every intermediary through to a customer so that merchandise can be produced and delivered in the right amounts, to the right location and in a timely manner to minimise the total cost of the whole system. Stadtler (2005) states that the goal of supply chain management is to coordinate movement of units, materials, money, and information so that supply chain efficiency continues to be improved. Acquisition of raw materials, transformation into a product, sales and distribution must all be managed in order to achieve these goals (Christopher, 2011).

There is exhaustive research on route and fleet optimisation in more general fields of logistics that are continually improved upon which can be related back to underground coal mining material delivery. The customer could be considered the production district and the warehouse considered pit bottom. The research in this thesis develops a system that will deliver from pit bottom to a production district where inventory is held. The system assumes that any goods upstream of pit bottom are considered procurement, which are travelling up and down a drift from a surface warehouse.

2.5.1 <u>Fixed Partition Policy</u>

Anily and Federgruen (1990) introduce the term fixed participation policy (FPP). In FPP, customers are grouped together based on proximate geographic location. Every group then has an optimal route to replenish supplies whilst minimising transportation and holding costs through developing a distribution system that had a single holding depot with multiple receivers of supplies. The system developed included all inventory being held by the receiver. This is very similar to the delivery system proposed in this thesis. The depot being pit bottom and the multiple geographical routes for delivery are within the production district. The system includes deterministic rate of goods movement between a warehouse supplier to a customer, like the deterministic development rate and consumables used in a production district. However, (Anily & Federgruen, 1990) assume that only sufficient machines are available, which may be reasonable on unconstrained roadways in daylight. However, machine numbers are vital in understanding the practicality of the required system especially in a constrained roadway network, most of the time single lane, for two-way traffic, that mostly occurs in an underground coal mine.

2.5.2 <u>Inventory Management and Routing</u>

Andersson et al. (2010) focused on the combination inventory management and the transport route of delivery vehicles. Better known as the inventory routing problem (IRP), it was first discussed by Golden (1984). It is also recognised that the combined practice of route and inventory is prioritised in maritime and road compared with rail and airborne transport. Andersson et al., (2010) also introduced two ends of the supply chain spectrum, firstly convergent supply, where many components are brought together to make a product, and secondly, a divergent supply chain where a single raw material is distributed for processing into many products. Underground coal mining includes both. Coal production itself utilises a divergent supply chain, for example, it would be used for steelmaking, power generation, cement products, coal-to-fuel products and some clothing. Therefore, the face to portal supply chain would be considered divergent. Conversely, portal-to-face supplies, which is what is being studied here, takes a range of products to deliver coal production and is therefore convergent supply. Whilst the paper by Anderson et al., (2010) is useful for theory and definition of supply chain management it is limited to a tactical and/or operational levels, which would be considered day-to-day activities/planning. The research in this thesis is to develop a model at a strategic level which will identify logistics bottlenecks well in advance when rectifying costs are at their minimum.

2.5.3 Route and Fleet Design

Raa and Dullaert (2017) recognised that Anily (Anily & Federgruen, 1990), Anily and Bramel (2004) and Chan et al. (2013) only assume that the distance between the warehouse and the customer was small and therefore assumed there were sufficient vehicles available, which interestingly was found in Section 2.6 and is how strategic mine planning is done within Australia. (Raa & Dullaert, 2017) introduce a new approach to planning distribution from a single depot to multiple customers to minimise the combination of fleet cost, distribution cost and holding costs. It is important to note that each customer has a unique supply rate. The solution is broken into two phases, Phase 1, efficient route design, and Phase 2 determining the fleet that is required.

In Phase 1, a route was determined that could visit multiple customers which is considered a subset of all customers. A route was determined that for that subset of customers focused on savings. Then this route was further optimised by then optimising the route within the subset, for example, moving customer order around, and removing customers to another subset until a final suite of routes was determined for all customers.

In Phase 2, as this is metaheuristic the routes remain unchanged, where micro adjustments could be made to a route, but cycle times are adjusted to maximise utilisation of vehicles in the fleet and therefore minimise the number of delivery vehicles required to be purchased.

In underground coal mining the customer moves to a new location at any instant in time. The routes are governed by roadways already driven and those roadways being in intake airways, so the routes are fairly fixed therefore making route selection redundant. The size of deliveries is limited by the dimensions of the roadway cross section and therefore “mail run” routes to customer subsets to production districts are not typical nor are they warranted if there is ample laydown area for inventory within the production district. This is because the cost of holding delivered inventory is already borne when the surface warehouse bought it, they are not two separate commercial entities and therefore at this stage supply chain in an underground coal mine is a day-to-day routing problem and not fully IRP. The work of Raa & Dullaert (2017) does not address the dynamic nature of mining nor the fact that changes to the supply rate can occur. This problem was recognised earlier by Dror et al. (1985) who stated that the inventory routing problem has a different demand each day from a different customer. Whilst important in cost saving in traditional supply chains, it overcomplicates a solution for any given day in a mine and it cannot easily be applied across multiple mining schedules for comparison, and it does not provide a strategic outlook that this thesis will solve.

2.5.4 The Application of Industry 4.0 Standards

Blöchl and Schneider (2016) describe in their paper in Simulation Games for Logistics optimisation learning that Industry 4.0 is the application of information technologies for supply chain and assembly optimisation. They talk of logistics transmission as gears that are reflective of the cycle time of each delivery as shown in Figure 2-13:

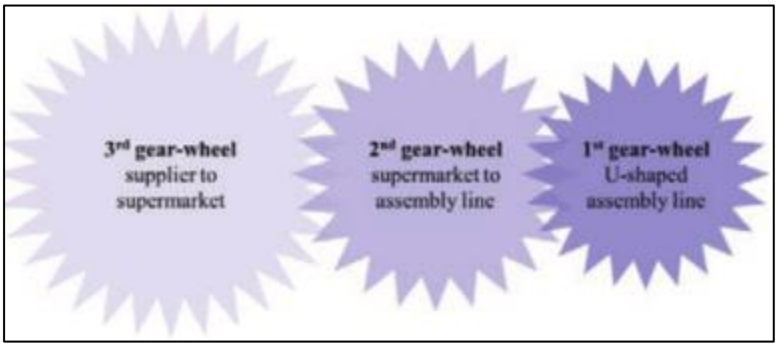

Figure 2-13: Gears of logistics transmission (after Blöchl & Schneider, 2016)

Now the above theory is applicable to a typical supply chain system for an existing coal mine. One gear wheel would be the delivery to the surface store which has a large cycle time and therefore requires large batch size deliveries. Gear cog two may represent portal to the storage area of a production district, which has a smaller cycle time but still represents some form of batch system. Gear three would be for the intra-production district from storage area to face. As can be seen this system of delivery is quite simple but it is questionable if it is truly optimal when applied across several production districts. This is typically how the Australian coal mine supply chain logistics is today.

Industry 4.0 standards unlock gains in supply chain productivity by being able to address complex interactions between stages of demand within each production panel for part picking, utilisation of autonomous vehicles and smart intralogistics. Yen-Chun Jim (2002) talks of lean logistics systems in the automotive industry as an example, the use of industry 4.0 has the capacity to increase cost savings in smarter lean logistics within operations such as a coal mine of the future. This means that delivery systems could be more responsive in a coal mine because what is being delivered is what is required rather than a standardised package of materials.

For example, let us say there are two development panels in a coal mine, one is in green support using only 2.4 m roof bolts and the other is in a red support using four x 2.4 m roof bolts but is also installing 2 x 6 m grouted tendons every metre. A standard delivery package that consists of both roof bolts and tendons would mean Panel #1 would receive a surplus of tendons that need to be taken with them as they advance and potentially a deficit in 2.4 m roof bolts and chemicals. In contrast, a standard delivery package to Panel #2 would mean potentially a surplus in roof bolts that need to be stored and potentially a deficit in tendon and grout availability! So, both panels could slow down either through managing production district surplus storage or lack of suitable supplies being able to keep up with production.

Now it would be argued that supplies are not always standardised, that tendon supply would be increased for Panel #2, but at present this would be managed manually through a daily meeting with the mining logistics department typically headed by the “Outbye Coordinator”, and therefore response times would be comparatively slow when compared to an automated system. On the other hand, Industry 4.0 would for example know that Panel #2 is in red support through smart intralogistics, the supplies would be picked from the store automatically based upon the rate of consumption of current supplies at the face, delivered by autonomous guided vehicles without any human intervention.

Industry 4.0 will not be able to be employed within coal mines at present as the regulatory framework currently would present a number of barriers. These would include autonomous vehicle interaction with the workforce on foot or regulations pertaining to electrical systems that would be required so that these barriers will be lowered in time. Therefore, setting up operations for long-term success with an Industry 4.0 mindset will reduce human interaction and systemise supply chain delivery able to deal with the day-to-day complexity experienced within a typical underground coal mine.

In a strategic sense and relating the application of Industry 4.0 back to this thesis, smart movements mean less movement because it is metaphorically surgical in its delivery mechanism. It would not have to wait for a human decision to respond to changes and then deliver a backlog of supplies further clogging the road system. Therefore, what would be traditionally a bottleneck strategically would no longer present a risk because of the reduction in on-road delivery vehicles which are also spread out throughout the day.

2.5.5 Lean and its Application to Logistics

Lean streamlines manufacturing and service processes by removing waste while continuing to deliver value to the customers (goleansixsigma.com, 2012). Waste is defined as anything that is not actually required to complete a process.

Yen-Chun Jim (2002) states an operation cannot be a lean operation without an efficient and reliable logistics system. An underground coal mine strategic/long-term plan rarely considers logistical supply so to say that lean thinking has been considered in coal mine supply chain management would be rare. One exception was during the 2007 ACARP conference West (2007) suggested its adoption with a simple heading stating, “Pull system for supplies?”. The presentation had no elaboration but did identify the need for further study in this field.

2.5.6 Theory of Constraints

Developed by management consultant Eli Goldratt in (1993) and expressed in the text/novel “The Goal”, the Theory of Constraints (TOC) outlines that if a business wants to improve overall productivity the following must take place:

1. Identify each stage in the total productive process.
2. Understand the mechanism of the actual constraint.

   It is found that the average travel speed is low due to poor roadway conditions due to the presence of mudstone and water in the floor which in turn turned to mud and meant frequent bogging of the trailer.
3. Prioritise management of the constraint with the goal to increase the throughput of the constraint.
4. Once the constraint is removed expose the next constraint and re-start the process.

   With concreting of the roadways reducing delivery times LHD reliability is exposed as the next constraint, limiting the number of transfers per day.

TOC can be used in the context of pipe delivery to the face within a coal mine supply chain. A hydraulic pipe trailer is shown in Figure 2-14 which is one of many types of rubber tyred trailers and implements required in the supply chain. Constraint points are identified in Figure 2-15.

Figure 2-14: Hydraulic pipe trailer attached to LHD (Source: Macquarie Manufacturing (2016a))

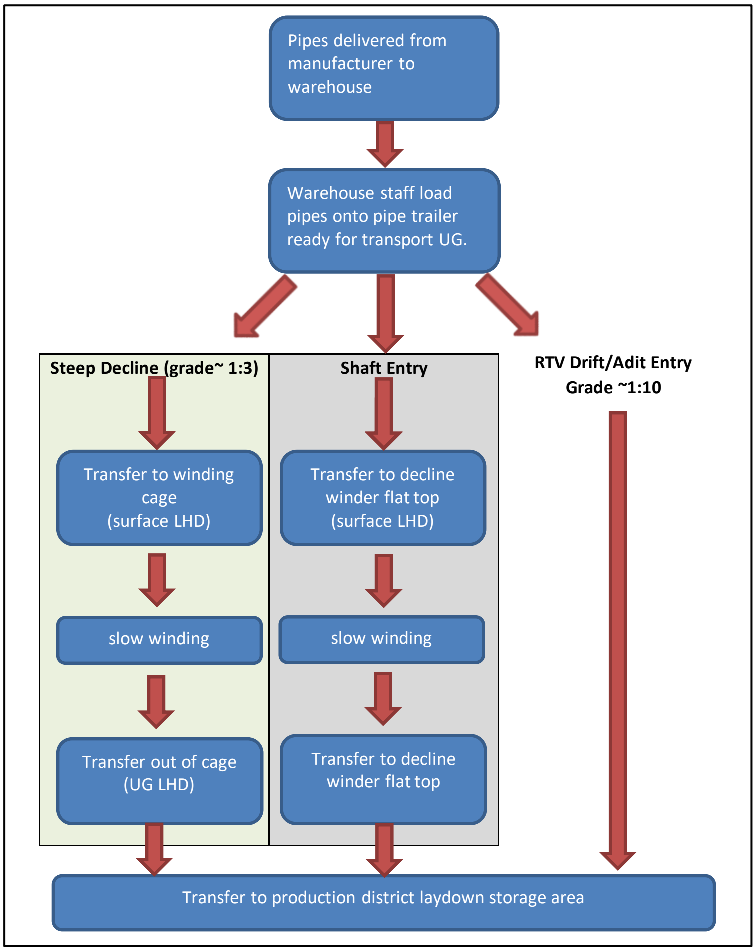

Figure 2-15: Typical constraint points for pipe delivery to a production district

2.6 Benchmarking Study of Underground Coal Mine Logistics

2.6.1 Introduction

Knowing that optimal supply chain management has been identified as critical in achieving higher development rates from the work of (Gibson 2005), in late 2018, a study was commissioned by ACARP to investigate supply chain management in underground coal mines in Australia and with these findings identify what could be done to streamline supply of materials and personnel transport across the industry (Walker et. al, 2020). The study encompassed multiple operational visits and interviewing key stakeholders whilst observing logistics practices on site to identify bottlenecks and best practice from a range of operational respondents from the General Manager to the delivery driver themselves.

The number one finding in this study was that logistics management is not considered in strategic planning and it is assumed the logistical operations can keep up with any production profile scheduled. The number one short-term recommendation from this study was to incorporate logistics management into the long-term strategic mine plan. For example, consider a mine plan for a longwall operation that requires two development units to sustain a production rate of 4Mtpa ROM. This will require less overall infrastructure than a mine operating four or five development units for the same ROM tonnes. If a mine plan has optimistic development rates to maximise value, the following ripple effect occurs:

1. Planned high development rates.
2. Leads to less planned development units to sustain longwall production.
3. Leads to less ventilation required in and about the mine.
4. Leads to less designed roadways required for ventilation.
5. Leads to less total supporting infrastructure.
6. Smaller workforce.
7. Leads to lower operating cost.
8. Leads to less logistical supply movements underground.
9. Less complexity.
10. Allows management to focus on maintaining high development rates.

When the operation gets underway in execution and it is found that actual development rates are half than that planned, the mine design in turn is set up for a highly efficient operation but now must carry four development units instead of two which places the entire original mine design and total managerial system for the mine at risk of irrelevance either in part or full.

This finding and recommendation are the reason why this thesis is being undertaken.

2.6.2 Approach

The study reviewed the logistics practices of 11 underground coal mines and two metalliferous mines currently operating in Australia. The focus of this was to understand how each operation managed its supply chain and highlight shortfalls and best practice, and give key recommendations in the short, medium, and long-term to continually increase logistics efficiencies.

Thirteen mine sites were studied, 11 being underground coal operations and two being metalliferous operations. The metalliferous operations were studied to see if any best practice could be transferred to underground coal and or if they shared similar logistical constraints. Site visits were made to 10 out of the 11 coal mining operations. One coal mining operation would not allow access to the team due to it being in a longwall changeout and the two metalliferous operations requested to be interviewed over the phone. A questionnaire targeted to each stakeholder's position interviewed was constructed. This was done to ensure the right stakeholder could give the most accurate answer, for example there is no reason to ask a general mine manager a delivery driver question asking, what is the biggest impediment to speed of a delivery LHD and there is no reason to ask a machine operator and general mine manager question asking, if the strategic mine plan considers future logistics constraints.

Prior to release of the questionnaire, feedback was sought and given on its content from senior coal mining personnel to ensure the right questions were being asked at the right stakeholder or positional level. This questionnaire is shown in Table 2-2 and was modified to suit the two metalliferous mines:

Table 2-2: Logistics Questionnaire seeking specific stakeholder responses (source: Walker et. al, 2020).

<u>MINE LOGISTICS QUESTIONNAIRE</u>

	MINE:-	We collect as much information as possible from staff that are available to minimise disruption to operations. Not all people need to be spoken to, rather this questionnaire is a prompting for the research.
Management and Technical Services	**MINE MANAGER**	**RESPONSE**
	In your opinion does the mine plan identify and account for logistics bottlenecks within any forecast timeframe?	
	Does general weekly plan compliance exceed 80%?	
	Do you have a weekly plan compliance review?	
	Is there an ongoing risk of negative float in this operation?	
	What would be one thing you would do to streamline delivery of materials onto the face machinery?	
	What are your top 3 biggest issues which slow delivery of materials?	
	What would be one thing you would do to streamline delivery of materials?	
	Do you think other delays mask "wait on materials delays"?	
	On a scale of 1-10 (where 10 is world's best practice) how would you rate your logistical supply chain at this mine?	
	Are Injuries due to materials handling and personnel transport recorded separately? If so how many per year?	
	MINE PLANNER	**RESPONSE**
	In your opinion does the mine plan identify and account for logistics bottlenecks within any forecast timeframe?	
	What is your range of depth of cover?	
Finance and Warehousing	**ACCOUNTANT**	**RESPONSE**
	Do you see supply and warehousing as a significant cost to this operation?	
	Are supplies delivery total cost easily tracked in your operation?	
	What would be one thing you would do to streamline delivery of materials and personnel onto the face machinery?	
	WAREHOUSE SUPERVISOR	**RESPONSE**
	What would be one thing you would do to streamline delivery of materials onto the face machinery?	
Outbye Services	**OUTBYE CO-ORDINATOR**	**RESPONSE**
	What are your top 3 biggest issues which slow delivery of materials and personnel?	
	Cycle time for delivery?	
	What would be one thing you would do to streamline delivery of materials?	
	Do you have dedicated material delivery windows?	
	How do we prioritise delivery to the panel?	
	During longwall changeout do you see a significant change in material supply delivery productivity?	
	How is Roadway maintenance managed?	
	What is the best number of deliveries per day?	
	CONTROL ROOM	**RESPONSE**
	Time to first coal?	
	What are your top 3 biggest issues which slow delivery of materials?	
	Delivery time for delivery of materials?	
	How are supply drivers reached underground?	
	Travel time to face from walking into cage / drifty to panel crib room?	
	What are the best number of deliveries per day?	
	SUPPLIES DRIVER	**RESPONSE**
	What are your top 3 biggest issues which slow delivery of materials?	
	How often is roadway maintenance undertaken?	
	Cycle time for delivery?	
	What would be one thing you would do to streamline delivery of materials?	
	Do you believe you make plan for deliveries per shift? How many times out of ten shifts would you make the quota?	
	How are unused supplies managed? Is there a problem with wastage and repackaging unused supplies?	
	What is the primary means of communication of the delivery work required?	
Production	**UNDERMANAGER / CO-ORDINATOR**	**RESPONSE**
	How often is "Wait on materials" booked as a delay?	
	Are there any specific shift change road rules to reduce time to first coal delay?	
	Do you think other delays mask "wait on materials delays"?	
	Are secondary support requirements handled separately and how?	
	What would be one thing you would do to streamline delivery of materials and personnel onto the face machinery?	
	Travel time to face from walking into cage / drifty to panel crib room?	
	During longwall changeout do you see a significant change in material supply delivery productivity and personnel travel times?	
	PANEL DEPUTY	**RESPONSE**
	How often is "Wait on materials" booked as a delay?	
	Do you think other delays mask "wait on materials delays"?	
	What would be one thing you would do to streamline delivery of materials and personnel onto the face machinery?	
	Travel time to face from walking into cage / drifty to panel crib room?	
	What is the mechanism for the order of supplies to the panel?	
	FACE OPERATOR	**RESPONSE**
	How often is "Wait on materials" booked as a delay?	
	Do you think other delays mask "wait on materials delays"?	
	What would be one thing you would do to streamline delivery of materials and personnel onto the face machinery?	

A general observation checklist to ensure consistency in data collection is included Table *2-3*.

Table 2-3: Site visit observational checklist *(source: Walker et. al, 2020).*

OBSERVATIONS	
Lighting (any?, Mains only?)	
Floor conditions , concrete/ ballast, how is the water managed off the roads?	
Methods for delivery request?	
Transport vehicle availability?	
Delivery windows. Deliver in batch or Just-In-Time (JIT)?	
Packaging of goods, how are they packed?	
Ancillary interference light sections, outbye movements of other machines?	
Surface Entry Type?	
Mode of Transport Continuous Portal to Panel / Pit Bottom Lay down / Transfer Area (Y/N)?	
If Yes How does transfer occur?	
PED Trackers of personnel?	
Other systems Diesel Hydraulic Oil Solcenic Stone dust	
Logistical supply 1. How many hands does it pass through? 2. How many departments does it pass through? 3. How many people are involved in the delivery process?	
Are there any parallel task portals or holes? Pipes - diesel, solcenic, stone dust? Ballast and concrete drop holes?	
Inbye diesel stations (what is their distance from face)?	
Underground (UG) Welding Bay for overhauls. Are these preplanned plug and play or ad hoc?	
Chock lay down area?	
How many PODS are in the system per panel?	

CHECKLIST OPERATIONAL DATA	
FY17,18,19 Production and delay data available?	
Mine plan highlighting transport routes and intermediate storage points (if needed) available?	
PED Tracking of all data available?	
Cycle time?	
Production tonnage and rates?	
Longwall Float?	
PHOTOS	
Storage Facilities	
Materials UG Transport Dedicated trailers, pods, vs ad hoc bucket / pjb / ute / other deliveries.	
Personnel UG Transport	
Control Room screen shot of logistics	
Delivery work order sheet	
Surface Portal / Entry	
Transfer points or nodes for materials	
Final Delivery point storage point	
Packaging of goods	
Typical loaded supplies transport	
Storage at panel end. Storage at pit bottom. In between.	
VIDEO	
Transfer materials to UG transport	
Video of typical transport into pit for materials	
Unloading points	
Video of typical transport into pit for personnel	

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2.6.3 Findings

Table 2-4 summarises the observations that Walker et al. (2020) found after visits and interviews of 11 Australian east coast coal mines and two Australian metalliferous mines. It was important to capture a large spectrum of operational conditions including depth, age of the operation and productivity. The operations ranged in depth for coal between 130 m and 600 m and for metalliferous between 800 m and 1800 m. Year-in, year-out productivities ranged from 2.5 through to 8.4 Mtpa for coal mines and 1.1 to 10 Mtpa for metalliferous mines.

Table 2-4: Consideration of logistics in medium to long-term planning from mines interviewed / visited (source: Walker et. al, 2020).

Mine No.	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	#11	M#1	M#2
Type	Coal	Coal	Coal	Coal	Coal	Coal	Coal	Coal	Coal	Coal	Coal	Metal	Metal
ROM Mtpa	4	2.5	2.5	4	6.5	5	2.5	4	6.4	5.25	8.4	10	1.1
Depth of cover (DOC)	600	500	520	430	130	350	240	500	350	270	350	860	1800
ACCESS	Drift and Shaft	Drift and Shaft	Drift	Drift	Adit	Drift	Drift	Drift	Drift	Adit	Drift	Decline and Shaft	Decline and Shaft
Transport	RTV	Mix RTV + Rail	RTV	RTV	RTV	RTV	RTV	RTV	RTV	RTV	RTV	Mix RTV + Rail	RTV
LONG TERM LOGISTICS CONSTRAINT IDENTIFIED?	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO

Walker et al. (2020) found through site visits and interviews of these 13 operations that logistics was known to have significant delays in at least one large operation based on anecdotal off the record conversations, particularly with respect to critical development, that was not captured in management reporting systems and was masked by process delay. To rephrase, if there was a materials delay to primary support, rather than book the delay the production face would undertake other stand-by work such as re-routing electrical cables, statutory inspections or extending ventilation tubes. As an experienced operational supervisor and engineer, the author of this thesis believes this is the right thing to do, but such work may not be undertaken at an optimal time and therefore it is entirely conceivable that this may create delays and inefficiencies into the future. For example, if there was a materials supply delay that brought on a premature re-route of a cable, this may increase the total number of re-routes for the pillar drivage sequence which may in turn decrease direct operating hours. Therefore, without capturing this delay, data management cannot identify the true reason for redeployment and inefficiency which in turn would have a reasonable expectation of driving down total development productivity.

2.6.3.1 Access Type and Productivity

In a coal mining operation, productivity, or lack of, cannot be solely attributed to logistics management, but there is a definite association of inverse proportionality between logistics complexity and productivity. As can be seen in Table 2-5, the lowest producing operations (<2.5 Mtpa ROM), material and personnel transport from portal to production district used a sequence, in series, three material delivery machinery types, a drift dolly car then rail to a delivery hub and then RTV to the face. Operations between 2.5 Mtpa and 4 Mtpa, used two material delivery types, where material supply and personnel transport with either a dolly car or shaft to pit bottom and then transfer to RTV from pit bottom to the production district. Higher producing operations which were greater than 4.0 Mtpa used RTV drive-in drive-out material and personnel supply minimising any interruption due to transfer onto a different type of transport.

Rail deliveries were typically done with large batch deliveries and there was dedicated equipment used to speed up material transfer with the use of cranes in laydown areas / logistics hubs, but it was found that the transfer between the machinery types themselves cancelled any productive gain made. Rail was inflexible. If a roof fall occurred in the transport roadway, the system would need to be abandoned until the roadway could be recovered, which would entirely change the delivery process from large batch delivery on rail flat tops to smaller RTV loads. With rail and in turn batch delivery, if a last-minute change to roof support required supplies directly from the surface due to a lack of end of rail supply hub stock this would require significant planning and a drop in efficiency of the rail network as the customised supply was prioritised over the normal batch requirements. RTV on the other hand could react quickly, albeit with smaller loads, these could be delivered in less time, without interrupting the normal supply chain if it was done for example by a super-numery panel machine leaving the dedicated RTVs to deliver their standard loads.

Table 2-5: Production vs transport type. (source: Walker et al.,2020)

Current Mine Production Range	Number of Transport Types between surface and Production Zone	Transport Type from surface
<2.5Mtpa	3	Surface to Pit Bottom: Dolly Car / Shaft Pit Bottom to Outbye delivery Hub: Rail Delivery Hub to Face: RTV
2.5 - 4Mtpa	2	Surface to Pit Bottom Dolly Car Pit Bottom to Face: RTV
4.0 - 8Mypa	1	RTV Only

2.6.3.2 Lighting, Roadway Conditions and Time to Production District

Well lit, concreted and well drained roadways led to between roadway higher delivery speeds as operators had confidence of what they could see and the conditions of the roadway “underfoot”. Well drained roadways meant the floor could be seen well while travelling at speed and reduced the risk of damage or premature wear to machinery and loads or injury to personnel or damage to the road itself particularly if the floor was soft like a mud or siltstone. Table 2-6 highlights the findings of the incidence of lighting and concreting at each operation interviewed / visited. It should be noted that concreting was not required to take place in the metalliferous mines because the country rock drivage was hard and performed at least to the standard of concrete.

In interviews with critical personnel, 60% of higher producing operations included some level of lighting in transport roads. It was also found that half of the remaining high producing operations deemed the installation of lighting as an operational priority to assist in streamlining logistics.

Concreting and proactive water management was undertaken in all higher producing operations. The highest producing operation only concreted on an ad-hoc basis typically in areas of water make and weaker floor as the remaining floor was suitable for higher speeds. When considering travel times, it was found that six operations that had long travel times exceeding one hour to the production district did not prioritise concreting the floor which may be reflective of floor conditions or worse, they cannot economically justify the investment in doing so.

Table 2-6: Incidence of lighting and concreted roadways from mines interviewed / visited. (source: Walker et al.,2020)

Mine No.	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	#11	M#1	M#2
Type	Coal	Coal	Coal	Coal	Coal	Coal	Coal	Coal	Coal	Coal	Coal	Metal	Metal
ROM Mtpa	4	2.5	2.5	4	6.5	5	2.5	4	6.4	5.25	8.4	10	1.1
DOC	600	500	520	430	130	350	240	500	350	270	350	860	1800
ACCESS	Drift and Shaft	Drift and Shaft	Drift	Drift	Adit	Drift	Drift	Drift	Drift	Adit	Drift	Decline and Shaft	Decline and Shaft
Transport	RTV	Mix RTV + Rail	RTV	RTV	RTV	RTV	RTV	RTV	RTV	RTV	RTV	Mix RTV + Rail	RTV
Lighting	Critical Infrastructure only	Partial Mains and Critical Infrastructure	Critical Infrastructure only	Partial Mains and Critical Infrastructure	Partial Mains and Critical Infrastructure	Critical Infrastructure only	Critical Infrastructure only	Critical Infrastructure only	Critical Infrastructure only	Mains and Critical Infrastructure	Mains and Critical Infrastructure	Critical Infrastructure only	Critical Infrastructure only
Concrete Travel Roads	No	No	No	No	Mains + Partial Gates	Gates	Main @ 50%	No	Gateroads	As needed	Intersections and as needed	No	No
Time to First Prodn (mins)	75	70	75	75	75	35	100	80	45	60	110	60	65

2.6.4 Logistics Bottlenecks

Table 2-7 shows the top three biggest logistical impediments on a per site basis from which machine reliability was a common impediment between coal and metalliferous mining. Labour albeit specifically trades availability in metalliferous #2 was also a shared impediment with coal.

Table 2-7: Top three logistics impediments by operation. (source: Walker et al.,2020)

Mine No.	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	#11	M#1	M#2
Type	Coal	Coal	Coal	Coal	Coal	Coal	Coal	Coal	Coal	Coal	Coal	Metal	Metal
ROM Mtpa	4	2.5	2.5	4	6.5	5	2.5	4	6.4	5.25	8.4	10	1.1
DOC	600	500	520	430	130	350	240	500	350	270	350	860	1800
ACCESS	Drift and Shaft	Drift and Shaft	Drift	Drift	Adit	Drift	Drift	Drift	Drift	Adit	Drift	Decline and Shaft	Decline and Shaft
Transport	RTV	Mix RTV + Rail	RTV	RTV	RTV	RTV	RTV	RTV	RTV	RTV	RTV	Mix RTV + Rail	RTV
3 Biggest Logistical Impediments	1. Supplies Labour 2. Implement Management 3. Tyranny of Distance	1. Winding process, limited nos on winding. 2. Height and width of roadways clearance. 3. RTV to rail.	1. Machine Reliability 2. Labour 3. Drift bottleneck	1. Labour 2. Machine Reliability 3. Implement Management	1. Mine Design Pit Bottom significant distance from Portal 2. Road conditions / Road Maintenance 3. Management of implements (tracking batteries not large enough)	1. LHD reliability 2. Prioritisation 3. Materials not delivered to the right spot at the right standard.	1. Machine reliability 2. Implements management (no implement tracking) 3. Labour (culture)	1. Road Conditions 2. Labour transport 3. Tyranny of distance	1. Road Conditions and water management 2. Poor Payload 3. Machine Reliability	1. Machine Reliability 2. Labour (numbers and culture) 3. Lack of planning		1. Clearance time on blasting, uranium in the orebody moving ventilation (no series ventilation) 2. Equipment reliability and the number (12 jumbo, 20-30 trucks and workshop space) 3. Surface - UG shift offices - then using taxis around to get to the face. Moving people hundreds at a time.	1. Lack of local stores. Equipment has to be delivered from overseas or interstate at high cost. 2. Lack of trained trades. 3. Blockages at the surface store due to deliveries

Table 2-8 shows the percentage of operations that regard a particular bottleneck within their top three impediments to the supply chain. Labour culture and availability was a "TOP Three" impediment in 67% of operations visited / interviewed. Machine reliability was a "TOP 3" logistics impediment in 58% of the operations.

Table 2-8: The combined operations percentage of times for a bottleneck to appear as a TOP three impediment to logistics productivity. (source: Walker et al.,2020)

Bottleneck	**% of Operations that identify this bottleneck in their "TOP 3"**
Labour (availability and/or culture)	67%
Machine Reliability	58%
Implement Management	33%
Portal / Pit Bottom Delays	25%
Distance	25%

2.6.4.1 Labour and Machinery

It was shown that 67% of all visited / interviewed operations highlighted either labour shortages or a negative culture as a Top Three impediment to streamlined logistics. Labour and machine availability was found to be a low priority and at risk of redeployment at any time. If a production district was missing a LHD and / or personnel, dedicated logistics personnel and machinery would be redeployed out of logistics to make up the shortfall in production. All coal operations experienced a significant shortfall in supply when a longwall changeout occurred when staff would be re-deployed with near certainty for the transport of longwall machinery which could last typically anywhere between 20 and 50 days.

Some operations had a stigma attached to supply personnel which gave a perception of a negative culture within the logistics team typically from other departments that required but did not control the logistics team. The most vocal were control officers, who monitor and sometimes control machine movements underground in their assessment. It must be pointed out that this issue was not at all mines with some delivery drivers observed being well respected by their peers and taking great pride in their work.

Logistics delivery LHD reliability was a significant issue with 58% of respondents identifying this as a Top Three impediment to streamlined logistics. Some operations based upon priorities in the daily plan gave the least reliable machines to delivery which in turn promoted the stigma that logistics was low priority, which in turn contributed to the perception sometimes of a poor labour culture. The interconnection between priority of logistics being low, flailing culture and machine reliability may in turn lead to a continued downward spiral in performance and culture.

2.6.5 Best Practices

Initiatives already used at operations were identified and are shown in Table 2-9. These could then be applied to other operations without any change to technology or additional research as they deem fit.

Table 2-9: Best practice observations that could be implemented now. (source: Walker et al.,2020)

Mine No.	#1	#3	#5	#6	#9	#10	#11
Type	Coal	Coal	Coal	Coal	Coal	Coal	Coal
ROM Mtpa	4	2.5	6.5	5	6.4	5.25	8.4
DOC	600	520	130	350	350	270	350
ACCESS	Drift and Shaft	Drift	Adit	Drift	Drift	Adit	Drift
Transport	RTV	RTV	RTV	RTV	RTV	RTV	RTV
Observed Best Practice	Cloud based ordering of supplies with mobile phones, ipads and computers in cribrooms being used.	The underground warehouse should be fit for purpose, well lit and well organised with stock levels being tracked. Cardinal rules for loaders: No loader is to move inbye with a supplies load or outbyre without a backload. Tracking and maximising haulage tonnes per kw of machine power	Well lit and concreted roadways to enable high speed travel. Use of a concrete pavement make with a built in agitator is planned. Easy identification through coloured flashing lights different machines whilst travelling to assist with right of way.	Use of underground welding bays to maximise machine availability. Discipline in supplies ordering system based on continuous miner position in the pillar cycle. Inbye and outbye well lit and maintained travel roads with good drainage and water management.	Automated light sections using proximity sensors to minimise stopping of RTV's. Minimising RTV haulage distance by using drop holes from the surface for diesel, ballast, concrete as close to current face zones as possible.	Single implements used for machines. E.g. Rapid Attachment System (RAS). Focus on minimising rehandling of materials as it travels from the portal to the face.	Single implements used for machines. E.g. Rapid Attachment System (RAS). Focus on minimising rehandling of materials as it travels from the portal to the face.

2.6.6 Recommendations:

The following recommendations are likely to improve logistics management. They have been divided into immediate, medium-term and long-term timeframes based upon available technology now and how likely the technology would be available in the future.

2.6.6.1 Immediate

All logistics planning should be incorporated into the long-term planning schedule.

As mine workings increase there is an increasing likelihood of logistics being more complex as distances increase. There is a risk that at some point production will be capped based on the supply rate at that point in time. The life of mine schedule should consider these factors regularly within the planning cycle to allow identification and if possible either delay or mitigate the risk.

This first immediate recommendation is what this thesis seeks to develop.

2.6.6.1.1 Standard Equipment Used in Logistics

Equipment should be standardised to maximise efficiency of supply. This includes the delivery LHDs themselves, so standard spares and expertise is available to minimise down time. It should also include standardised implements to minimise time lost searching for the correct implement that fits a delivery LHD. Too many mines carry multiple implement systems e.g., Quick Detach Systems (QDS) or Rapid Attachment Systems (RAS) and should migrate to a single implement system, which would free up time of line management to manage rather than search.

2.6.6.1.2 Real Time Tracking

To make the best predictions of future logistics strain the historical data needs to be available to better understand the immediate effects of the logistics teams' capacity. Real time tracking of delivery LHDs and personnel transport (e.g., PED tracking) will identify immediate improvement opportunities and ensure predictive tools in the future are well calibrated. The tracking must be well maintained as the reliability of some of these systems has been found to be lacking in the past, and there must be sufficiently experienced people in the operation to correctly interpret and action the information acquired.

2.6.6.1.3 Use of computer-based technologies for supply orders

By implementing a supply ordering system that is ordered directly from the panel which talks directly to the stores system ensures loads can be customised. This will likely reduce the expense of carrying large inventory and ensure that the right supplies are prioritised.

2.6.6.2 Medium Term

2.6.6.2.1 LED Lighting

The use of LED road lighting systems is much cheaper and faster to install retrospectively than traditional fluorescent tube lighting. Lighting increases safety, particularly with pedestrian interaction and collision avoidance with stationary equipment and will likely decrease travel times by giving the driver a greater distance of vision to maintain confidence in the speed of the machine being driven. Well-lit logistics transfer points will also reduce the loading and unloading time for supplies.

2.6.6.2.2 Concreting

If a transport road is soft or is affected by geotechnical or water issues concreting will allow the operator confidence to maintain higher speeds from pit bottom to the production district. Higher speeds will in turn reduce cycle times which in turn will reduce the amount of delivery LHDs on the road. From a personnel transport perspective concreted roads are safer as they minimise the risk of unseen obstacles that could cause the transport to bump which could in turn create back and neck injuries.

Personnel travelling to and from the face at higher speeds also increase production machine utilisation and therefore at the same productivity (metres per hour for development or tonnes per hour for longwall) there will be an increase in tonnes mined or development metres driven.

2.6.6.2.3 Dedicated Single Direction Travel Roads

Single directional travel roads will reduce the need for shunting as machines travelling in the opposite direction will not be required to shunt which increases delivery delays. With single direction travel roads shunting will only occur when a slower machine (materials delivery LHD) must give way to a faster priority machine (personnel transport) which would occur relatively less frequently. Delivery machines would not need to shunt for each other as they would be travelling at approximately the same speed.

This is studied within this thesis as a solution to reduce logistics strain in the strategic and tactical timeframe.

2.6.6.2.4 Automated Light Sections

Delivery cycle times can be higher where a light section is operating because in some circumstances, the vehicle must either slow down or come to a complete stop to “claim the light section”. If a vehicle was tracked and a light section was automatically claimed this would allow machines to maintain top speed. Constant communication using a heads-up display of real time locations of other machines would also prevent slowing down and could also prevent delays waiting for permission to travel into a ventilation split where a machine may be off but still incorrectly claiming air that prevents entry.

Single direction roadways would eliminate the need for many outbye light sections used typically around corners, and the risk of head on collisions would be predominantly mitigated.

2.6.6.2.5 Increase Payload Through Braked Trailers

Increasing payload using trailers with brakes will increase the tonnes hauled per kw ratio. This will reduce overall emissions, fuel consumption, less machine movements per tonne of supplies and over a longer haulage distance reduce cycle time. Higher payloads travelling shorter distances may not be as beneficial because the time taken to load and unload larger payloads may offset the travel time saving. However, when dedicated loading and unloading equipment is implemented in combination with increased payload overall cycle times would likely decrease.

Payload variability is studied in this thesis both strategically and tactically.

2.6.6.2.6 Dedicated Supply Hubs

With supply hubs, delivery LHDs haul from pit bottom along the mains to a designated laydown area close to the production district. The supplies are unloaded at the supply hub for that production district. The delivery LHD then travels form the face to the hub, typically along a gate road and picks up what is required. It was found that the slowest speeds encountered in a haulage route was along the gate road. These were typically wetter and had not been concreted or laid with ballast and graded. Therefore, by restricting larger haulage units to mains roadways maintains a higher average speed, whilst the less utilised lighter production district machines pick up the supplies from the hub and delivered them to the production face. Purpose built supply hubs will reduce loading and unloading delays and will reduce the haulage cycle time and assist in loading and unloading of larger payload delivery LHDs especially when the areas are well lit.

2.6.6.3 Long Term

2.6.6.3.1 Automated Supplies Ordering System

This entails wholistic tracking of all supplies as they are transported, stored, and then consumed automatically triggering a replacement. All supplies are therefore monitored at all locations on the surface and underground at any given time.

2.6.6.3.2 High Speed Autonomous Delivery

For the most basic situation, machines would operate autonomously between pit bottom or with drive-in drive-out, portal, to a fixed position portal inbye supply hub. The transport system could use retrofitted delivery LHDs with autonomous haulage capability which would travel along haulage roads much like traditional haulage. Other types of haulage would prioritise getting the delivery LHDs off the road and use a monorail system where no interaction with personnel could occur and where no roadway maintenance is required. This would increase the speed of personnel transport and roadways would be slower to deteriorate and supplies could have a choice of any intake roadway that is cordoned off to pedestrians.

2.7 Chapter Conclusion

From the original work of Gibson (2005), where he states that one major impediment to increasing development rates within underground coal mines is “The logistics of supply transport distribution and handling of roof support consumables is an issue at older extensive mines immediately while the achievement of higher development rates will compound this issue at most mines." (p.1). The research since has been sparse and only undertaken by the same researchers between 2012 and present. The multiple simulation works of authors such as Cai (2015), Baafi et al. (2015), Baafi et al. (2019), Cai et al. (2011, 2012a, 2012b, 2013, 2014) and Cai (2017) used simulation to optimise productivity within the production district but did not study the supply chain from the portal to the production district. Cai (L) estimates that outbye ongoing logistical bottlenecks have a significantly larger impact on development productivity over any reasonable delay experienced within a development panel. Walker et al. (2020) highlighted that out of the 13 mines visited and/or interviewed none had prioritised logistics bottleneck identification into their strategic life of mine plan and they noted that a mechanism to do this must be a top priority in the short term. This thesis addresses these major recommendations.

Chapter 3

RESEARCH METHODOLOGY

3.1 Introduction

This chapter outlines the development and application of a system to identify strategic logistics bottlenecks and attempts to rectify these as early as possible in the planning cycle. The system should be able to quickly and easily "bolt on" to existing life of mine schedules and not affect these in any way. To accomplish this, a generic mine design and its respective planned production rate, for both development and longwall will be developed using the Runge Pincock Minarco's XPAC scheduling software and is the strategic phase of the system. Snapshots in time of outcomes of this schedule will then be implemented into a FlexSim simulation model of the mine to see if the mine can achieve the schedule at a tactical level whilst also verifying independently the strategic model.

The system will then be flexed to see the resistance of the operation to logistics breaking strain. If logistics breaking strain is achieved then and if the mine plan can address any such inhibition, then it will be executed otherwise production will be scaled back to the constraints of logistics to therefore reduce the risk of an optimistic mine plan being incorrectly valued for the future.

Specific software is employed that allows for the design of the mine plan and the scheduling of reserves. The reserves and mine geometry are then exported into a scheduling tool known as XPAC where the data is built upon using multiple subroutines. Experiments using these new subroutines are then undertaken using two generic models that identify with the styles of underground mining identified in Chapter 1 known as "migration away and return to a central portal" and "migration away from a portal in a general direction from an adit / box cut / cut and cover mine". During this experimentation, changes are completed one variable at a time to capture the immediate impact of each single change to the logistics strain. Variables that are studied are mine design, placement of portals, effect of numbers of productive machines, the schedule sequence, speed of deliveries, the impact of new domains due to geological anomalies or other constraints and payload of deliveries.

The algorithms developed in this thesis are designed to be run quickly to be able to quickly identify and then remove or defer logistics breaking strain. This may be done through changes to: -

- Scheduling paths for machines.
- Changes to productivities.
- Changes to the mine design.
- Standing down of machines if the schedule allows and production is still sufficiently maintained.
- Upgrading of logistics infrastructure.
- Moving portals closer to workings.

At the worst, if removal or deferment of logistics breaking strain is not possible, it will at least give the mine planner a production cap to write down the value of the future operation so that decision makers can make a more informed decision inclusive of logistics that has not been considered in mine planning up to this point.

3.2 Computer Software

3.2.1 Overview

There are three computer systems necessary at this stage to develop the logistics simulation system. The analysis starts with ProgeSoft's ProgeCAD where a mine design is drafted up and mine reserves and physicals are calculated. These are fed in to Runge Pincock Minarco (RPM) XPAC software where these physicals are combined with machine productivities to generate a schedule and a mine plan. This is traditionally where the mine plan ends, and the financial analysis would typically begin. Iterations between the mine design, the schedule and financial analysis to optimise value would be undertaken as shown in Figure 3-1: -

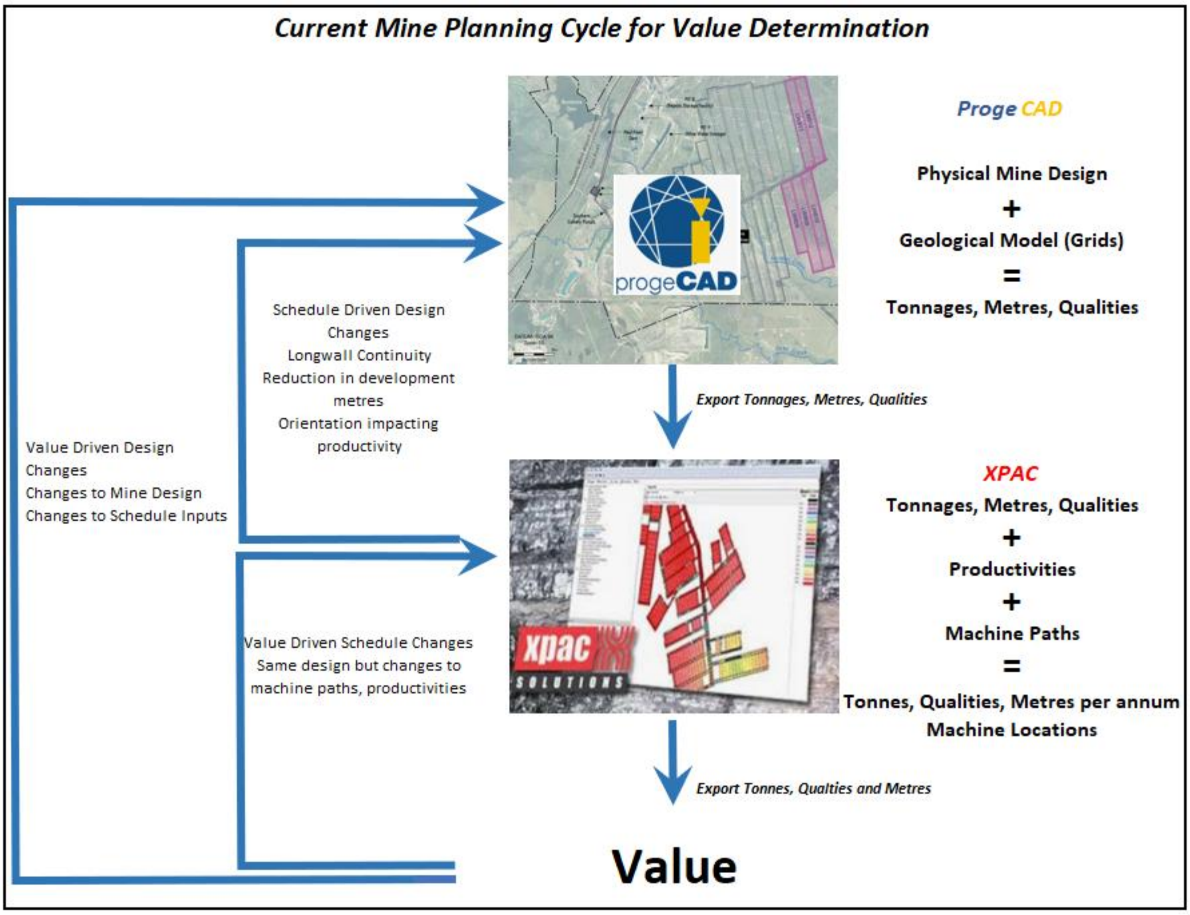


Figure 3-1: The traditional planning cycle and software used for value determination.

As already discussed, the planning cycle and iterations of it do not consider any form of logistical supply. The key assumption is that whatever the schedule produces can be logistically achieved. If a search for logistics bottlenecks is not undertaken, then the planner does not truly know if the value realised in the schedule is incorrect and optimistic.

This thesis proposes that the planning cycle must consider the supply chain and therefore design and schedule the mine to alleviate/defer logistics strain for as long as possible. FlexSim is proposed to be introduced within this part of the planning process for two reasons. Firstly, it will be a used to study the effect of the schedule on the supply chain, introduced as a pass / fail check and to transfer between XPAC and the financial analysis to ensure the eventual value proposition is more realistic as shown in Figure 3-2. Secondly as FlexSim provides discrete event simulation, the materials flow is studied for peak events at a "microscopic level" to determine if a solution can be found for relief of logistics strain that can be transferred back up to the macroscopic (XPAC) level which could increase the threshold of logistics breaking strain.

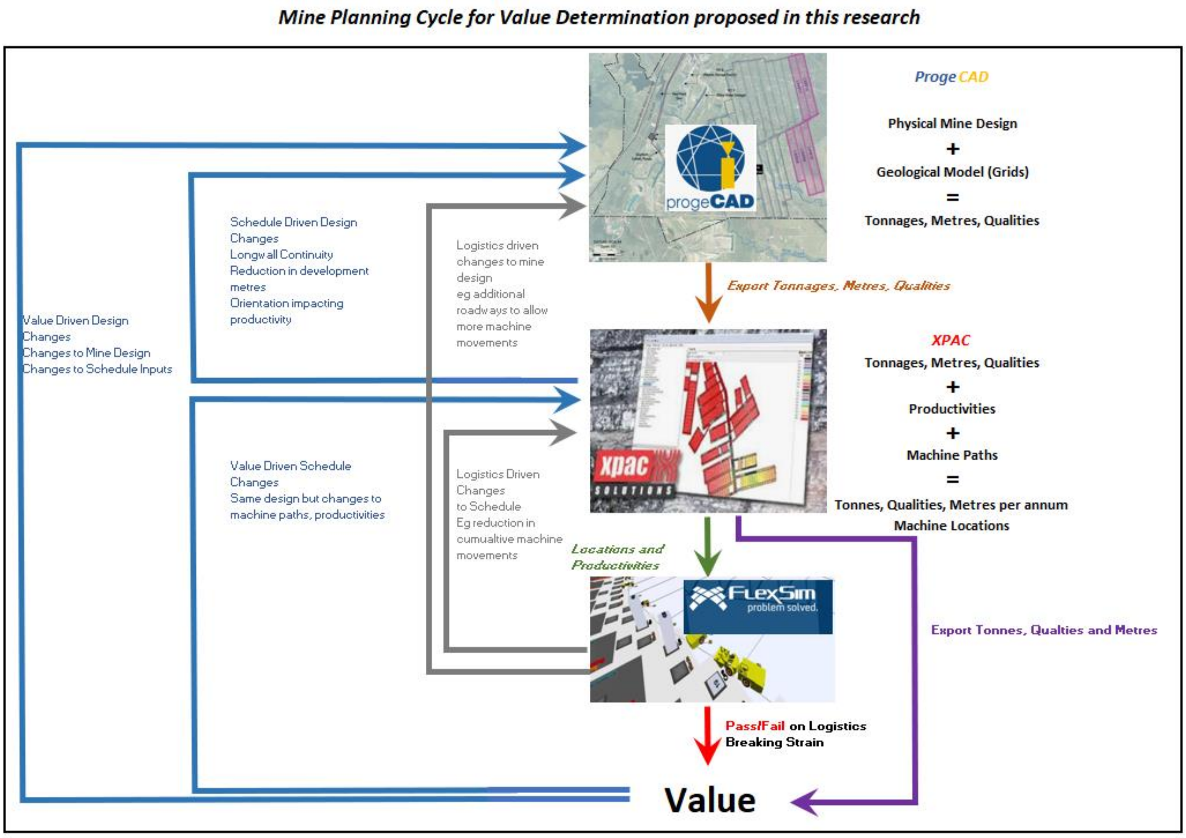


Figure 3-2: The insertion of FlexSim between schedule output and financial evaluation as proposed in this thesis.

3.2.2 <u>ProgeCAD</u>

ProgeCAD is an AutoCAD software package that allows other software companies to add proprietary software in the form of plug-ins. In this case Runge Pincock Minarco has an additional plug-in known as XPAC UG, which has specific underground coal design tools. For the purposes of explaining the mine design drafting software for this thesis ProgeCAD + XPAC UG will simply be known as it is in industry as ProgeCAD.

ProgeCAD is the mine design software where all mine geometry is constructed and then reserves are run ready to export into XPAC scheduling software. This includes mains headings, gateroads, longwalls and / or pillar extraction panels. Essentially the software demarcates between development (first workings) and longwall or pillar extraction (second workings). The roadways are constructed using automated tools which calculate:

- The type of panel.
- For development and pillar extraction panels:
    - The number of roadways per panel.
    - Roadway dimensions.

- Pillar width.
- Cut through distances.

- Longwall panels are "infilled" between gateroads.
- Scheduling block lengths for all types of panels.

ProgeCAD can design at the full spectrum of detail, from a single cut through roadway through, to a mine with several domains (groups of longwalls) through to multiple mines with multiple domains and is only limited by the expanse of the geological model or the power of the computer itself.

A typical pillar layout is shown in Figure 3-3:

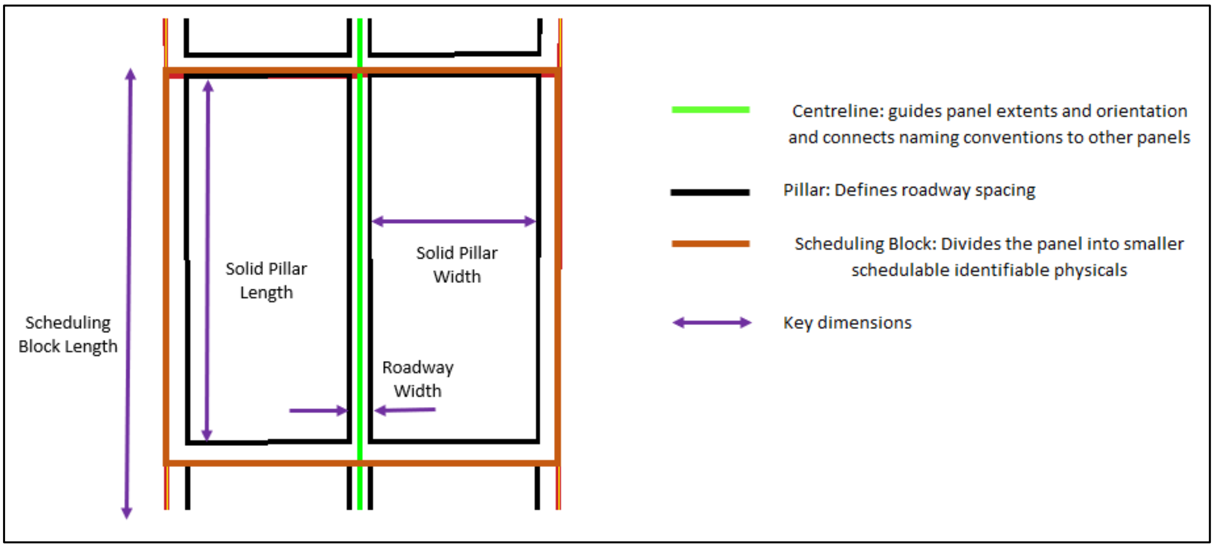


Figure 3-3: An example of a triple heading gateroad pillar highlighting key dimensions used by ProgeCAD.

In scheduling first workings (roadway development) is usually measured in metres, whereas second workings are usually measured in tonnes or linear retreat metres. ProgeCAD does not deal with these differences, it only calculates areas per scheduling block. Firstly, ProgeCAD calculates the area of the polygon in its entirety. Second workings are calculated by the cumulative pillar areas within the scheduling block. First workings area per scheduling block is calculated by subtracting the cumulative pillar area from the scheduling block area. Development metres are calculated within the scheduling software XPAC by dividing the first workings area by the roadway width.

In order to calculate qualities (Yield, Ash, RD, Moisture, ROMAX, Vitrinite) and tonnages, the polygon area is given attributes from a geological model imported into ProgeCAD (known as an XGF file). The XGF contains multiple grids calculated from the geological model, for example Seam Thickness Grid, Relative Density Grid, Raw Ash Grid, Product Ash Grid and so on. The physical location of the scheduling block is paired with each grid using grid nodes that exist within the scheduling block. These grid nodes are weight averaged based on their respective area of influence to form one singular quality attribute associated with that scheduling block. Figure 3-4 shows a typical grid overlaying a scheduling block in a triple heading gateroad. In this case the grid mesh (node to node distance) is 10 m x 10 m and therefore there are 110 grid nodes that must be weight averaged by area within the polygon to give a single quality attribute for that quality grid associated with that scheduling block.

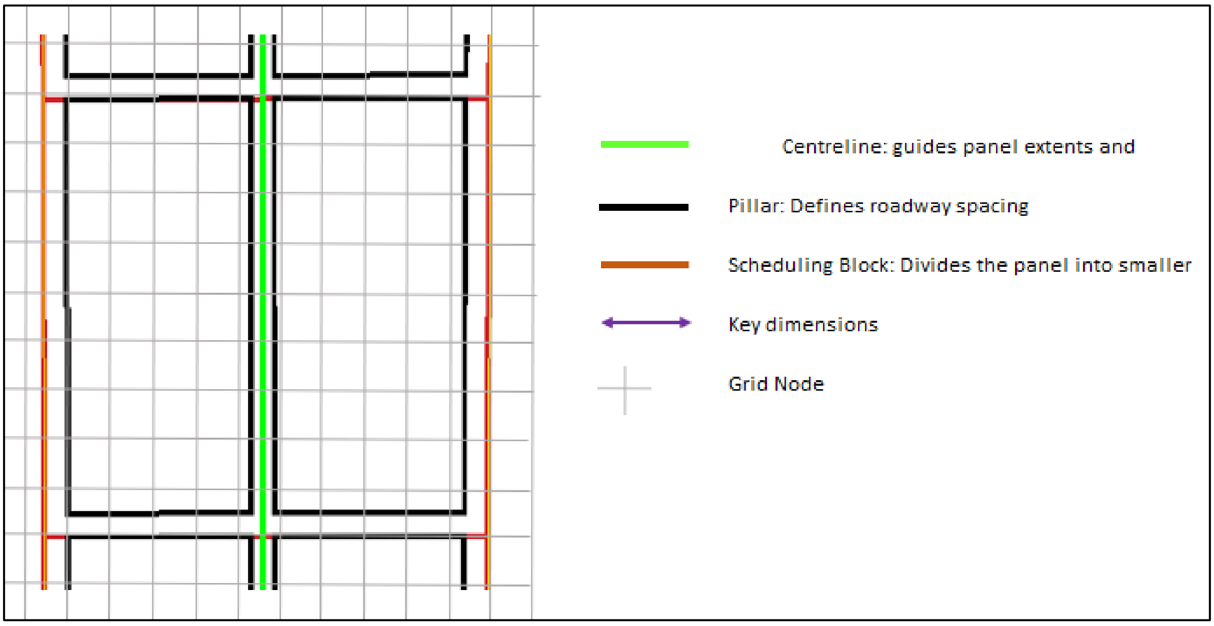


Figure 3-4: A typical 10 m x 10 m grid mesh overlaying a scheduling block. Each node's value is weight averaged by area to form a singular quality attribute for that scheduling block to represent that quality grid value in this geographical location.

Figure 3-5 illustrates ProgeCAD multiple pit designs highlighting a triple-heading gateroad and where that fits in a holistic mine design. As can be seen, the mine is split into multiple scheduling blocks typically reflecting a pillar length in gateroads and 100 m in a longwall panel.

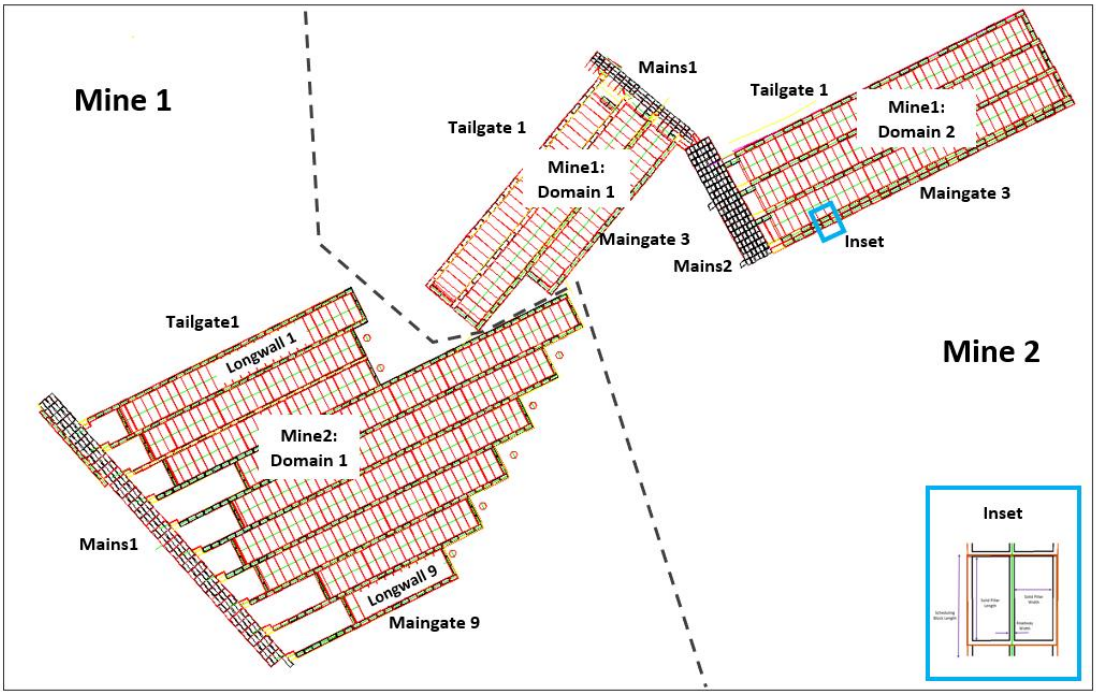


Figure 3-5: Basic multiple pit design

Note that there can be the same names for different panels across multiple mines, for example Tailgate1 exists on three occasions, Mains1 exists twice which could be confusing when trying to schedule. To address this issue, the design is then split into a hierarchy for identification much like folders and sub-folders within a computer filing system. Whilst hierarchies can be customised the common underground coal hierarchy is:

Mine -> Domain -> Process -> Panel -> Scheduling Block

Where:

Mine is the unique mine name usually associated with its own portal entry, coal clearance system and enclosed ventilation system. For single seam operations the term "Mine" will typically be bounded by the jurisdiction of a statutory mine manager. Multiple seams may be also demarcated here using the mine name with a seam name suffix, e.g., SB_BUL and SB_WON which "Mine" name represents the SB Mine but the BUL or WON represents the BULLI or WONGAWILLI seams respectively.

Domain is known in the more traditional term district and is a group of consecutive longwall or pillar extraction panels in a particular geographical area. A domain boundary exists where significant development of Mains drivage must occur to access the next group of longwall or pillar extraction panels. Domains can have multiple names, with examples being "100", "200", "300", to "Area1", "Area2", "Area3" or simply "North", "South", if each domain name is unique within each mine.

Process is the term use to divide first workings from second workings. However, this can be more elaborate. Typically, a longwall process is known as "LW" or "L", pillar extraction as "PILLAR" or "EXTRACT", and development as "DV" or "G".

Panel is the unique name of a typical ventilation split associated with production being undertaken either in first or second workings. Gateroad naming conventions are TG1, MG1, MG2 and so on. Longwall naming is LW1, LW2 and so on. All these names can be more elaborate with a prefix of the mine domain for example if you are in "Domain 9" your tailgate might be known as TG901 and maingate's would be known as MG901, MG902 and so on. Mains headings usually have the prefix MH but typically carry more elaborate names reflective of the domain, e.g., MHSouth1 for first mains headings in South Domain.

Scheduling Block: A unique number usually starting from one (at most outbye) and increasing by one for typically each cut through moving inbye on development. On longwall block 1 is the first extracted block at the installation face and increases by one as the longwall retreats to the take-off.

The inset block first studied in Figure 3-5 previously would therefore be named:

1. Mine = Mine 2
2. Domain = Domain 2
3. Process = DV
4. Panel = MG3
5. Block = 6

Mine 2 -> Domain 2 - > DV -> MG3 -> Block 6

3.2.3 XPAC

NB: The following is not to be a detailed explanation of XPAC, rather it is a broad outline of this tool to assist in the understanding of how the work of this thesis was completed.

XPAC is a proprietary mine scheduling software database package developed by RPM Global Ltd. The design and reserves are exported into XPAC where the mine schedule is developed. XPAC consists of several databases used as inputs to run a complex mine schedule. Combining data from the Main Database, the Calendar Database, Machine Productivity, timing, and paths a schedule can be run for a specific duration as outlined in Figure 3-6: -

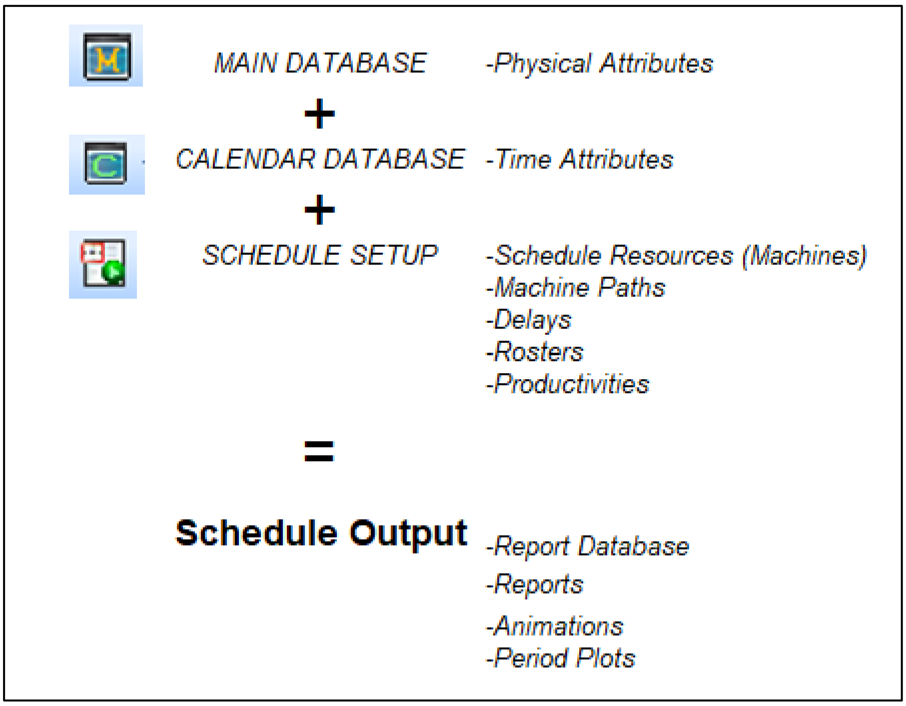
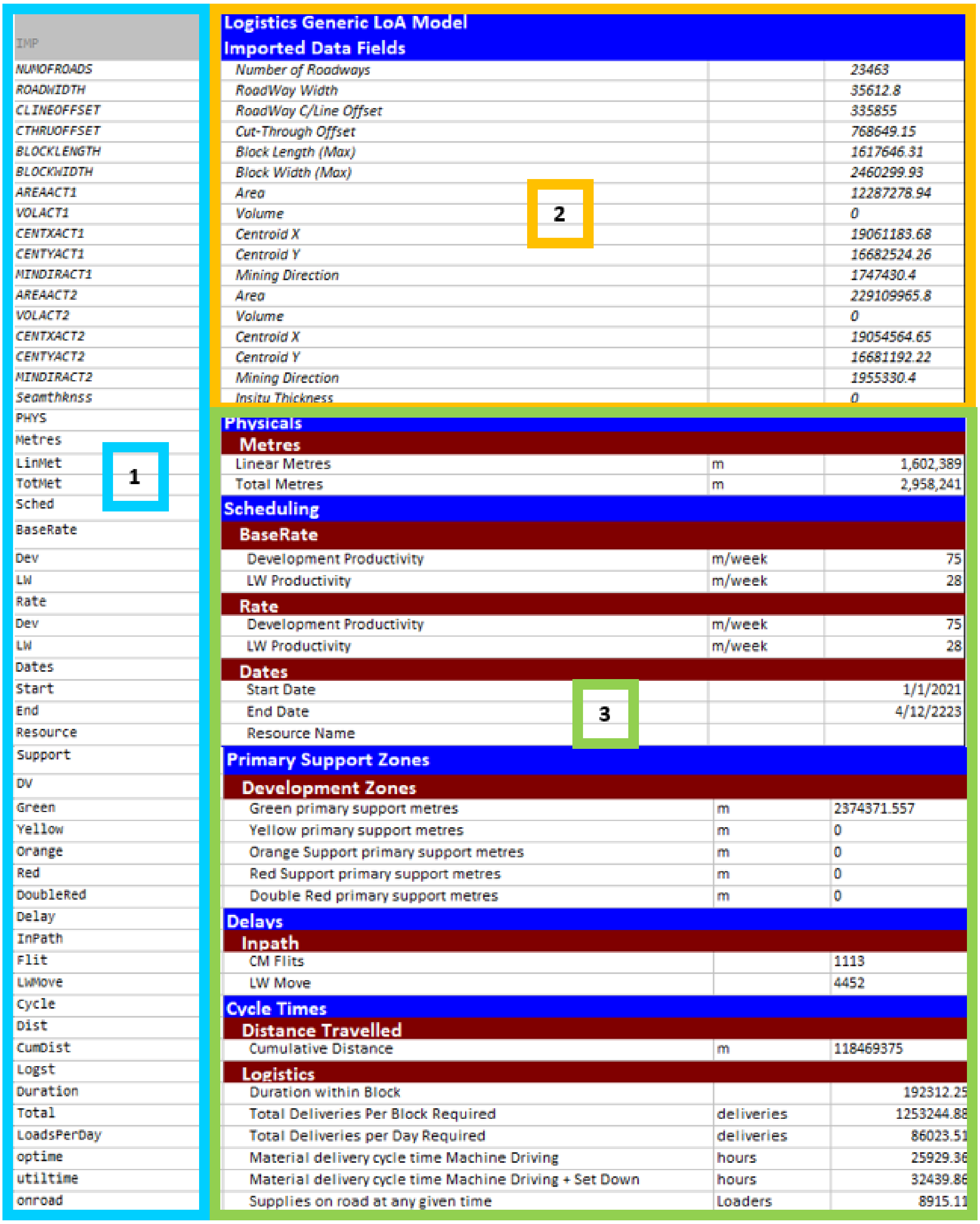


Figure 3-6: A basic outline of how an XPAC schedule is generated.

3.2.3.1 Main Database

The Main Database is where physical attributes are stored for each of the blocks that have been exported from ProgeCAD. For example, for a coal seam scheduling block, associated attributes would include the physical dimensions of the block such as volume, thickness, surface area, centroids and quality variables including but is not limited to ash, grade, swell, yield.

The attributes stored within a database record (e.g., Block 6) are typical of Figure 3-7. An attribute is the data stored on each row and can be imported from ProgeCAD reserves, or subsequently calculated from the imported ProgeCAD reserves.



IMP	Logistics Generic LoA Model Imported Data Fields		
NUMOFROADS	Number of Roadways		23463
ROADWIDTH	RoadWay Width		35612.8
CLINEOFFSET	RoadWay C/Line Offset		335855
CTHRUOFFSET	Cut-Through Offset		768649.15
BLOCKLENGTH	Block Length (Max)		1617646.31
BLOCKWIDTH	Block Width (Max)		2460299.93
AREAACT1	Area		12287278.94
VOLACT1	Volume		0
CENTXACT1	Centroid X		19061183.68
CENTYACT1	Centroid Y		16682524.26
MINDIRACT1	Mining Direction		1747430.4
AREAACT2	Area		229109965.8
VOLACT2	Volume		0
CENTXACT2	Centroid X		19054564.65
CENTYACT2	Centroid Y		16681192.22
MINDIRACT2	Mining Direction		1955330.4
Seamthknss	Insitu Thickness		0
PHYS	Physicals		
Metres	Metres		
LinMet	Linear Metres	m	1,602,389
TotMet	Total Metres	m	2,958,241
Sched	Scheduling		
BaseRate	BaseRate		
Dev	Development Productivity	m/week	75
LW	LW Productivity	m/week	28
Rate	Rate		
Dev	Development Productivity	m/week	75
LW	LW Productivity	m/week	28
Dates	Dates		
Start	Start Date		1/1/2021
End	End Date		4/12/2223
Resource	Resource Name		
Support	Primary Support Zones		
DV	Development Zones		
Green	Green primary support metres	m	2374371.557
Yellow	Yellow primary support metres	m	0
Orange	Orange Support primary support metres	m	0
Red	Red Support primary support metres	m	0
DoubleRed	Double Red primary support metres	m	0
Delay	Delays		
InPath	Inpath		
Flit	CM Flits		1113
LWMove	LW Move		4452
Cycle	Cycle Times		
Dist	Distance Travelled		
CumDist	Cumulative Distance	m	118469375
Logst	Logistics		
Duration	Duration within Block		192312.25
Total	Total Deliveries Per Block Required	deliveries	1253244.88
LoadsPerDay	Total Deliveries per Day Required	deliveries	86023.51
optime	Material delivery cycle time Machine Driving	hours	25929.36
utiltime	Material delivery cycle time Machine Driving + Set Down	hours	32439.86
onroad	Supplies on road at any given time	Loaders	8915.11

Figure 3-7: A simple XPAC Main Database showing block attributes outlining key Zones 1,2 and 3

In Figure 3-7, there are three distinct zones: -

Zone 1: These are called “Row Codes” and are unique identifiers of each attribute. These identifiers are critical in calculating, modifying, or presenting data using the XPAC Command Module or XCM.

Zone 2: This is imported data. These row codes are defined in ProgeCAD and come directly from the Reserve run.

Zone 3: These are calculated attributes. Typically, this section contains *In-situ* Reserves, ROM Reserves, Product Reserves, and their respective qualities. Scheduling physicals, metres, productivities and delays are also stored here. This thesis has introduced a group of logistics attributes which will be explained in more detail following on in this chapter which are critical for identification of bottlenecks over time.

The main database can vary in size considerably depending on what is required to be output. The main database in this thesis is formed only to create a basic LoM schedule including productivities, schedulable physicals in this case linear metres (for longwall) and total metres (for development) to enable the new logistics sub-section. This research can operate within any sized main database and is therefore scalable.

3.2.3.2 Calendar Database

This database is used to divide the schedule into milestones or periods and will store schedule inputs that change over time such as direct operating hours (February for example with 28 days will have less direct operating hours than March with 31 calendar days). For example, if it is anticipated that a "wet season" will reduce productivity for January and February of each year, a productivity derating factor would be entered into the calendar database for these two months. When a schedule is being generated each period will be accessed from the Calendar Database and a deration will be applied. A typical Calendar Database is shown in Table 3-1.

Table 3-1: XPAC calendar database

		Calendar Database, Record(s) \Top\FY2022\+											
	Code	**Data Field Name**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**
–		**Financial Years**												
.	Start	Calendar Start Date	1/07/2021	1/08/2021	1/09/2021	1/10/2021	1/11/2021	1/12/2021	1/01/2022	1/02/2022	1/03/2022	1/04/2022	1/05/2022	1/06/2022
.	End	Calendar End Date	1/08/2021	1/09/2021	1/10/2021	1/11/2021	1/12/2021	1/01/2021	1/02/2022	1/03/2022	1/04/2022	1/05/2022	1/06/2022	1/07/2022
.	Days	Calendar Days	31	31	30	31	30	31	31	28	31	30	31	30
.	CT	Calendar Time	744	744	720	744	720	744	744	672	744	720	744	720
.	Weeks	Number of Weeks in Period	4	4	4	4	4	4	4	4	4	4	4	4
.	WEnd	Weekend Days	9	9	8	10	8	8	10	8	8	9	9	8
+	Unit1	**Unit 1**												
+	Unit2	**Unit 2**												
–	Unit3	**Unit 3**												
–	LW	**Longwall**												
.	CRMod	Cut Rate Modifier	110.0%	110.0%	100.0%	100.0%	110.0%	110.0%	110.0%	100.0%	100.0%	100.0%	100.0%	100.0%
.	Avail	Availability	70.0%	70.0%	70.0%	70.0%	70.0%	70.0%	70.0%	70.0%	70.0%	70.0%	70.0%	70.0%
.	Util	Utilisation	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
–	Diggers	**CM1**												
.	CRMod	Cut Rate Modifier	97.0%	97.0%	97.0%	97.0%	97.0%	97.0%	97.0%	97.0%	97.0%	97.0%	97.0%	97.0%
.	Avail	Availability	91.7%	91.7%	91.7%	91.7%	91.7%	91.7%	91.7%	91.7%	91.7%	91.7%	91.7%	91.7%
.	Util	Utilisation	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
–	Dragons	**CM2**												
.	CRMod	Cut Rate Modifier	97.0%	97.0%	97.0%	97.0%	97.0%	97.0%	97.0%	97.0%	97.0%	97.0%	97.0%	97.0%
.	Avail	Availability	91.7%	91.7%	91.7%	91.7%	91.7%	91.7%	91.7%	91.7%	91.7%	91.7%	91.7%	91.7%
.	Util	Utilisation	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
–	Eagles	**CM3**												
.	CRMod	Cut Rate Modifier	97.0%	97.0%	97.0%	97.0%	97.0%	97.0%	97.0%	97.0%	97.0%	97.0%	97.0%	97.0%
.	Avail	Availability	91.7%	91.7%	91.7%	91.7%	91.7%	91.7%	91.7%	91.7%	91.7%	91.7%	91.7%	91.7%
.	Util	Utilisation	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
–	Broncos	**CM4**												
.	CRMod	Cut Rate Modifier	97.0%	97.0%	97.0%	97.0%	97.0%	97.0%	97.0%	97.0%	97.0%	97.0%	97.0%	97.0%
.	Avail	Availability	91.7%	91.7%	91.7%	91.7%	91.7%	91.7%	91.7%	91.7%	91.7%	91.7%	91.7%	91.7%
.	Util	Utilisation	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
–	Tigers	**CM5**												
.	CRMod	Cut Rate Modifier	97.0%	97.0%	97.0%	97.0%	97.0%	97.0%	97.0%	97.0%	97.0%	97.0%	97.0%	97.0%
.	Avail	Availability	91.7%	91.7%	91.7%	91.7%	91.7%	91.7%	91.7%	91.7%	91.7%	91.7%	91.7%	91.7%
.	Util	Utilisation	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%

The hierarchical structure of a calendar database is again time based. This structure will depend on how granular the schedule is required to be. A medium-term schedule which requires reasonably high granularity and therefore may have a hierarchy of: -

Week -> Month -> Quarter -> Year

A five-year plan: - Month -> Quarter -> Year for the first 24 months

Quarters -> Years next 3 years

Years -> Remainder of the LoM

Whereas a large life of mine schedule may only have a single level. It is important to note that for good mine scheduling practice, granularity of the calendar database should match the granularity of the mine design. For the purposes of this thesis a very simple annual calendar has been employed as it is an indirect input which means any granularity can be applied.

3.2.3.3 Schedule Setup

The schedule setup window enables the majority of schedule data to be entered to run a schedule including which resources will be employed including longwall and development units, input paths and productivities for each resource, constraints (such as resource proximity and non-productive activities), trigger XCM's which are programs run during the execution of a schedule that include in this thesis inputting dynamic delays for flitting or longwall moves and dependency rule sets determining what record can be released to be scheduled by when. A typical schedule setup window is shown in Figure 3-8:-

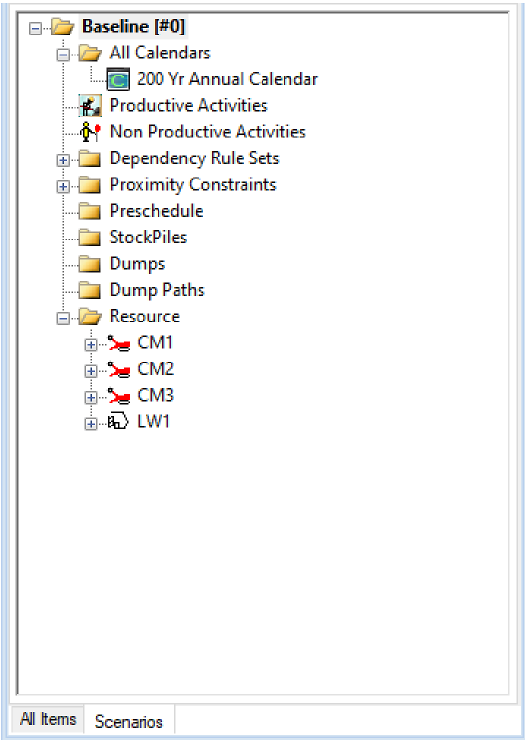


Figure 3-8: The XPAC schedule setup window

3.3 System Development

The method is defined into two phases. Firstly, the mine design phase where the design and export of reserves within ProgeCAD into XPAC occurs. Phase 1 is where overarching design changes can be made to address logistical bottlenecks. Phase 2 is the strategic identification phase where large-scale bottlenecks and increases to logistics strain can be quickly identified. It is a combination of XPAC scheduling, reports, and spreadsheet data manipulation. Bottlenecks or alleviation of logistics strain can potentially be addressed here through changes in schedule, or if unable to return to Phase 1 to address concerns through design changes. If either design or schedule changes cannot rectify any logistical bottlenecks or alleviate logistics strain, then consideration would be made to either constrain the design or constrain the schedule based on a cost-benefit analysis. The flowchart of the experimental method in totality is shown in Figure 3-9.

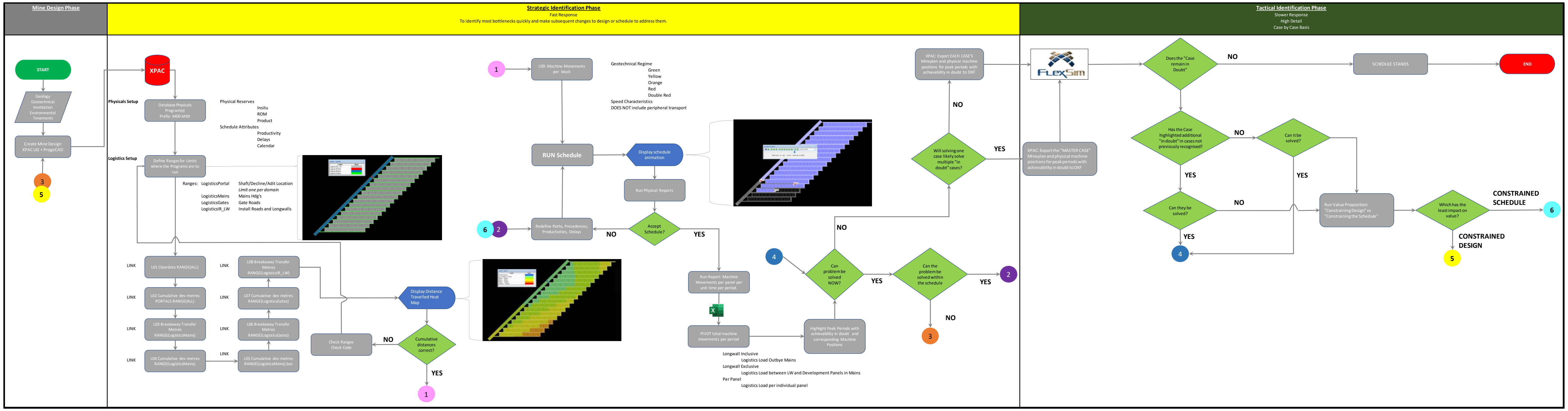


Figure 3-9: Flowchart of logistics bottleneck identification and rectification.

3.3.1 Mine Design and Reserves

As with any mine planning process, including this new process of including the logistics system, the physical mine design or Phase 1 must be completed and is the first step in the total mine planning process Phase 1 is shown in Figure 3-10. Typically, the collection of all key stakeholder requirements will occur at this point starting with tenement limitations (mine lease, exploration permits, etc) that will govern what is typically reasonably achievable in the normal course of business. For the purposes of the system designed within this thesis the design is undertaken in ProgeCAD so that it may be directly exported to XPAC.

Whilst what is about to be described is broader mine planning and is attached to significant research already undertaken and day-to-day operational procedures, it is nonetheless imperative to explain in a reasonable amount of detail as it is critical in the establishment of this new component of logistical consideration within a mine plan, within Phase 2.

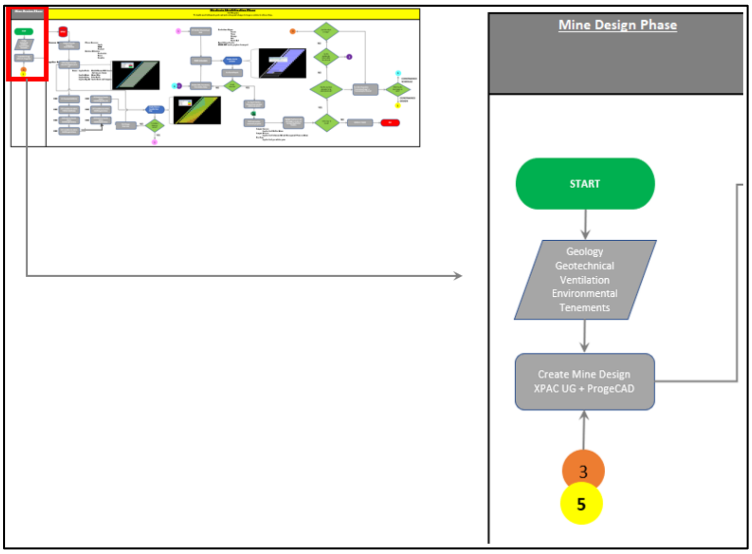


Figure 3-10: The mine design phase

Upon the overall mining boundaries being allocated good mine planning practice requires key stakeholders to be sought who will provide expertise. Geological input will provide the Structural information including the seam rood, the seam floor, depth of cover and the seam thickness. It will also provide Quality information that will impact the overall value of the mining operation which would include ROM ash, product ash, and product yield sometimes with multiple ash or relative density (RD) cut-offs, or other key variables such as grindability, mean maximum reflectance of vitrinite in oil (Romax) / reflectance, vitrinite and phosphorous, all of which may have an impact on revenue. Lastly Geological information will provide information on geological anomalies including faults and intrusions (dykes and sills), some of which may be mined through, and others may need to be avoided with only minimal drivage through those areas, for example high displacement thrust faulting combined with high gas content at risk of outburst. These various step arounds and new domains are anticipated to have a large impact on logistical supply chains.

Geotechnical input will determine longwall and development orientation. Well considered mine layouts that account for principal horizontal stress directions can mitigate the risk of slower production rates in both longwall (stress notches) and development (guttering, slabbing, rib instability). Depth of cover and associated vertical stress in combination with strong overlying strata that potentially could be deemed a rock burst, or a wind blast hazard that may force the operation to step away or defer a particular area in preference for a new domain and in turn affect the supply chain.

Geotechnical design considerations such as chain pillar width will have an impact on linear development advance rates. Linear advancement rate is the speed of development from cut through to cut through rather than absolute development metre rate. For example, a pillar may consist of two 120 m gateroads with a 50 m solid pillar, meaning that total development metres are 290 metres. If this takes two weeks to develop the rate per calendar day of a continuous miner will be slightly under 21 metres per day. Linear pillar length is 120 m therefore the linear advance rate is 8.6 linear metres per day, which is the length of cut through to cut through which is the distance travelled by the material delivery system as it travels down one road. The faster development linear advancement for development or retreat for longwall occurs the greater the impact on logistical supply strain. Wider pillars will increase total metres and will inevitably slow linear advancement and therefore less strain on logistical supply over time. This is demonstrated in Figure 3-11.

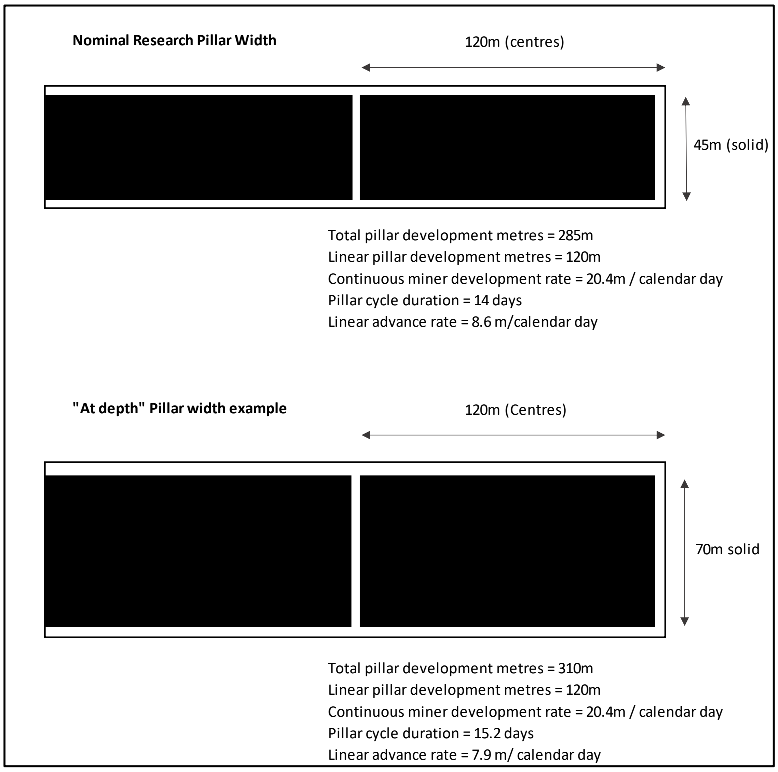


Figure 3-11: The impact on linear advancement from varying pillar widths based upon geotechnical conditions

Added to the broader layout question, primary and secondary support has a direct influence. To summarise this observation, the poorer the geotechnical conditions, the slower the continuous miner or longwall with potentially more deliveries being required to satisfy the primary support requirements. This will be discussed in more detail in Phase 2.

The ventilation, gas regime and spontaneous combustion risk will determine the number of mains to be driven to deliver adequate airflow to render gas concentrations below legislated requirements or to keep pressure differentials between intakes and returns to a minimum. The higher the ventilation requirements for gas management, or the lower the pressure differential required for spontaneous combustion, the more roadways in mains required. The more mains required the slower the linear advancement, in this thesis seven mains headings were nominally used comprising of four intakes and three returns to accommodate the higher tolerances for return airway velocities compared to intakes as shown in Figure 3-12: -

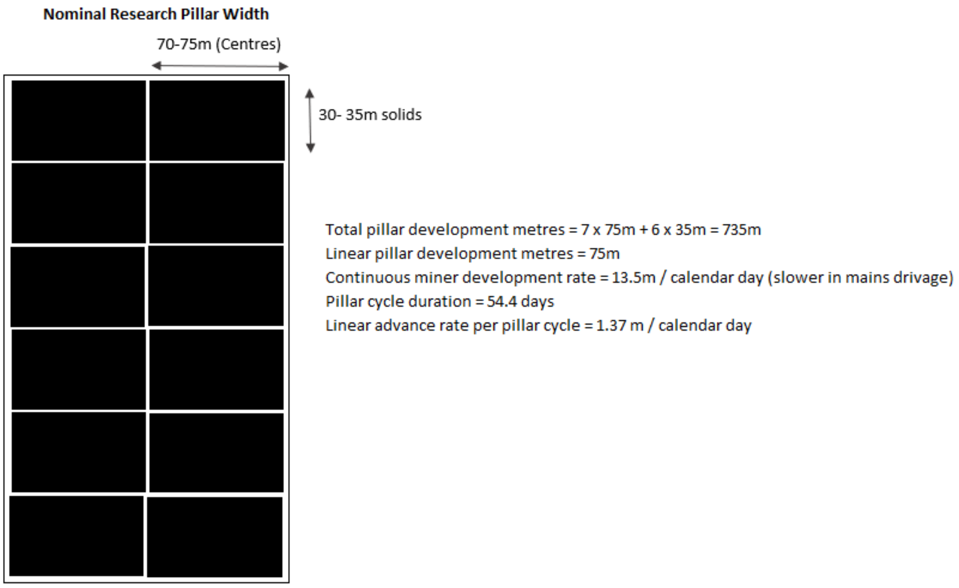


Figure 3-12: The impact on linear advancement from number of mains headings based upon ventilation requirements.

Ventilation, including leakage of seals will also determine the maximum practical length of a longwall and how many logistics deliveries can occur at any given time. For the purposes of method in this thesis, twin gateroad lengths of 4.2 km have been used based upon an average gateroad delivery of 50 m^3/s mid panel (accounts for seal leakage), with intake resistance of 0.09 Gauls and return with conveyor resistance at 0.26 Gauls meaning pressure drop at the coffin seal of ~ 900Pa which would be considered an upper practical limit.

3.3.2 Ventilation Considerations on LHD Limits per Panel

One of the most important constraints which limit the number of delivery LHDs is ventilation quantity, and it must be considered side-by-side with delivery LHD estimates. In an open-air environment, if there is a shortfall in supply, disregarding diseconomies of scale and other inefficiencies, a logistics management system can lead to a point make up for the shortfall by increasing the number of delivery units in the system.

Diesel machinery remains the primary delivery method for materials delivery within underground coal mines to date (Morla & Karekal, 2017). Mining legislation (NSW-Government, 1999) and (NSW-Government, 2014) regarding underground diesel particulate matter and ventilation quantities to dilute them imposes an additional constraint that caps the total number of diesel machines operating at any given time. Every ventilation split has a cap on the total number of machines that can operate within it.

For example, consider a mine which has 4 production districts, a longwall, two gateroad development panels and one mains development panel. Intake air travels along the main intake airways at 240 m^3/s. The intake air then splits into the longwall (80 m^3/s), the two gateroads (50 m^3/s each) and the mains (40 m^3/s) production districts with 20 m^3/s reporting to mains leakage. The quantity available to each split could severely limit machine operation within them. To make matters worse, other diesel machinery may already be operating within the ventilation split which means a delivery LHD may need to wait at a diesel tag board at split entry until inbye machines are shut down to free up committed air quantity. This reduces the total capacity of the materials delivery fleet. It is therefore imperative that ventilation at any mine be studied in conjunction with the calculated requirements for delivery that this thesis undertakes, otherwise the practicalities of the legislated limits on diesel machinery may prevent delivery rates from ever being achievable.

In 2014, NSW Resources and Energy released an industry profile which listed all LHD units by make and model for most underground coal mining operations within NSW. Table 3-2 highlights the number of each LHD at each mine as well as kw of each machine:

Table 3-2: NSW Resources and Energy 2014 mine equipment index (source: http://www.resourcesandenergy.nsw.gov.au/__data/assets/pdf_file/0005/664565/CIP-2014-Vol-2-final-accessible.pdf)

Make	Model	kw	m3/s	NSW Resources and Energy Registered (2014)	Mines (number of each model)						
EIMCO	913	101	6.06	13	Tahmoor(4)	Springvale(2)	Russell Vale(5)	Wongawilli (2)			
	130	170	10.2	14	Austar(2)	Mandalong(1)	Myuna(2)	Metropolitan(4)	Airly(1)	Springvale(4)	
	ED7/LS170	150	9	24	Wambo(4)	Austar(4)	Chain Valley(5)	Mandalong(5)	Myuna(1)	Metropolitan(1)	Tahmoor(4)
	ED10	153	9.18	13	Wambo(1)	Mandalong(7)	Metropolitan(5)				
	915/936	112	6.72	3	Wambo(2)	Tahmoor(1)					
Coaltram	CT08				Myuna(6)	Tahmoor(6)					
	CT10	168	10.08	12	Dendrobium(10	Airly(2)					
VLI	JUG-A-O Z1060/Z1210	122	7.32	31	ULAN WEST(5)	ULAN WEST(6)	Ashton(7)	Bulga(UG)(7)	Chain Valley (2)	Russell Vale(4)	
Sandvik	170/190	172	10.32	11	Narrabri(11)						

The NSW Government (2008, p.2) MDG29 states: “The use of diesel engines in an underground environment is considered a hazardous activity potentially associated with short and long-term adverse health effects.” The guideline covers all mines utilising diesel engines in an underground environment and specifically states in Section 4.3 under minimum ventilation quantity:

“The minimum ventilation quantity should also consider the total number and power of diesel engines operating in the same ventilation current at any one time. For a newly developing mine, good practice is to provide 0.1 m^3 /s/kW of diesel engine power to overcome, diesel emissions (gaseous, particulate) and heat stress.

“4.3.1 Gaseous Emissions For gaseous emissions the minimum ventilation quantity (volume of air) in each place where a diesel engine operates shall be such that a ventilation current of not less than: -

a) 0.06 m^3 /s/kW of maximum capacity of the engine, or

b) 3.5 m^3/s, whichever is the greater is directed along the airway in which the engine is operating.” *NSW Department of Primary Industries 2008*

Now considering the legislated requirement and the above typical LHD machines used, the following aggregated table of ventilation requirements is shown in Table 3-3.

Table 3-3: The number of LHD units in NSW coal mines and their respective minimum and good practice ventilation requirements.

Documented NSW Coal Mining LHD's in 2014				
KW Range	**LHD Units**	**Legislated Requirement Upper m^3/s $0.06m^3/s/kw$**	**Good Practice Upper m^3/s $0.1m^3/s/kw$**	**Comments**
80-115	16	7	12	Typically operated within production panel
120-160	68	10	16	Outbye and supplies haulage
160-180	37	11	18	Outbye and supplies haulage

As this thesis is on de-bottlenecking a strategic long-term mine plan, it would be prudent to use good practice ventilation requirements rather than the legislated minimum to prevent over-allocation of LHDs in a singular ventilation split if the legislation is increased into the future, although this model will have the capability to increase machine movements if deemed necessary to reduce logistics strain. It can be therefore seen that 87% of all diesel LHDs operating within NSW are of a capacity of 120kW or greater, meaning the ventilation requirements for good practice are at the very least 10 m^3/s and more likely to be in the vicinity of 16 m^3/s.

3.3.2.1 *Justification for a Single Supplies LHD Allowed per Panel*

It is important also to note that the smaller LHDs, typically four-cylinder and smaller six-cylinder diesels are used to run within the production district itself (transformer inbye) running supplies that have been dropped off by the larger machine to the continuous miner due to lower ventilation flows at the face. At times when the larger diesels are typically operating concurrently with outbye supply delivery, they are running into the panel creating a compounding diesel emission load on the ventilation split. Therefore, it is a reasonable assumption to cap delivery LHDs to a single supplies LHD operating at the same time as a smaller LHD within the production district within the same gateroad ventilation split.

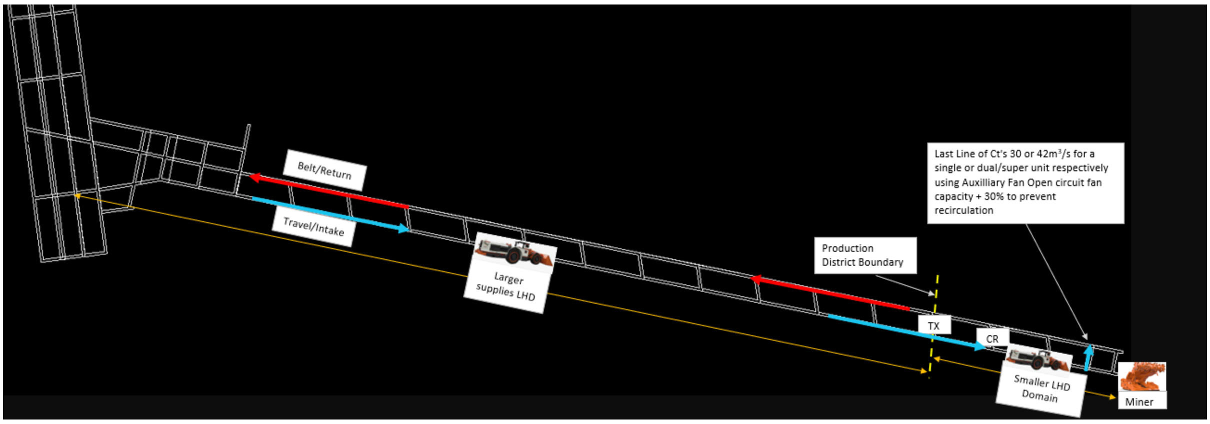


Figure 3-13: Typical diesels operating concurrently within a gateroad ventilation split.

The number of diesels that can operate within the ventilated split can be determined by:

Large Auxiliary Fan Open Circuit Capacity = 23 m^3/s

Additional Air Required to pass over the fan to prevent recirculation = 30% x 23 = 6.9 m^3/s

Total minimum air available at last line of cut throughs = 29.9 m^3/s ~ 30 m^3/s

Although there are larger quantities of air at the entrance of a ventilated split, the quantity will reduce from one cut through to next inbye due to stopping leakage until the last line of cut throughs. It is reasonable to assume that at any time, for the purposes of good practice that both the larger and smaller LHDs are concurrently operating at the worst place for airflow which will be nearest the last line of cut throughs. Therefore, the number of large LHDs that can be operated in a single development unit gateroad ventilation split can be determined by:

$Q_{\text{available o/b LHD}}(m^3/s) = Q_{\text{at last line of cut throughs}} - Q_{\text{Small LHD ventilation requirement}}$

$= 30 – 12\ m^3/s$

$=18\ m^3/s$ (available for Large Outbye Supplies LHD)

Number of large supplies LHDs per gateroad (m^3/s) $= Q_{\text{available o/b LHD}} /_{\text{per large outbye supplies LHD}}$

Knowing that a large outbye supplies LHD quantity is 16 m3/s from Table 3-3 then:

= 18/16 rounded down to whole number

=1 LHD.

In the case of a super unit 42 m^3/s is considered the minimum quantity of ventilation (2 x 18 m^3/s fans + 30% over a single fan to prevent recirculation). Super units are considerably less efficient and are considered reactionary to deliver immediate longwall continuity rather than build development inventory into the future. However, should super units be considered then:

$Q_{\text{available o/b LHD}}(m^3/s) = Q_{\text{at last line of cut throughs}} - S_{\text{mall LHD ventilation requirement}}$

$= 42 – 12\ m^3/s$

$=30\ m^3/s$ (available for Large Outbye Supplies LHD)

Number of large supplies LHDs per gateroad (m^3/s) $= Q_{\text{available o/b LHD}} /_{\text{per large outbye supplies LHD}}$

= 30/16 rounded down to whole number

=1 LHD (good practice) 2 legislative limit.

Therefore, the allocated outbye supplies LHD per gateroad is one initially and can be identified manually by the mine planner using the system developed from this thesis. Multiple LHDs can therefore only exist in higher ventilation panels such as in mains headings. To have two large supplies LHDs operating within a singular ventilation split that is not mains headings will be possible in this model but will be determined by strategic ventilation considerations but would be considered a premature solution at the mine planning phase until all other ways to reduce logistics strain are exhausted.

3.3.2.2 Licence to Operate

The environmental licence to operate will govern the layout of an underground mine. Subsidence in particular areas, such as drinking water catchments, inland swamps and other critical habitats, water courses, cliff lines and critical infrastructure increase the likelihood of new domains and longwall step arounds which in turn affect logistical supply strain. This impact can be seen regionally as longwall operations step around critical infrastructure in dam reservoirs and dam walls and named creeks such as in Figure 3-14: -

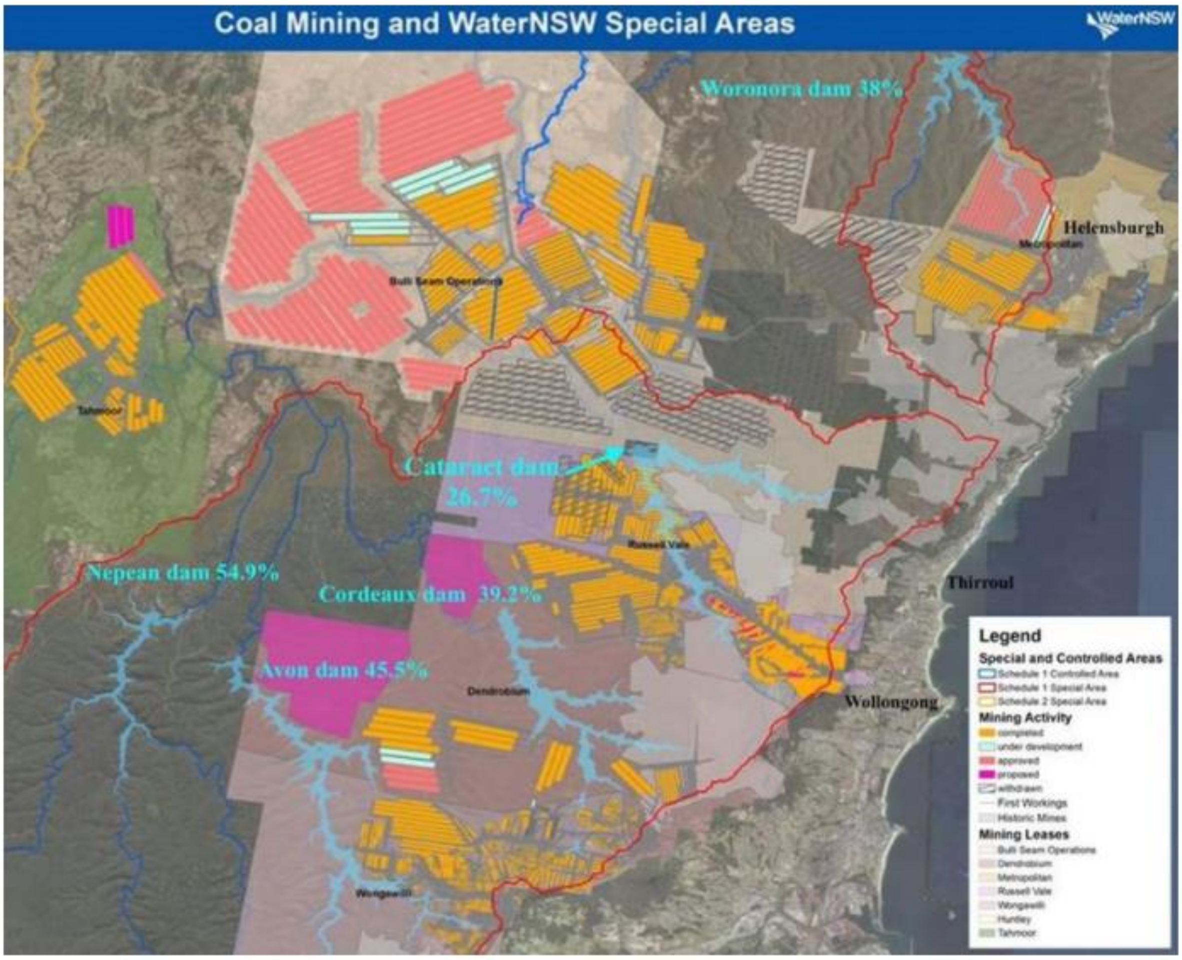


Figure 3-14 : NSW southern coal fields mine layouts affected by critical infrastructure and the need to establish new mining domains to accommodate these. (Source: https://www.9news.com.au/national/coal-mine-under-greater-sydneys-woronora-drinking-water-reservoir)

More specifically Figure 3-15 shows each new area/domain for Dendrobium Mine as it avoids critical surface infrastructure to maintain its licence to operate. Note should be made that mining domains “Area 1” and “Area 2” have limited longwalls to fit between the arms of Cordeaux Dam and Area 3A, being bound by a named watercourse in the west and a Cordeaux Dam arm in the east, and Area 3B being bound by an Avon Dam arm in the west and a named watercourse in the east. Each of these new domains represents more mains drivage and a step change in logistical supply strain which this thesis aims to prove occurs.

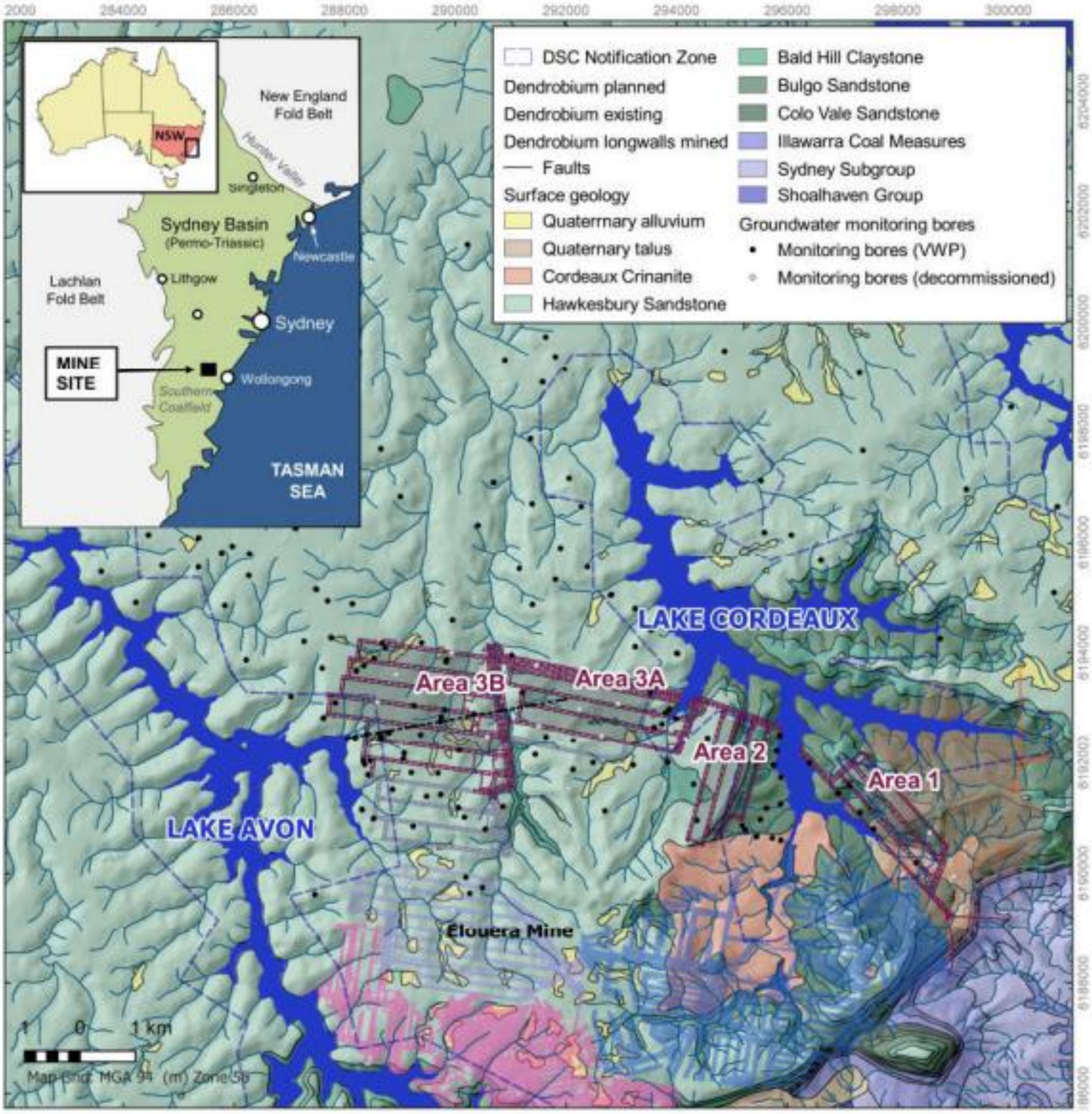


Figure 3-15: Dendrobium Mine stepping around critical infrastructure and environmental features to maintain its licence to operate. (Source https://www.south32.net/docs/default-source/illawarra-coal/dendrobium/dendrobium-longwall-10-end-of-panel-report/longwall-1)

3.3.3 Generic Mine Designs

To best represent the questions posed in Chapter 1, three mine designs were constructed for the purposes of this thesis. These designs are generic and have been specifically designed to understand the impact of machine path, productivity, layout including the extension away from portal access and their impact on logistics strain. It is important to note that such designs do not in reality exist once the impact of geotechnical factors, geological hazards, structure and quality, tenements, ventilation constraints, gas emissions, and spontaneous combustion all create the need for actual bespoke mine designs. Nonetheless the models in this thesis have been specifically constructed to be a reasonable generic representation of typical mine plans so that the inclusion of strategic logistical supply can be applied on any mine design. Table 3-4 lists the variables for all the designs. These have generally been constructed to give a realistic and reasonable range to test the logistics setup of the schedule.

Table 3-4: Key mine design configuration variables for all mine layouts.

Panel and Variables		Units	Comments
Mains			
Number of Intakes	4	headings	To minimise pressure loss and keep velocites down
Conveyor Roadway	1	heading	Single spine conveyor roadway in Mains
Number of Returns	3	headings	To minimise pressure loss, more tolerable to higher velocities
Cut Through linear Distance Centres	70	m	Actually varies based on drivehead and overcast positioning but 70m a conservative average inclusive of doglegs
Pillar width solids	35	m	Geotech, secondary support and depth dependent
Linear distance	4200	m	Based upon acceptable coffin seal pressure drop
Gates			
Number of Intakes	1	heading	Standard for twin gateroads
Number of Conveyor Returns	1	heading	Standard for twin gateroads
Cut Through linear Distance Centres	120	m	Optimal productivity in face zone.
Pillar width solids	45	m	Geotech, secondary support and depth dependent
Install Roadways			
Number of access cut throughs	2	cut throughs	For flexibility in longwall installation
Pillar width (solid)	45	m	Geotech, secondary support and depth dependent
Longwall			
Longwall Layout	Herringbone		Domains NE, NW, SE, SW
	Right side square		Domains NE Extended
Longwall Length	3675	m	Domains NE, NW, SE, SW
	3813	m	Domains NE Extended
Longwall width	320	m	All domains
Barrier Pillar	300	m	Average (Herringbone) Domains NE, NW, SE, SW
	170	m	Square: NE extension

3.3.3.1 Design 1: Migration Away and Return to a Central Portal

In Chapter 1 a question was posed as to what would happen to logistics supply strain if workings radiated out from a central portal and then, at a certain distance, a new domain starting back in the proximity of the shaft to repeat the radiation out. A large coal mining complex such an Appin Mine in Southern NSW is such a case (Figure 3-16).

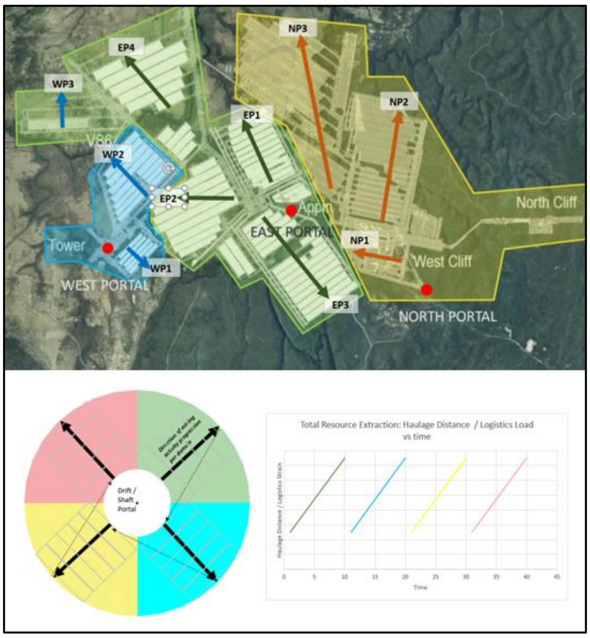


Figure 3-16: Reminder from (TOP) Figure 1-3 Appin Mine and the historical progression and return to a central portal access and the simplified generic model (BOTTOM) Figure 1-2 for the question posed on logistics supply strain in Chapter 1.

At this stage, Design 1 was to simply represent what could be seen as EP1, EP2 and EP3 all radiating away from, and returning to the shaft. The generic design was also used to represent such scenarios is shown in Figure 3-17.

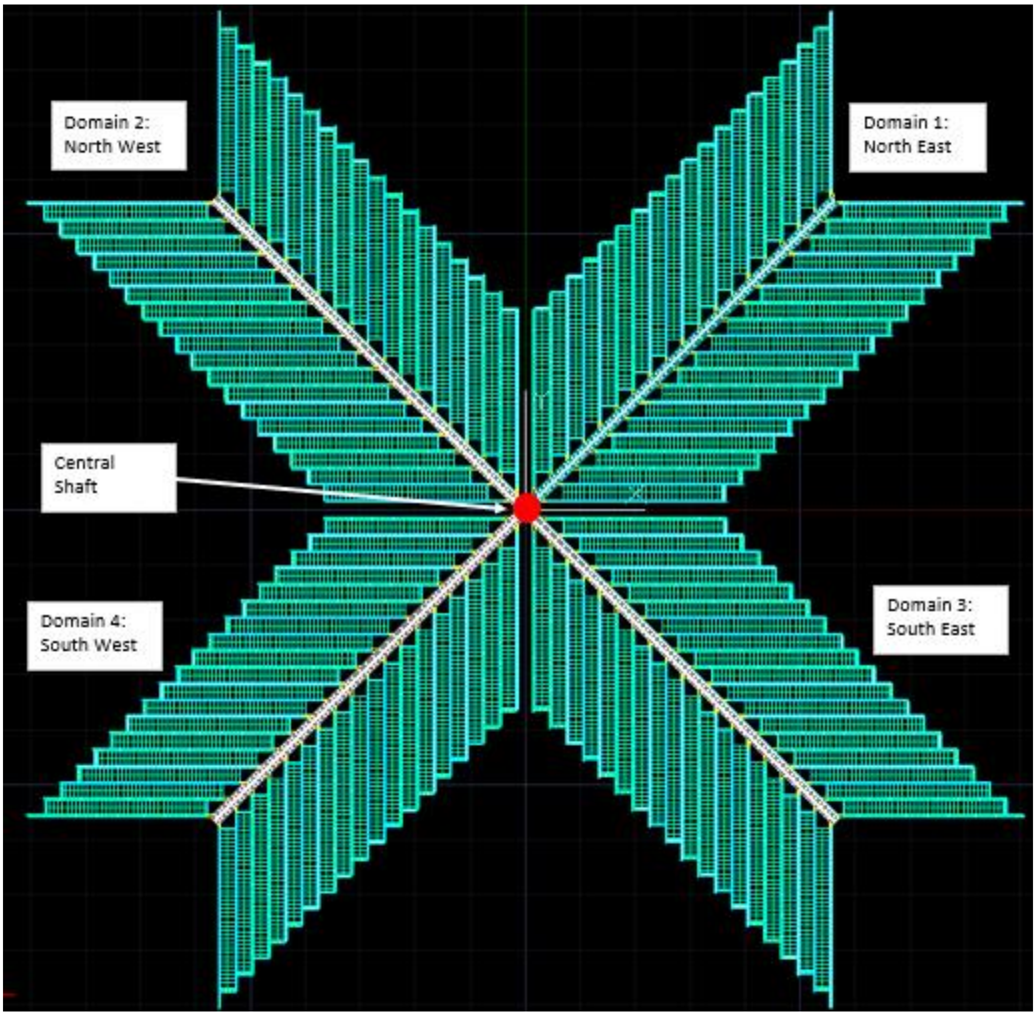


Figure 3-17: The ProgeCAD mine design to study migration away and return to a central portal.

The centralised shaft mine design consisted of four domains, "North East", "North West", "South East" and "South West". Each domain had 2 x 18 3650 m longwalls 320 metres wide in a herringbone design serviced from seven heading mains (four intakes three returns). A 3650 m longwall was the product of 4200 m linear length twin heading development gateroads with sufficient barrier pillars between the mains headings and longwall to ensure that the longwall take-off does not introduce a hazardous zone within the mains or impact the longwall belt drivehead electrics that may jeopardise the distribution of electricity.

3.3.3.2 Design 2: Adit / Box Cut / Cut and Cover Mine

In Chapter 1' a question was posed as to what would happen to logistics supply strain if the workings commenced at a portal and was constrained to move in a single direction away. A coal mining complex such as the Narrabri (North-western NSW) or Dendrobium (Southern NSW) Mine and the current Broadmeadow Mine configuration (in Central QLD after punch longwall ceased) represent this situation and shown in Figure 3-18.

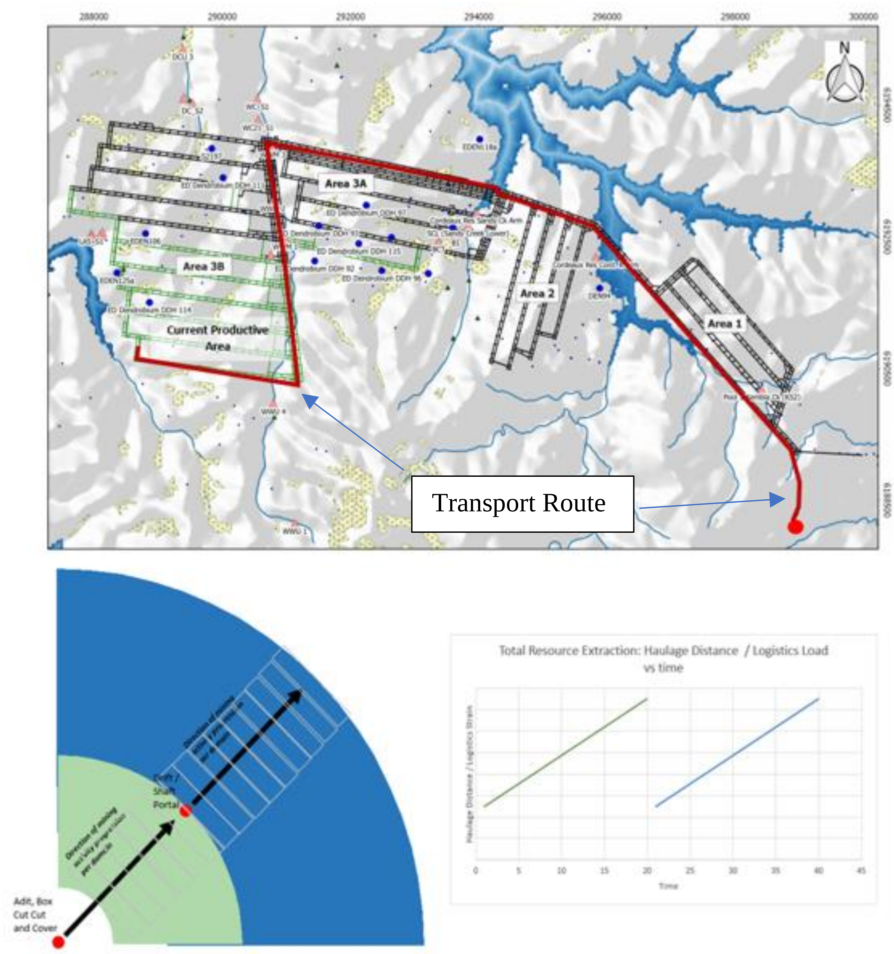


Figure 3-18: Reminder (TOP) Dendrobium Mine (Figure 1-6) highlighting the travelling distance to portals as the mine naturally migrates away from the adit, and of Figure 1-5 (BOTTOM). The simplified adit single direction generic model and the question posed on logistics supply strain in Chapter 1.

At this stage, Design 2 was to simply represent what could be seen as a natural migration away from portals with the future preserved option of a secondary shaft to alleviate logistics strain. The generic design to was used to represent such scenarios is shown in Figure 3-19.

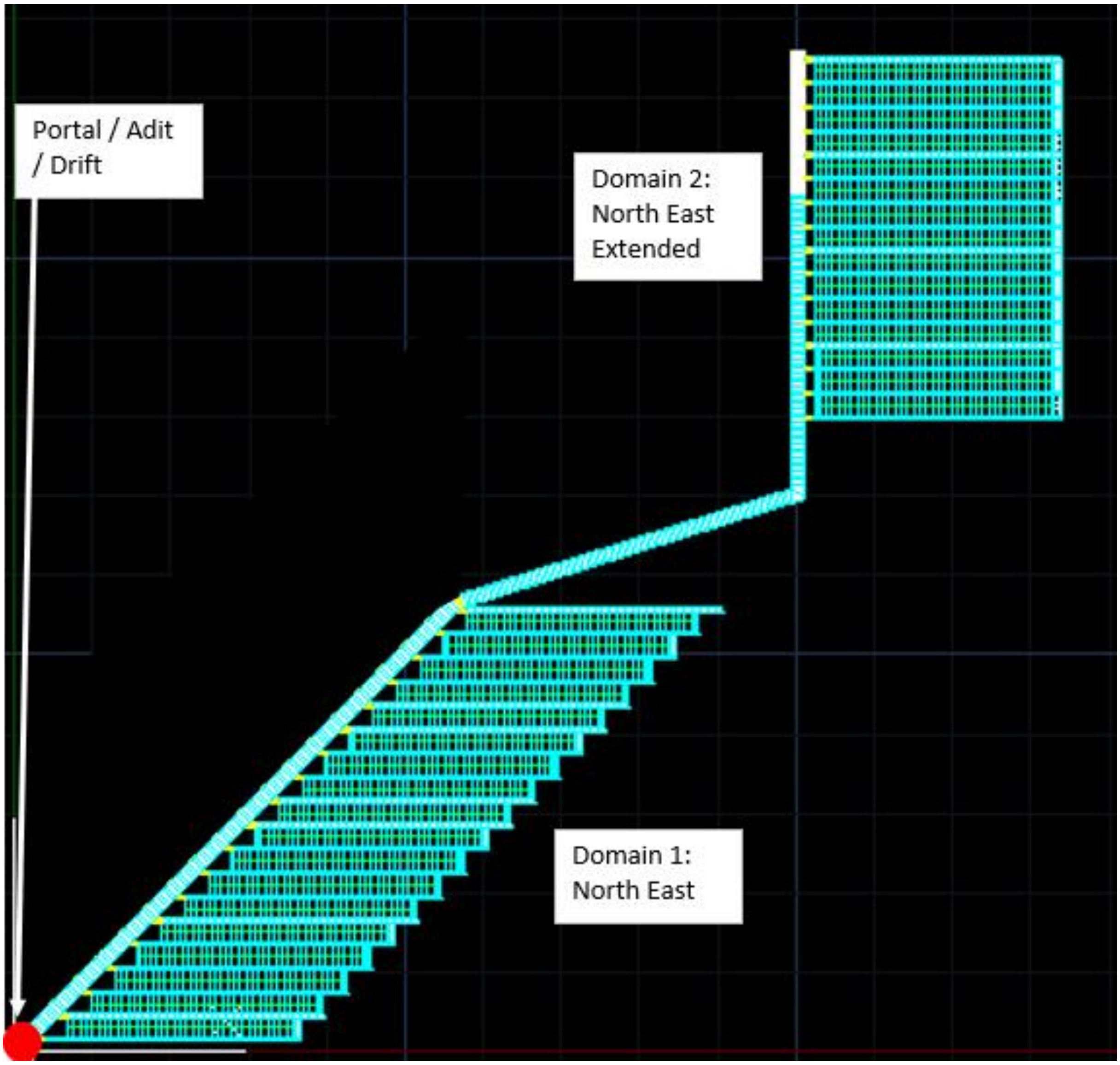


Figure 3-19: The ProgeCAD mine design to study migration away from a portal in a general direction from an adit / box cut / cut and cover Mine.

The generic adit / box cut / cut and cover mine design was built with a significant distance introduced between domains to highlight the perceived step change in logistics strain. The design consisted of two domains, Northeast and Northeast Extended. The Northeast Domain has 18 x 3650 m longwalls, and the Northeast Extended domain has 15 x 3813 m which are slightly longer because of the perpendicular orientation of the longwalls with respect to its mains which means that the longwall can come closer without impacting the longwall drivehead of mains electricity supply.

3.3.3.3 Design 3: Migration Away and Return to a Central Portal then an Extension Beyond Those Domains.

This design is an extension of Design 1 with an added domain beyond and is shown in Figure 3-20. This is to replicate an older mine that has a centralised shaft or larger mining domain that must step further away once its reserves nearest to the shaft are exhausted. If we recall Figure 3-16 previously for Appin Mine, Design 1 generically replicated EP1, EP2 and EP3. Over time the Appin Complex has expanded to EP4 but is still serviced by the original shaft. EP4 is represented in the generic mine design as Domain 5.

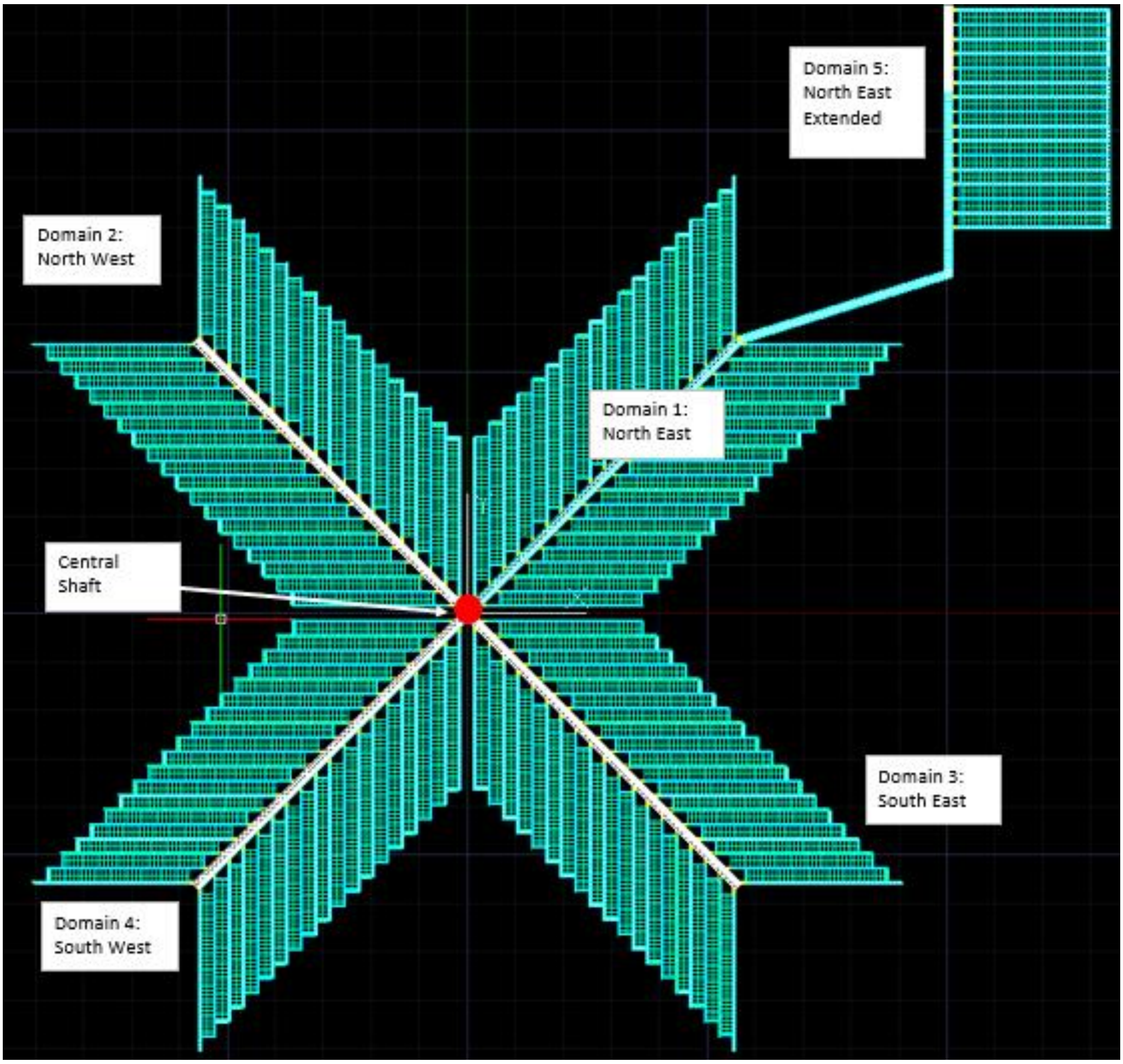


Figure 3-20: The ProgeCAD mine design to study migration away and return to a central portal with the additional of an extended domain to the Northeast.

The Northeast, Northwest, Southeast and Southwest domains all continue to have two x 18 3650 m longwalls 320 metres wide in a herringbone design. The North-East Extended Domain 5 has 15 x 3813 m longwalls. Gateroads remain 4200 m long. All mains drivage is seven headings (four intakes and three returns).

It should be noted that all these designs are very large. It is important to again reiterate these are not realistic mine designs, they are not meant to be, they are designed to provide bookend testing of a new method of strategically identifying logistics supply strain and such a large mine plan allows for many scenarios over very long periods of time. This gives confidence that the method of identification will be accurate on a significantly smaller actual mine plan in the future.

3.4 Strategic Identification Phase

Once the design is complete and reserves have been generated for the three designs, the research enters the scheduling phase highlighted in red in Figure 3-21 (Refer to specific detail in Figure 3-9) utilising the RPM Global software package XPAC combined with manipulation utilising MS Excel VBA programming. Broadly the purpose of this work is to calculate logistics strain at any given time through the life of mine.

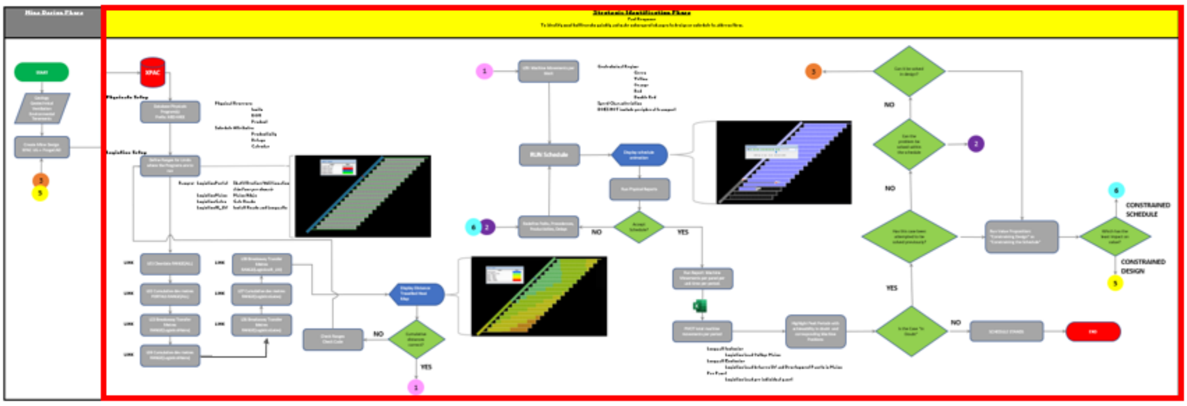


Figure 3-21: Reminder of Figure 3-9 of the strategic identification phase section highlighted in red.

The XPAC main database is by design, small to only report the necessary information for the purposes of scheduling and logistics strain for the life of mine. This is not a requirement for any future mine plan or any future XPAC model, no matter how large or small it is as the algorithms discussed here as well as the XPAC setup for logistics strain are completely independent of any other algorithms. Therefore, this thesis is designed to be completely scalable as different operations inevitably use different sized XPAC models.

This phase is designed to be very quick in the identification of logistics strain and is to work hand-in-hand with the mine schedule. Therefore, for this research to be effective, this phase must be as automated as possible to avoid human error and that it is directly bound to the schedule being calculated at that instant.

3.4.1 Import into the Physicals Setup

A standard step in all underground mine design to scheduling, is the combination of the geological model and the mine design that creates the Mine reserve database containing both polygon coordinates and reserves which are imported into XPAC shown in Figure 3-22 (Refer to specific detail in Figure 3-9). This is completed using the XPAC Command Module (XCM) using a sub variant of Visual Basic. The sub routine M02 Main DB.bas builds up key variables from the original imported data from the Mine Reserve Database in ProgeCAD.

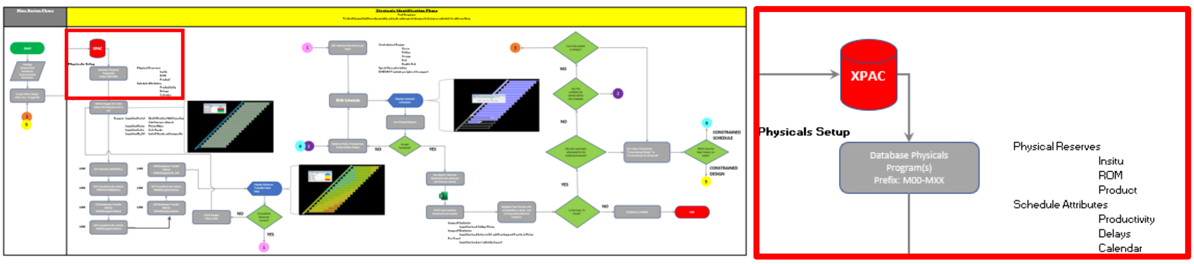


Figure 3-22: Reminder of Figure 3-9 of the flowsheet view section of setting up the XPAC main database highlighted in red

```
'Script: M02 Main DB.bas
' Author:  <David Walker>
' Position: <PhD Candidate UOW>
' Company: <University of Wollongong>
'
'
'Script description: Baseline Main Database Builder
' Execution:
'  Type:  Database/Trigger
'  Database: MAIN
'  Trigger: NA
'  Run type: Range
'  Range:  All
'
' Purpose: Generation of a simplified Main database for scheduling
''
'Script modification log:
' Date     Author/Company      Description of modifications
'~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
'8/8/2021   David Walker / UOW   First Write
'~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
'
'_
'Main subroutine
'Productivity deration by primary support type
Const cYellow_derate = 0.8
Const cOrange_derate = 0.6
Const cRed_derate = 0.4
Const cDRed_derate = 0.25

'Delivery per LW and Dev metre by primary support
Const cDelivperGreenm = 0.367
Const cDelivperYellowm = 0.825
Const cDelivperOrangem = 0.993
Const cDelivperRedm = 1.429
Const cDelivperDRedm = 1.8 'double red is very rare we do not have data for this.
Const cDelivperLWretm = 0.654

Sub Main()
 cleardata mPHYS, mCycle_Logst_LoadsPerDay

M(mPHYS_LinMet) = M(mIMP_BLOCKLENGTH)

If sProcessName = "DV" Then
 M(mSched_BaseRate_LW) = 0
 M(mPHYS_TotMet) = safedivide(M(mIMP_AREAACT1), M(mIMP_ROADWIDTH))
 If Left(sPanelName,2)="MH" Or Left(sPanelName,2)="IR" Then
  M(mSched_BaseRate_Dev) = 100
 Else                                                   [1]
  M(mSched_BaseRate_Dev) = 150
 End If
ElseIf sProcessName = "LW" Then
M(mPHYS_TotMet) = M(mIMP_BLOCKLENGTH)
M(mSched_BaseRate_Dev) = 0                             [2]
M(mSched_BaseRate_LW) = 60
End If

'In path delay
M(mDelay_InPath_LWMove)=0
M(mDelay_InPath_Flit) =0
If Left(sPanelName,2) = "IR" And islast() Then
 M(mDelay_InPath_Flit) = 7 'Development unit flit delay   [3]
ElseIf sProcessName = "LW" And islast() Then
 M(mDelay_InPath_LWMove) = 28 'LW move delay              [4]
End If

If sProcessName = "LW" then
 M(mSched_Rate_LW)= M(mSched_BaseRate_LW)                [12]
End If

'Distribution of primary support
If sProcessName = "DV" then

 If lBlockNum mod 23 = 0 then
  M(mSupport_DV_DoubleRed) = M(mPHYS_TotMet)                         [5]
  M(mSched_Rate_Dev) = M(mSched_BaseRate_Dev) * cDRed_derate         [6]
  M(mCycle_Logst_Total) = cDelivperDRedm * M(mPHYS_TotMet)           [7]
 ElseIf lBlockNum mod 17 = 0 then
  M(mSupport_DV_Red) = M(mPHYS_TotMet)                               [8]
  M(mSched_Rate_Dev) = M(mSched_BaseRate_Dev) * cRed_derate          [6]
  M(mCycle_Logst_Total) = cDelivperRedm * M(mPHYS_TotMet)            [7]
 ElseIf lBlockNum mod 7 = 0 then
  M(mSupport_DV_Orange) = M(mPHYS_TotMet)                            [9]
  M(mSched_Rate_Dev) = M(mSched_BaseRate_Dev) * cOrange_derate       [6]
  M(mCycle_Logst_Total) = cDelivperOrangem * M(mPHYS_TotMet)         [7]
 ElseIf lBlockNum mod 3 = 0 then
  M(mSupport_DV_Yellow) = M(mPHYS_TotMet)                            [10]
  M(mSched_Rate_Dev) = M(mSched_BaseRate_Dev) * cYellow_derate       [6]
  M(mCycle_Logst_Total) = cDelivperYellowm * M(mPHYS_TotMet)         [7]
 Else
  M(mSupport_DV_Green) = M(mPHYS_TotMet)                                     [11]
  M(mSched_Rate_Dev) = M(mSched_BaseRate_Dev) 'Green support no derate       [6]
  M(mCycle_Logst_Total) = cDelivperGreenm * M(mPHYS_TotMet)                  [7]
 End If

elseif sProcessName = "LW" then
  M(mSched_Rate_LW) = M(mSched_BaseRate_LW)                      [12]
  M(mCycle_Logst_Total) = cDelivperLWretm * M(mPHYS_LinMet)      [7]

End If

End Sub
```

Table 3-5: ROWS built highlighted in yellow from M02 Main DB.bas and corresponding code in boxes.

Box	Code	Data Field Name	Units	Central\NE\DV\MG101\17	Central\NE\DV\MHNE\8	Central\NE\LW\LW101\19
				Gateroad Block	Mains Block	LW Block
		LoA Model				
	IMP	**Imported Data Fields**				
	mIMP_NUMOFROADS	*Number of Roadways*		*2*	*7*	*1*
	mIMP_ROADWIDTH	*RoadWay Width*		*5.2*	*5.2*	*0*
	mIMP_CLINEOFFSET	*RoadWay C/Line Offset*		*50*	*40*	*0*
	mIMP_CTHRUOFFSET	*Cut-Through Offset*		*120*	*75*	*0*
	mIMP_BLOCKLENGTH	*Block Length (Max)*		*151.87*	*75*	*100*
	mIMP_BLOCKWIDTH	*Block Width (Max)*		*55.2*	*245.2*	*320*
	mIMP_AREAACT1	*Area*		*1517*	*3815.76*	*0*
	mIMP_VOLACT1	*Volume*		*0*	*0*	*0*
	mIMP_CENTXACT1	*Centroid X*		*2734.76*	*321.76*	*2704.83*
	mIMP_CENTYACT1	*Centroid Y*		*575.27*	*321.76*	*387.67*
	mIMP_MINDIRACT1	*Mining Direction*		*90*	*45*	*90*
	mIMP_AREAACT2	*Area*		*5107*	*14574.24*	*32000*
	mIMP_VOLACT2	*Volume*		*0*	*0*	*0*
	mIMP_CENTXACT2	*Centroid X*		*2721.65*	*312.89*	*2704.83*
	mIMP_CENTYACT2	*Centroid Y*		*575.27*	*312.89*	*387.67*
	mIMP_MINDIRACT2	*Mining Direction*		*270*	*225*	*270*
	mIMP_Seamthknss	*Insitu Thickness*		*0*	*0*	*0*
	mPHYS	**Physicals**				
	mPHYS_Metres	**Metres**				
	mPHYS_LinMet	Linear Metres	m	152	75	100
	mPHYS_TotMet	Total Metres	m	292	734	100
	mSched	**Scheduling**				
	mSched_BaseRate	**BaseRate**				
1	mSched_BaseRate_Dev	Development Productivity	m/week	150	100	
2	mSched_BaseRate_LW	LW Productivity	m/week			60
	mSched_Rate	**Rate**				
6	mSched_Rate_Dev	Development Productivity	m/week	60	100	
12	mSched_Rate_LW	LW Productivity	m/week			60
	mSched_Dates	**Dates**				
	mSched_Dates_Start	Start Date		19/08/2023	11/12/2021	25/03/2025
	mSched_Dates_End	End Date		22/09/2023	18/01/2022	6/04/2025
	mSched_Dates_Resource	Resource Name		CM2	CM1	LW1
	mSupport	**Primary Support Zones**				
	mSupport_DV	**Development Zones**				
11	mSupport_DV_Green	Green primary support metres	m	0	734	0
10	mSupport_DV_Yellow	Yellow primary support metres	m	0	0	0
9	mSupport_DV_Orange	Orange Support primary support metres	m	0	0	0
8	mSupport_DV_Red	Red Support primary support metres	m	292	0	0
5	mSupport_DV_DoubleRed	Double Red primary support metres	m	0	0	0
	mDelay	**Delays**				
	mDelay_InPath	**Inpath**				
3	mDelay_InPath_Flit	CM Flits		0	0	0
4	mDelay_InPath_LWMove	LW Move		0	0	0
	mCycle	**Cycle Times**				
	mCycle_Dist	**Distance Travelled**				
	mCycle_Dist_CumDist	Cumulative Distance	m	3371	450	3371
	mCycle_Logst	**Logistics**				
	mCycle_Logst_Duration	Duration within Block		34.04	38.69	11.67
7	mCycle_Logst_Total	Total Deliveries Per Block Required	deliveries	416.88	269.30	65.40
	mCycle_Logst_LoadsPerDay	Total Deliveries per Day Required	deliveries	12.25	6.96	5.61
	mCycle_Logst_optime	Material delivery cycle time Machine	hours	0.67	0.09	0.67
	mCycle_Logst_utiltime	Material delivery cycle time Machine	hours	1.17	0.59	1.17
	mCycle_Logst_onroad	Supplies on road at any given time	Loaders	0.60	0.17	0.27

The program clears previous data to ensure that cumulative overwrite errors do not occur in subsequent subroutines. The subroutine then has three major functions: -

1. Calculate linear longwall and development metres. Total development metres are calculated for development scheduling. Linear development metres are used for longwall scheduling and more critically form the basis for all logistics distances for future subroutines.
2. Nominate changes in primary support for development. Each of these primary support regimes have different delivery requirements.
3. Calculate development based upon primary support and longwall productivity. With this, combining the development productivity, distance from portal to production face for each productive unit and material delivery requirement forms the basis for evaluating logistics strain.

3.4.1.1 Primary Support, Productivity and Delivery Requirements

Primary support is based on the geotechnical management plan and is the support that is put in during the cutting sequence of the continuous miner and directly affects the productivity of the continuous miner, not to be confused with secondary support which is done behind the continuous miner and does not affect productivity of the development. This data was extracted from "Mine 1" of the NSW Sydney Basin Coalfield logistics system. Essentially the more primary support required per metre the more deliveries. Also, the more primary support the slower the development productivity. Figure 3-23 outlines Mine 1's primary support plan which would be considered fairly standard across industry with perhaps bolt length being modified from 1.8 to 2.4 m if seam thickness and overhead strata warrant it.

Mine 1 does not have a Double Red support regime. This support plan is considered very rare and caters for the absolute worst of conditions. Whilst very rare, the logistics component of the XPAC model accommodates a fifth primary support regime which for the purposes of this thesis has been nominated as Double Red Support, which would mean significantly lower productivity and higher deliveries than that of red support and was estimated for this thesis to be a 75% reduction in productivity from baseline green support.

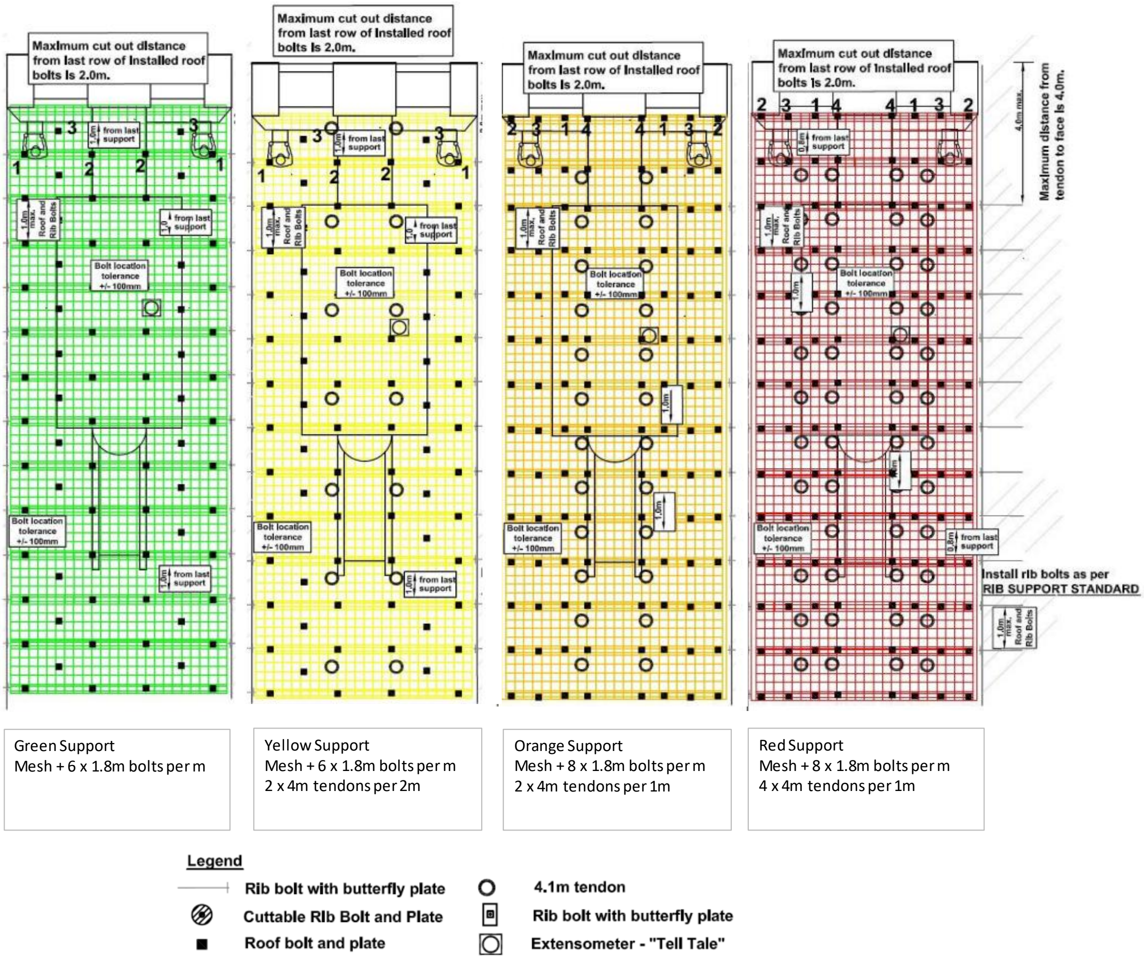


Figure 3-23: "Mine 1" Primary Support Plans

To calculate deliveries per development metre for Mine1, this data was collected between January and March 2018 using the production panel shift reports written by the mine deputies, the sum of development advance by primary support type for two continuous miners was divided by the total deliveries for each day that primary support Trigger Action Response Plan (TARP) was executed according to the formula (Prow 2018): -

$$\text{Deliveries per dev metre by support TARP} = \frac{\sum_{i}^{k} D_i}{\sum_{i}^{k} m_i}, \; i = 1, 2 \ldots k \text{ days in support TARP}$$

Where k = the number days in that TARP Primary Support regime.

D = Deliveries required in the TARP Primary Support regime.

m = metres advanced TARP Primary Support regime.

Table 3-6: Deliveries required per primary support metre of development for Mine 1.

	Development			
Primary Support TARP	Green	Yellow	Orange	Red
Deliveries per dev. Metre	0.367	0.825	0.993	1.429

For Double Red support deliveries per development metre has been nominally estimated to be 1.8 deliveries per development metre advanced.

For longwall, deliveries per linear metre of retreat was calculated from Machine Personal Emergency Device (PED) tracking along the longwall gateroad which averaged five deliveries per day equating to a total of 325 deliveries. For the same time the longwall retreated 497 m. The number of deliveries was therefore 0.654 per linear metre of retreat.

3.4.1.2 *Nominal Primary Support Locations Within the Generic Mine*

To understand the impact of different delivery requirements, scheduling blocks within XPAC have been allocated different primary support TARP regimes. For the purposes of the generic model Double Red has been allocated to every 23rd gateroad or mains block (around one per gateroad – to capture the impact of this rare event), Red support every 17 blocks, (around two times per gateroad), Orange every seven blocks and Yellow every 3rd Block. Every remaining Block is allocated as green support. These allocations are illustrated in Figure 3-24: -

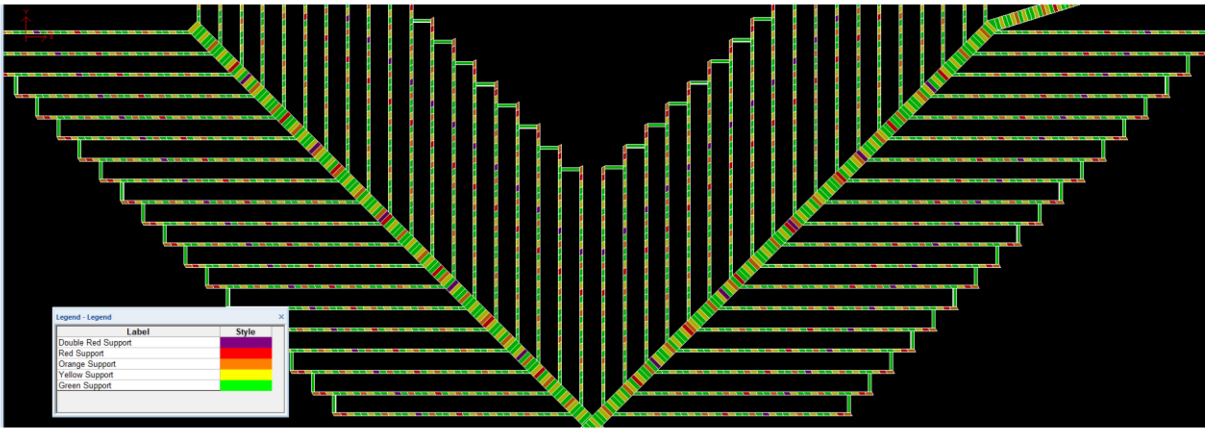


Figure 3-24: Primary support TARP allocation within the generic model for the Northern Domains. The same logic applies to other domains.

With the above allocations for primary support total deliveries per scheduling block which is calculated from total development metres per scheduling block multiplied by deliveries per development metre. Total deliveries per scheduling block is a key metric in total delivery requirements at any instant in time which will constantly change with the schedule that will be run.

Again, the model being developed is designed so that it can be changed for real-world geotechnical data at any time. The geologist, geotechnical engineer or mine planner can use multiple techniques including polygons, depth of cover triggers or manual range allocations of specific blocks to modify the primary support requirements for any real-world scenario.

3.4.1.3 *Machine Productivity*

Development productivity will vary based upon primary support. Green primary support requires only six bolts per development metre in "Mine 1", whereas red support is significantly slower as it must install two extra 1.8 m bolts and four 4 m tendons per metre. For the purposes of this schedule the green development nominal baseline rate is 150 metres per week for gateroads and 100 metres per week for mains drivage. Mains drivage has a considerably lower rate to reflect the complicated drivage that includes drivehead excavations, complex sequencing and shuttle car wheeling and overcasts associated with longwall gateroad breakaways. Development rates per week based upon the primary support TARP are shown in Table 3-7. Table 3-8

Table 3-7: Generic model development productivities based on primary support TARP.

Primary Support TARP	Gateroad	Mains
	metres per week	metres per week
Green	150	100
Yellow	120	80
Orange	90	60
Red	60	40
Double Red	37.5	25

Longwall productivity is scheduled at nominally 60 metres per week. This can be altered at any stage for any location to reflect actual longwall productivities or any other scheduling drivers such as tonnes per week productivity. The model is again flexible to modify productivity rates for both longwall and development anywhere within the mine plan to account for a wide range of scheduling input parameters that would be tracked.

3.4.1.4 *Combining Rate, Primary Support, and Deliveries*

By combining primary support, total development metres per scheduling block and deliveries per metre, then total deliveries per scheduling block can be calculated. Deliveries per scheduling block is the first step in studying logistics strain. Applying a machine path to a scheduling block will therefore give timing of when a block will be scheduled to be excavated which can be studied across all machines. The following is an example of how this is used and is the foundation of this thesis.

Consider three development units (CMs) and a longwall unit. On the 1st of March 2025, the longwall is commencing Longwall 5 Block 4, CM1 is commencing MG6 Block 25, CM2 is commencing in MG7 Block 3 and CM3 is commencing mains drivage Block 17. All development units enter a "perfect storm" of double red support shown in Table 3-8. It is important to note that the probability that all units are commencing a scheduling block considered zero percent mined at the same time apart from the start of a schedule (or restarting an operation) is near impossible but is still a good way to explain the mechanics of the calculations as they form.

Table 3-8: Impact on total deliveries per day for double red support

Location	Primary Support	Development metres	Deliveries per metre	Total Deliveries	Productivity metres/week	Mining Duration (days)	Start Date	End Date	Deliveries per Day	Grand Total Deliveries per day
		A	B	C = A x B	D	E = A x 7 / D	F	G = F + E	H = C / E	
MG6 B25	Double Red	292	1.8	525.6	37.5	54.5	1/03/2025	24/04/2025	9.6	
MG7 B3	Double Red	292	1.8	525.6	37.5	54.5	1/03/2025	24/04/2025	9.6	
MH B17	Double Red	734	1.8	1321.2	25	205.5	1/03/2025	22/09/2025	6.4	
LW5 B4	N/A	100	0.654	65.4	60	11.7	1/03/2025	12/03/2025	5.6	**31.3**

Now consider if these panels are no longer double red but green support, which has less deliveries per development metre but is more productive meaning deliveries will be required at a higher rate with respect to time as shown in Table 3-9.

Table 3-9: Impact on total deliveries per day for green support

Location	Primary Support	Development metres	Deliveries per metre	Total Deliveries	Productivity metres/week	Mining Duration (days)	Start Date	End Date	Deliveries per Day	Grand Total Deliveries per day
		A	B	C = A x B	D	E = A x 7 / D	F	G = F + E	H = C / E	
MG6 B25	Green	292	0.367	107.2	150	13.6	1/03/2025	14/03/2025	7.9	
MG7 B3	Green	292	0.367	107.2	150	13.6	1/03/2025	14/03/2025	7.9	
MH B17	Green	734	0.367	269.4	100	51.4	1/03/2025	21/04/2025	5.2	
LW5 B4	N/A	100	0.654	65.4	60	11.7	1/03/2025	12/03/2025	5.6	**26.6**

Now consider all yellow support in Table 3-10.

Table 3-10: Impact on total deliveries per day for yellow support

Location	Primary Support	Development metres	Deliveries per metre	Total Deliveries	Productivity metres/week	Mining Duration (days)	Start Date	End Date	Deliveries per Day	Grand Total Deliveries per day
		A	B	C = A x B	D	E = A x 7 / D	F	G = F + E	H = C / E	
MG6 B25	Yellow	292	0.825	240.9	120	17.0	1/03/2025	18/03/2025	14.1	
MG7 B3	Yellow	292	0.825	240.9	120	17.0	1/03/2025	18/03/2025	14.1	
MH B17	Yellow	734	0.825	605.6	80	64.2	1/03/2025	4/05/2025	9.4	
LW5 B4	N/A	100	0.654	65.4	60	11.7	1/03/2025	12/03/2025	5.6	**43.3**

All orange support in Table 3-11: -

Table 3-11: Impact on total deliveries per day for orange support

Location	Primary Support	Development metres	Deliveries per metre	Total Deliveries	Productivity metres/week	Mining Duration (days)	Start Date	End Date	Deliveries per Day	Grand Total Deliveries per day
		A	B	C = A x B	D	E = A x 7 / D	F	G = F + E	H = C / E	
MG6 B25	Orange	292	0.993	290.0	90	22.7	1/03/2025	23/03/2025	12.8	
MG7 B3	Orange	292	0.993	290.0	90	22.7	1/03/2025	23/03/2025	12.8	
MH B17	Orange	734	0.993	728.9	60	85.6	1/03/2025	25/05/2025	8.5	
LW5 B4	N/A	100	0.654	65.4	60	11.7	1/03/2025	12/03/2025	5.6	**39.7**

All red support in Table 3-12: -

Table 3-12: Impact on total deliveries per day for red support

Location	Primary Support	Development metres	Deliveries per metre	Total Deliveries	Productivity metres/week	Mining Duration (days)	Start Date	End Date	Deliveries per Day	Grand Total Deliveries per day
		A	B	C = A x B	D	E = A x 7 / D	F	G = F + E	H = C / E	
MG6 B25	Red	292	1.429	417.3	60	34.1	1/03/2025	4/04/2025	12.2	
MG7 B3	Red	292	1.429	417.3	60	34.1	1/03/2025	4/04/2025	12.2	
MH B17	Red	734	1.429	1048.9	40	128.5	1/03/2025	7/07/2025	8.2	
LW5 B4	N/A	100	0.654	65.4	60	11.7	1/03/2025	12/03/2025	5.6	**38.3**

Or a mix of primary support and rates in Table 3-13:

Table 3-13: Impact on total deliveries per day for mixed support

Location	Primary Support	Development metres	Deliveries per metre	Total Deliveries	Productivity metres/week	Mining Duration (days)	Start Date	End Date	Deliveries per Day	Grand Total Deliveries per day
		A	B	C = A x B	D	E = A x 7 / D	F	G = F + E	H = C / E	
MG6 B25	Green	292	0.367	107.2	150	13.6	1/03/2025	14/03/2025	7.9	
MG7 B3	Yellow	292	0.825	240.9	120	17.0	1/03/2025	18/03/2025	14.1	
MH B17	Orange	734	0.993	728.9	60	85.6	1/03/2025	25/05/2025	8.5	
LW5 B4	N/A	100	0.654	65.4	60	11.7	1/03/2025	12/03/2025	5.6	**36.1**

As can be seen based on the productivity and delivery rates that are being used, if all CMs were in yellow support, then this would require the most deliveries per day at 43.3. The system must be flexible though. If Green support becomes more productive for example and can achieve 250 metres per week whilst all other primary support regimes remain constant this would surpass yellow support at 44.9 deliveries per day as shown in Table 3-14: -

Table 3-14: Impact on total deliveries per day for green support with an increase in productivity.

Location	Primary Support	Development metres	Deliveries per metre	Total Deliveries	Productivity metres/week	Mining Duration (days)	Start Date	End Date	Deliveries per Day	Grand Total Deliveries per day
		A	B	C = A x B	D	E = A x 7 / D	F	G = F + E	H = C / E	
MG6 B25	Green	292	0.367	107.2	250	8.2	1/03/2025	9/03/2025	13.1	
MG7 B3	Green	292	0.367	107.2	250	8.2	1/03/2025	9/03/2025	13.1	
MH B17	Green	734	0.367	269.4	250	20.6	1/03/2025	21/03/2025	13.1	
LW5 B4	N/A	100	0.654	65.4	60	11.7	1/03/2025	12/03/2025	5.6	**44.9**

Therefore, the model being constructed must be flexible enough to be able to change, the delivery and productivity rates at any given time within the schedule to correctly reflect the latest information as the mine progresses. Whilst this is a crucial first step in understanding logistics strain throughout a strategic mine plan, it does not consider distance. About 45 deliveries may be very easy to achieve if delivery distance is less than 5 km. On the other hand, if the delivery distance is 15 km, then there is a higher risk of a logistics bottleneck that will hobble development rates which leads us to the next phase of the developed model, distance from workings to portal.

It must be pointed out that productivities and deliveries for both longwall retreat and development provides a sanity check for the research. It is not critical to the research itself as other mines will operate with larger payloads or faster speeds or both but does provide the research with industry credibility. Therefore, the system developed in this thesis is designed for flexibility to ensure accurate actual mine calibration to ensure the best possible prediction of logistics strain.

3.4.2 Logistics System Setup

The next stage in model development is the development of distance algorithms from the designated portal where supplies enter the mine. As previously discussed, total deliveries per day are a first glance indicator of logistics strain, but it does not consider how far away each productive face is from the portal. It also does not highlight the impact of the relocation of productive faces as the mine schedule progresses. Through the next round of algorithms distance from the portal is calculated at any given time combined with delivery speed and deliveries on any given day and is designed to automatically calculate the number of supply vehicles that are on the mine roadway system.

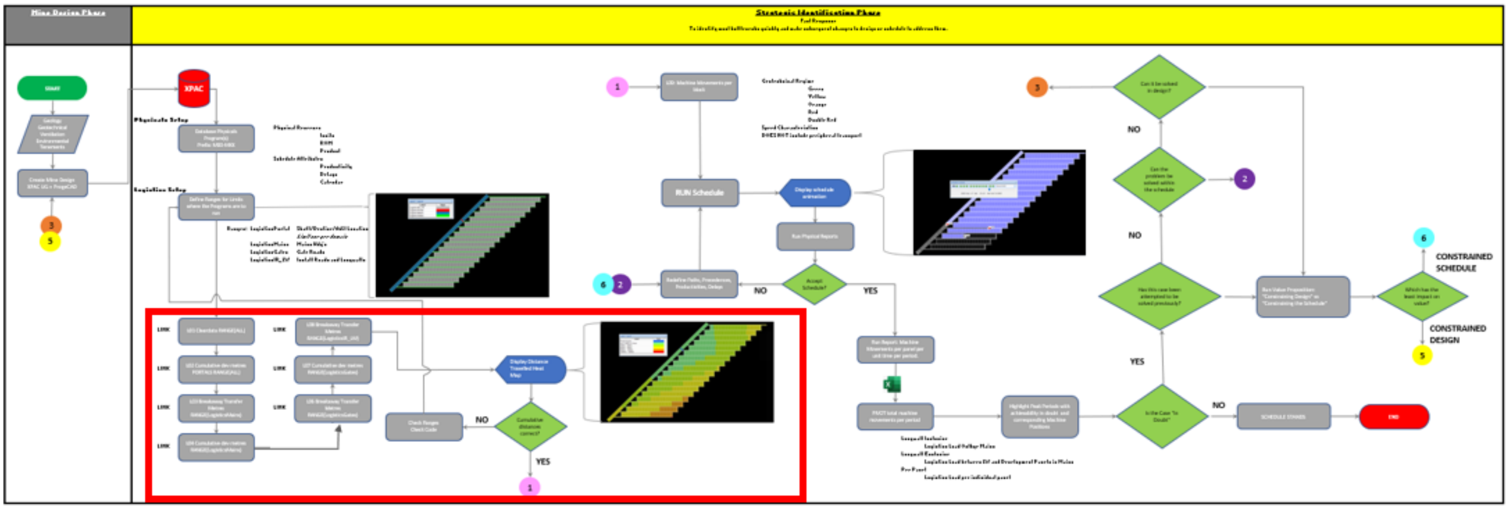


Figure 3-25: Reminder of Figure 3-9 of the logistics programming sequence setup section highlighted in red.

The previous method of estimating the distance from a portal was using centroids. The simplest being the distance between the scheduling block centroid to portal centroid. This typically created a radiating distance which was considered at best rudimentary and at worst entirely incorrect. Figure 3-26 illustrates the simple centroid to centroid distance from the portal.

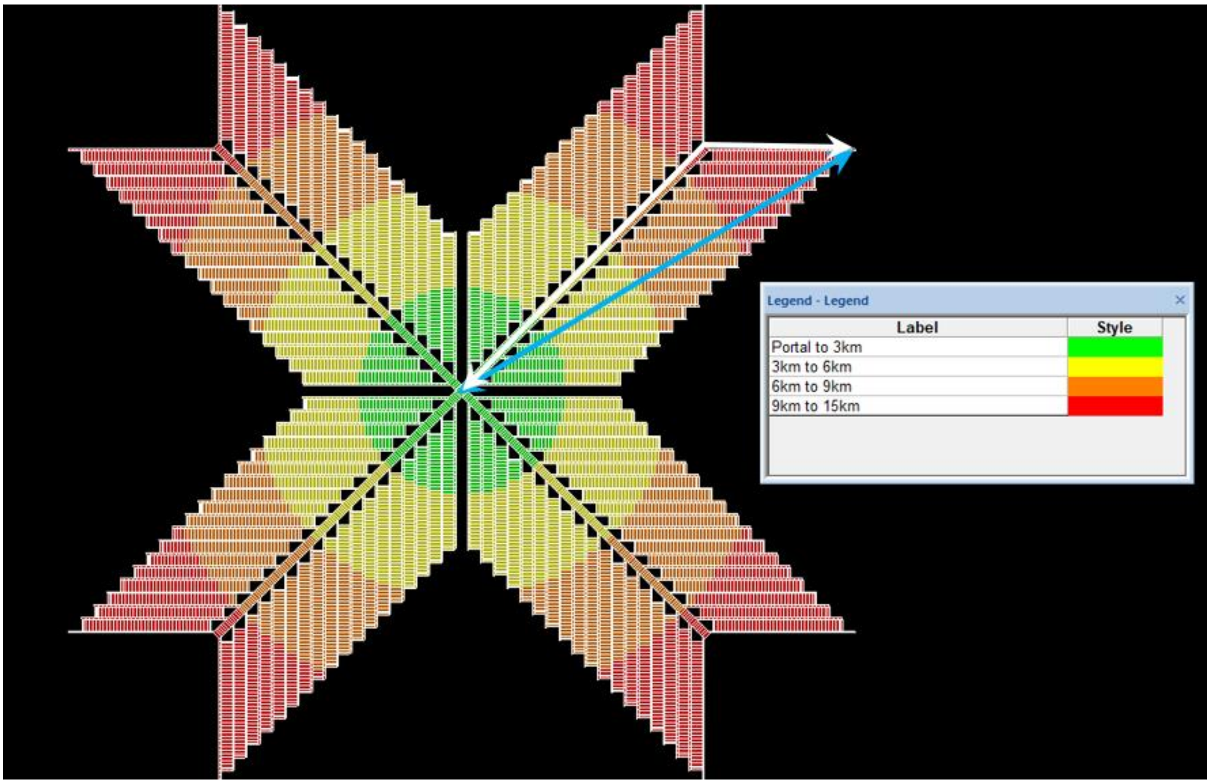


Figure 3-26:Centroid to centroid distances

As can be seen in Figure 3-26, two arrows are illustrated. The blue arrow represents the portal to block distance, which, in this case is to the centroid of MG18 scheduling block 35 (or 35ct) of the Northeast Domain. The distance for this design that the blue arrow represents is 13.25 km. The white arrow represents the actual distance travelled by machinery from the portal, along the mains roadways and then out to MG18 35ct which is 14.36 km. Depending on the design the distance error could be significantly worse. Take Dendrobium Mine for example shown in Figure 3-27, the true distance represented by the white arrow, to the face is considerably different from centroid-to-centroid distance represented by the blue arrow.

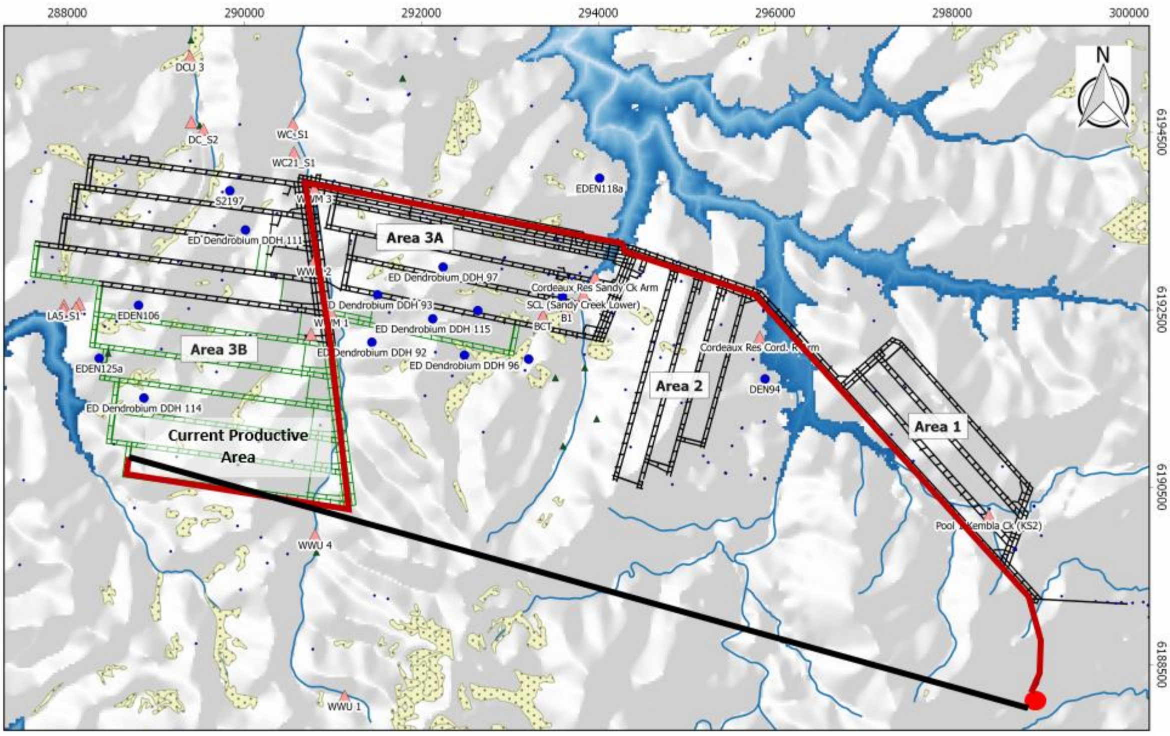


Figure 3-27: Working face centroid to centroid distance (black) vs true (red) travel distance for Dendrobium mine.

As can be seen this method is clearly wrong and will underestimate the travel times and logistics strain. An algorithm was required that would estimate the total actual travel distance from the portal to each scheduling block in the LoM plan.

3.4.2.1 Defining Ranges

Ranges are defined as sets of scheduling blocks that have been filtered to a common criterion or manually selected. An example of a range might be longwall scheduling blocks that are less than two metres thick. Ranges can be used to run XCM programs over specific scheduling blocks and will not run over other blocks that are not in the range therefore protecting them from executing algorithms.

There are eight logistics programs that must be run over various ranges to define the distance to portal. These programs must be also run in a specific sequence to correctly propagate as travelled distance. The ranges used for these programs are:

1. ALL: This is every scheduling block in the Main Database.
2. LogisticsPortal: These are specific blocks where the portals exist.
3. LogisticsMains: Mains headings scheduling blocks.
4. LogisticsGates: Gateroad scheduling blocks.
5. LogisticsIR_LW: Installation Roads. bleeders and Longwall Panel scheduling blocks.

The various ranges used for the logistics setup are illustrated in Figure 3-28. It is imperative for the success of the XCM programs that these are precise, and blocks exist uniquely in ALL only one of the logistics ranges.

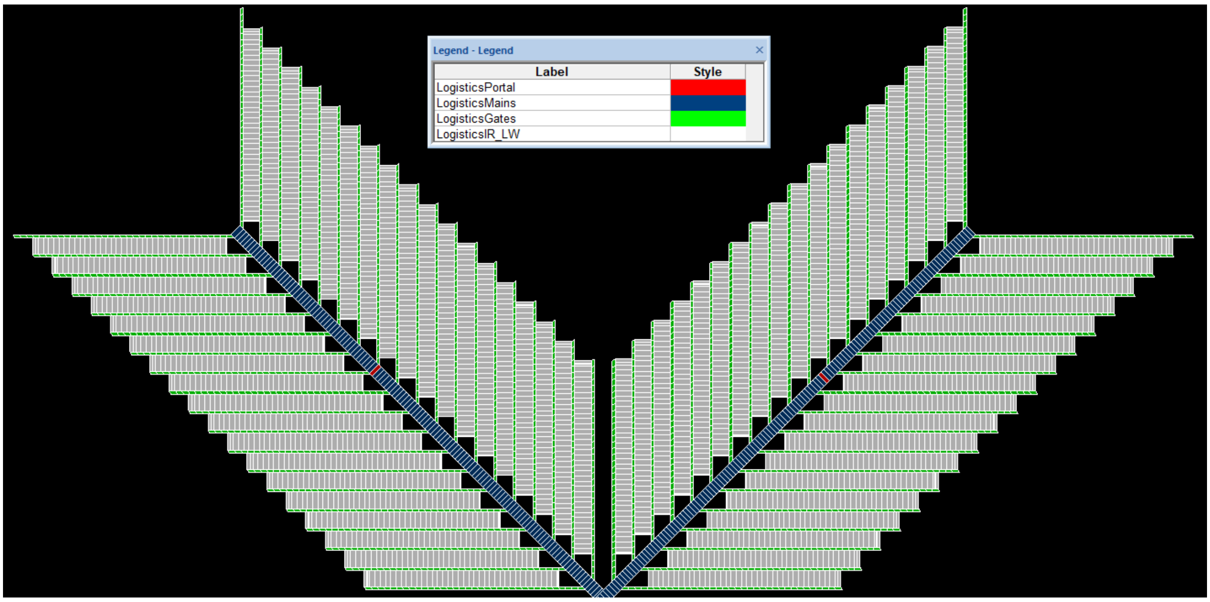


Figure 3-28: Defined ranges for logistics setup for NE and NW domains.

The XCM subroutines within XPAC execute within a single scheduling block at a time. After execution within each scheduling block the “END SUB” is achieved and the program moves to the next block. At the completion of the subroutine in the block, all variables that may be required to be carried over are initialised. It was originally anticipated that a master subroutine would call all other subroutines, but with the loss of variable values a limiting factor within XPAC, execution of the subroutines in a specific sequence over specific ranges to replicate a master subroutine without the need for the formation of additional databases being required. In future other user preferences may be to utilise this alternative method but it was deemed non-critical for this thesis. The batch sequence and associated ranges that all logistics subroutines must be run are shown. The subroutines build upon each other and therefore must be executed consecutively in this precise sequence to avoid cumulative errors.

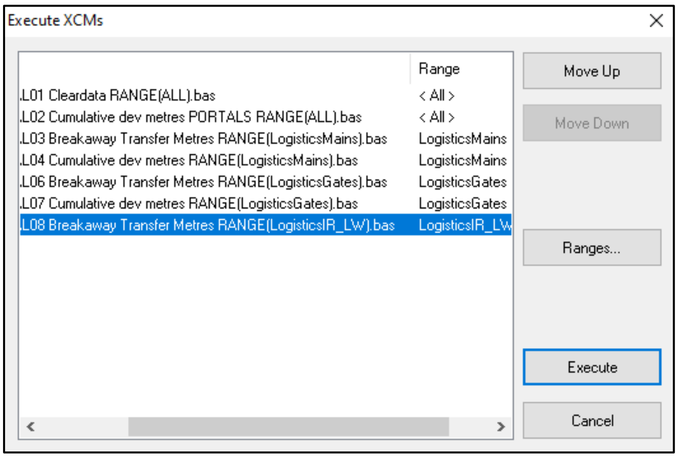


Figure 3-29: XCM subroutine batch execution sequence

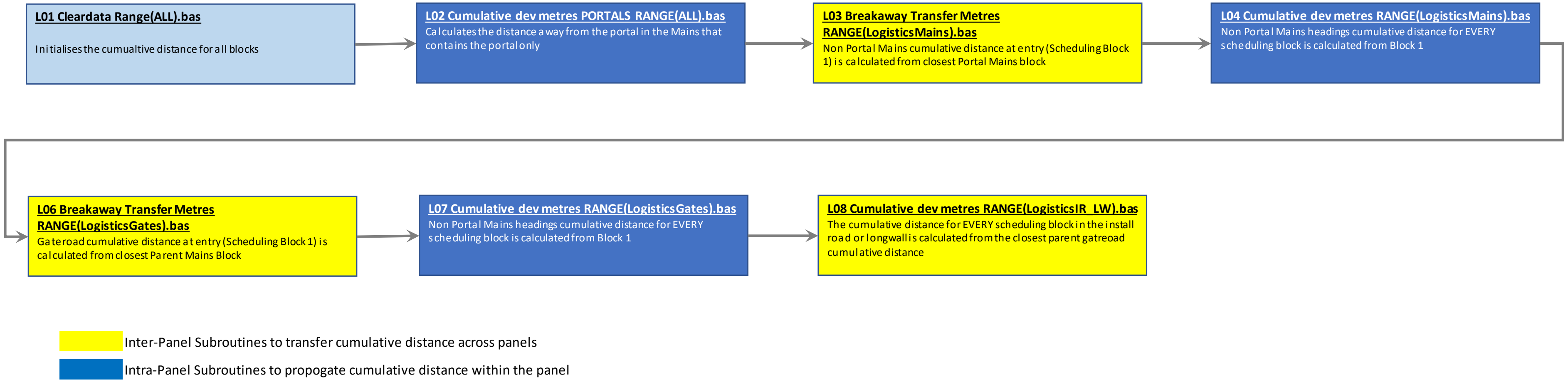


Figure 3-30: Overview and sequencing of subroutines.

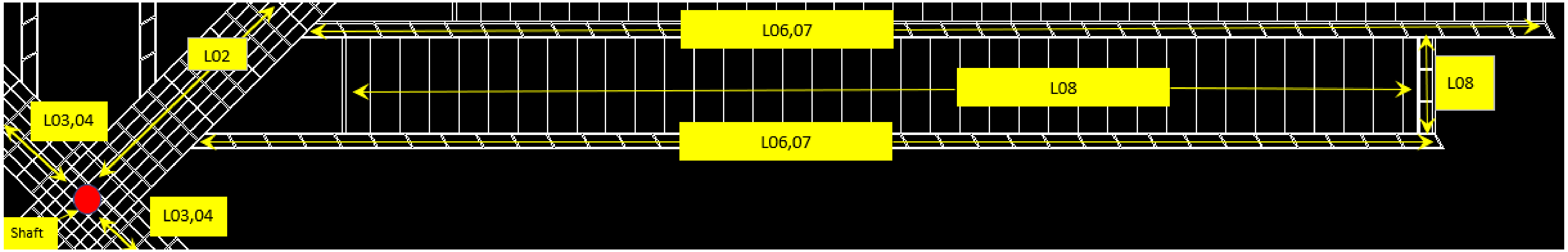


Figure 3-31: The targeted panels that each subroutine impacts to calculate cumulative distance.

3.4.3 The Subroutines

Overall, for these subroutines, the only output is cumulative distance (known as variable “mCycle_Dist_CumDist”). Numerical inputs from the database only include centroid x and y coordinates (mIMP_CENTXACT1, mIMP_CENTYACT1 respectively), previous cumulative distance and linear metres (mPHYS_LinMet), which is also known as block length.

3.4.3.1 L01 Cleardata RANGE(ALL).bas

The subroutine L01 Cleardata RANGE(ALL).bas abbreviated to L01, clears the cumulative distance from all scheduling blocks. This is because the sequence from L02 thereafter rely on cumulative distance being transferred from one subroutine to the next. If the cumulative distance is not cleared within the subroutine sequence, there is a risk that old redundant metres will be added to new metres resulting in overestimating the distance from the portal. In Figure 3-32 all cumulative distances are initialised, and identification of the portal has been made.

```
'Script creation:L01 Cleardata RANGE(ALL)
' Author:  <David Walker>
' Position: <PhD Candidate UOW>
' Company: <University of Wollongong>
'
'Script description:
' Execution:
'  Type:  Database
'  Database: MAIN
'  Trigger: NA
'  Run type: Range
'  Range:  All
'
' Purpose: Clearing all previous cumulative distance data to prevent old distances being added to new distances
'Script modification log:
' Date    Author/Company     Description of modifications
'~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
'       David Walker      First Write
'~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
'
'Main subroutine
Sub Main()

M(mCycle_Dist_CumDist) = 0  1

End
Sub'~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
```

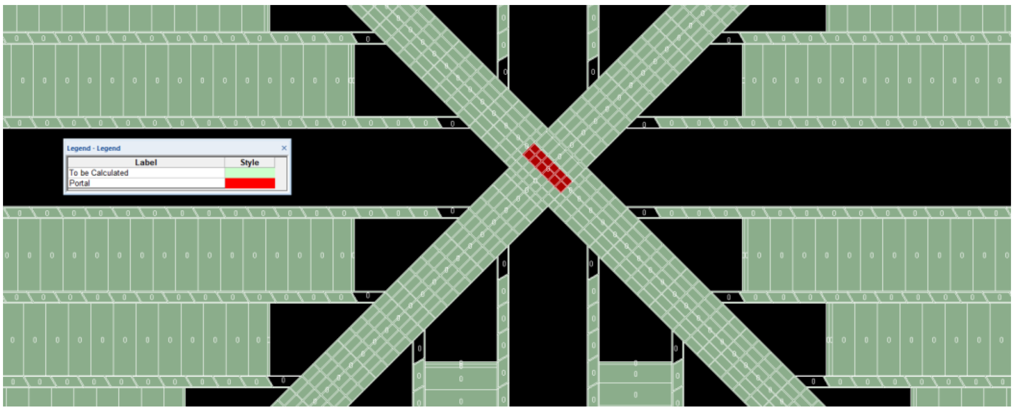


Figure 3-32: After executing L01, resetting the cumulative distance and highlighting portal position.

3.4.3.2 L02 Cumulative dev metres PORTALS RANGE(ALL)

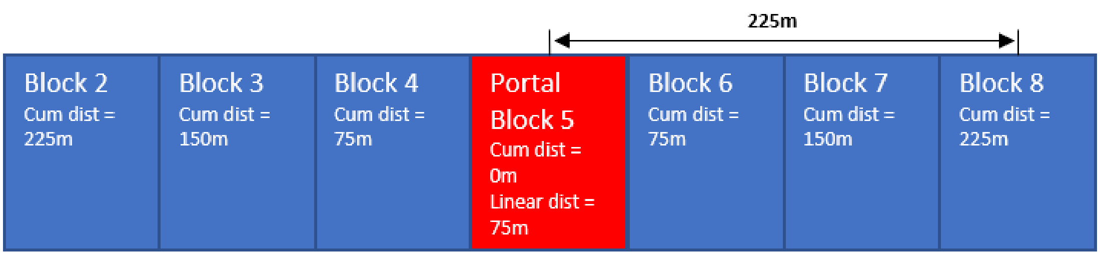
```
'
'Main subroutine
'Script creation:L02 Cumulative dev metres PORTALS RANGE(ALL)
' Author:  <David Walker>
' Position: <PhD Candidate UOW>
' Company: <University of Wollongong>
'
'Script description:
' Execution:
'  Type:  Database
'  Database: MAIN
'  Trigger: NA
'  Run type: Range
'  Range:  All
'
' Purpose: Finds the Scheduling Block that contains the portal and then cumulate distance in that Mains Panel away from the portal
' Block by block
'Script modification log:
' Date     Author/Company      Description of modifications
'~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
'        David Walker      First Write
'~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
'
'Main subroutine
Dim PortalRecNum As Long

Sub Main()

Dim j As Integer
Dim lNumberofblocksinportalmains As Long
Dim lPortalRecNum as Long
Dim sCurrentPanelName as String
'Dim lCurr_rec As Long
 'Dim lPrev_rec As Long
 Dim lPrev_dist As Long
 Dim lPanel_dist As Long
 Dim lReverseNumberofBlocks as Long
 Dim lForwardNumberofBlocks as Long


 'we only want to do this following once when we hit the portal block (otherwise inefficient code)
 If isinrange("LogisticsPortal") Then ' find the portal block
  Call gorec(UP)
  lNumberofblocksinportalmains = GetNumChildren(GetRecNum(CURRENT))
  call goRec(HOME)

  M(mCycle_Dist_CumDist) = 0
  lPortalRecNum = getrecnum(CURRENT) ' this is the portal block record number
  'we now need to assign cum dist's around the portal for all the blocks in the Portal Mains
  lReverseNumberofBlocks = lBlockNum - 1 'if portals are
  lForwardNumberofBlocks = lNumberofblocksinportalmains - lBlockNum

  j = 1
  For j = 1 To lReverseNumberofBlocks ' find the portal block
  'work backwards to start of block
   lPrev_dist = M(mCycle_Dist_CumDist)
   lPanel_dist = M(mPHYS_LinMet)
   call GoREC(PRVSIB)
   M(mCycle_Dist_CumDist) = lPrev_dist + lPanel_dist

  Next j
 Call goREC(lPortalRecNum)
  j = 1
  For j = 1 To lForwardNumberofBlocks ' find the portal block
  'work backwards to start of block
   lPrev_dist = M(mCycle_Dist_CumDist)
   lPanel_dist = M(mPHYS_LinMet)
   call GoREC(NXTSIB)
   M(mCycle_Dist_CumDist) = lPrev_dist + lPanel_dist

  Next j

 End If
 End Sub
```

Table 3-15: The Main Database outlining input (Green) and Output (Yellow) from L01 Cleardata Range (ALL).bas and L02 Cumulative dev metres PORTALS RANGE(ALL).

Code	Data Field Name	Units	Central\NE\DV\MG101\17	Central\NE\DV\MHNE\8	Central\NE\LW\LW101\19
			Gate road Block	Mains Block	LW Block
	IC LoA Model				
mIMP	Imported Data Fields				
mIMP_NUMOFROADS	*Number of Roadways*		2	7	1
mIMP_ROADWIDTH	*RoadWay Width*		5.2	5.2	0
mIMP_CLINEOFFSET	*RoadWay C/Line Offset*		50	40	0
mIMP_CTHRUOFFSET	*Cut-Through Offset*		120	75	0
mIMP_BLOCKLENGTH	*Block Length (Max)*		151.87	75	100
mIMP_BLOCKWIDTH	*Block Width (Max)*		55.2	245.2	320
mIMP_AREAACT1	*Area*		1517	3815.76	0
mIMP_VOLACT1	*Volume*		0	0	0
mIMP_CENTXACT1	*Centroid X*		2734.76	321.76	2704.83
mIMP_CENTYACT1	*Centroid Y*		575.27	321.76	387.67
mIMP_MINDIRACT1	*Mining Direction*		90	45	90
mIMP_AREAACT2	*Area*		5107	14574.24	32000
mIMP_VOLACT2	*Volume*		0	0	0
mIMP_CENTXACT2	*Centroid X*		2721.65	312.89	2704.83
mIMP_CENTYACT2	*Centroid Y*		575.27	312.89	387.67
mIMP_MINDIRACT2	*Mining Direction*		270	225	270
mIMP_Seamthknss	*Insitu Thickness*		0	0	0
mPHYS	Physicals				
mPHYS_Metres	Metres				
mPHYS_LinMet	Linear Metres	m	152	75	100
mPHYS_TotMet	Total Metres	m	292	734	100
mSched	Scheduling				
mSched_BaseRate	Base Rate				
mSched_BaseRate_Dev	Development Productivity	m/week	150	100	
mSched_BaseRate_LW	LW Productivity	m/week			60
mSched_Rate	Rate				
mSched_Rate_Dev	Development Productivity	m/week	60	100	
mSched_Rate_LW	LW Productivity	m/week			60
mSched_Dates	Dates				
mSched_Dates_Start	Start Date		19/08/2023	11/12/2021	25/03/2025
mSched_Dates_End	End Date		22/09/2023	18/01/2022	6/04/2025
mSched_Dates_Resource	Resource Name		CM2	CM1	LW1
mSupport	Primary Support Zones				
mSupport_DV	Development Zones				
mSupport_DV_Green	Green primary support metres	m	0	733.8	0
mSupport_DV_Yellow	Yellow primary support metres	m	0	0	0
mSupport_DV_Orange	Orange Support primary support metres	m	0	0	0
mSupport_DV_Red	Red Support primary support metres	m	291.7307692	0	0
mSupport_DV_DoubleRed	Double Red primary support metres	m	0	0	0
mDelay	Delays				
mDelay_InPath	Inpath				
mDelay_InPath_Flit	CM Flits		0	0	0
mDelay_InPath_LWMove	LW Move		0	0	0
mCycle	Cycle Times				
mCycle_Dist	Distance Travelled				
mCycle_Dist_CumDist	Cumulative Distance	m	3371	450	3371
mCycle_Logst	Logistics				
mCycle_Logst_Duration	Duration within Block		34.04	38.69	11.67
mCycle_Logst_Total	Total Deliveries Per Block Required	deliveries	416.88	269.30	65.40
mCycle_Logst_LoadsPer	Total Deliveries per Day Required	deliveries	12.25	6.96	5.61
mCycle_Logst_optime	Material delivery cycle time Machine Driving	hours	0.67	0.09	0.67
mCycle_Logst_utiltime	Material delivery cycle time Machine Driving + Set Down	hours	1.17	0.59	1.17
mCycle_Logst_onroad	Supplies on road at any given time	Loaders	0.60	0.17	0.27

The purpose of L02 Cumulative dev metres PORTALS RANGE(ALL).bas, abbreviated to L02, is to run through the entire main database and find a scheduling block that exists inside the range "Logistics Portal" (LINE18). It then looks a level upwards (LINE19) to the parent record (much a like a folder) and finds how many child records (which includes the portal scheduling block) are below it (LINE20). It then returns to the Portal Scheduling Block (LINE21). The number of blocks in the mains before and after the portal scheduling block is calculated (LINE26 and LINE27 respectively) and these numbers are used as counters in the "FOR/NEXT" loops.

The first loop starts at the portal scheduling block and works its way backward one scheduling block at a time to block number 1. Cumulative distance for the current block is from the start of the current block, otherwise you are overestimating travel distance if you include the current blocks lineal metres. LINE32 and LINE33 calculate and store these numbers prior to going to the previous sibling block (LINE34). LINE35 then enters the cumulative distance into the current scheduling block. This is explained in Figure 3-33:



Each Block has a linear length of 75m

Block 5 (Portal) Cum Distance = 0 (Subroutine forced)
Block 6 Cum Distance = Block 5 (Portal) Cum Distance + Linear Distance Block 5 = 75 + 0 = 75m
Block 7 Cum Distance = Block 6 (Portal) Cum Distance + Linear Distance Block 6 = 75 + 75 = 150m
Block 8 Cum Distance = Block 7 (Portal) Cum Distance + Linear Distance Block 7 = 150 + 75 = 225m

Block 4 Cum Distance = Block 5 (Portal) Cum Distance + Linear Distance Block 5 = 75 + 0 = 75m
Block 3 Cum Distance = Block 4 (Portal) Cum Distance + Linear Distance Block 4 = 75 + 75 = 150m
Block 2 Cum Distance = Block 3 (Portal) Cum Distance + Linear Distance Block 3 = 150 + 75 = 225m

Figure 3-33: The calculation of cumulative distance

The second loop (LINES 38-47) is near identical to the first loop except for LINE44 which tells the algorithm to move forward to the end of the panel rather than backward. Once this subroutine is run, all cumulative distances are calculated along any set of headings that have a portal in them.

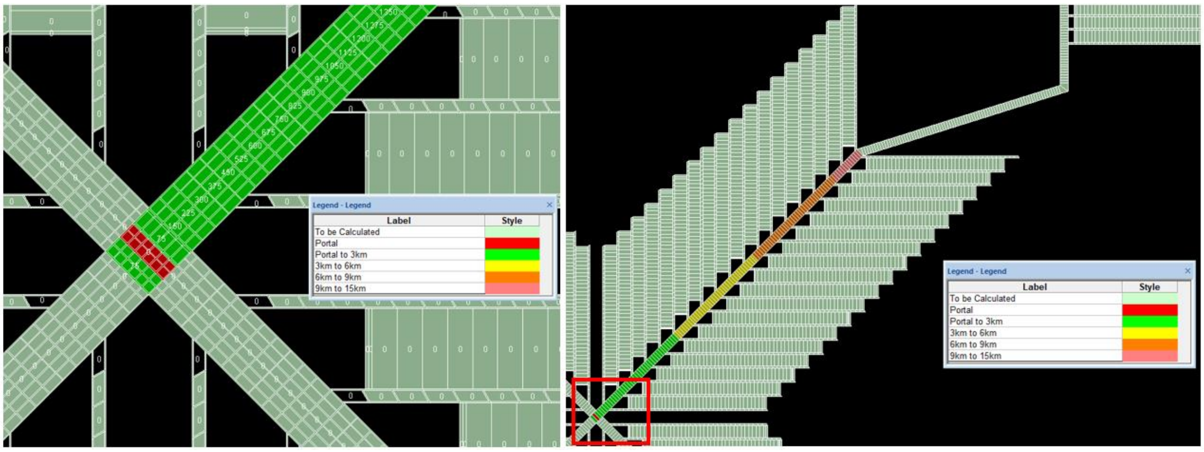


Figure 3-34: After executing L02.

As can be seen in the Figure 3-34, after L02, each scheduling block in the main headings, which contain the portal, now have an assigned cumulative distance from the portal.

3.4.3.3 L03 Breakaway Transfer Metres RANGE(LogisticsMains)

L03 Breakaway Transfer Metres, abbreviated to L03, calculates the cumulative distance of any scheduling block that exists in the mains headings and does not have a portal in it. The subroutine is limited to run over mains drivage only using the "LogisticsMains" range. This allows the continuation of cumulative distance from the mains with portals to any other Mains in the mine plan. Sometimes mains headings may not start at block 1 next to Mains with a portal, therefore every scheduling block is checked within the mains to find the minima, because this will be where transport will transfer from the portal mains to the other adjacent mains and start the next cumulative distance calculation from there.

```
'Script creation:L03 Breakaway Transfer Metres RANGE(LogisticsMains)
' Author:  <David Walker>
' Position: <PhD Candidate UOW>
' Company: <University of Wollongong>
'
'Script description:
' Execution:
'  Type:  Database
'  Database: MAIN
'  Trigger: NA
'  Run type: Range
'  Range:  LogisticsMains
'
' Purpose: Finds breakaway blocks that that are closest to Portal Mains drivage then adds the cumulative distance
'If the closest Portal Mains block to the breakaway block and work block by block
'Script modification log:
' Date     Author/Company      Description of modifications
'~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
'       David Walker      First Write
'~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
'
'Main subroutine

Dim sParentPanel As String
Dim sGateroadNumber As String
Dim sPortalPanel As String
dim sBasePanelName as string
Const sMinePortal = "Central"
Const sAreaPortal = "NE"
Const sProcessPortal = "DV"
Const sPanelPortal = "MHNE"
Dim PortalRecNum As Long
Dim dMinimumDistance As Double
Dim dBreakawayCentroidx As Double
Dim dBreakawayCentroidy As Double
Dim lMinDistRecNum As Long
Dim lMainsCumMetres As Long
'Main subroutine
Sub Main()
dMinimumDistance = 20000 ' ensures you always start with a high minimum distance
PortalRecNum = GetRecFromName(sMinePortal, sAreaPortal, sProcessPortal, sPanelPortal,1 )
If Left(sPanelName,2) = "MH" And lBlockNum = 1 And getRecNum(Current) <> PortalRecNum Then
'Print getRecNum(Current)
'get centroid
dBreakawayCentroidx=M(mIMP_CENTXACT1) 'centroid of the "CHILD MAINS"
dBreakawayCentroidy=M(mIMP_CENTYACT1) 'centroid of the "CHILD MAINS"
' print "Main subroutine First" & dBreakawayCentroidx
sBasePanelName = sAreaName & sPanelName

MainsHeadingsCumdist
If lMinDistRecNum = PortalRecNum then 'The PortalRecNum cum metres is zero so all other MH blocks will be zero that it is closest to
 Call gorec(lMinDistRecNum)
 lMainsCumMetres = M(mIMP_BLOCKLENGTH) / 2 'assume the machine has to travel 0.5 x blk length to get to the next Mains
 Call gorec(home)
 If M(mCycle_Dist_CumDist) = 0 then
  M(mCycle_Dist_CumDist) = lMainsCumMetres
 End If
else 'once we have the min blk dist we Get that cum metres And add it To blk cum metres In the GR.
 Call gorec(lMinDistRecNum)
 lMainsCumMetres = M(mCycle_Dist_CumDist)
 Call gorec(home)
 If M(mCycle_Dist_CumDist) = 0 then
  M(mCycle_Dist_CumDist) = lMainsCumMetres
 End If

End If
end if

' print "Main subroutine Last" & dBreakawayCentroidx
End Sub
'
'
'
'~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
'
Sub MainsHeadingsCumdist()
Dim lNumBlocksInPanel As Long
Dim i As Integer
Dim p As String
Dim sCurrentPanel As String
'find the domains "Mains Headings"
Dim dBreakawayCentroidx As Double
Dim dBreakawayCentroidy As Double
Dim dDisttoCentroid As Double
Dim dMinimumDistance As Double
Dim lRecNum As Long
Dim lPanelRec As Long
Dim lMineChildren As Long
Dim lCurrentArea As Long

' print "1st Sub routine" & dBreakawayCentroidx
' Need to find every Mains heading across the entire deposit and then find the closest centroid.
Call GoRec(GetRecFromName(sMinePortal))

lMineChildren = GetNumChildren(GetRecNum(CURRENT))

i = 1
For i = 1 To lMineChildren ' we need to loop inside a loop to find all MH
If i = 1 Then
 Call gorec(downfirst) 'For i = 1
Else
 Call gorec(lCurrentArea)
 Call gorec(NXTSIB)
End If

lCurrentArea = GetRecNum(CURRENT)
'this is where we will go down to find the MH and each block distance

lRecNum = GetRecFromName(sMinePortal, sAreaName, "DV")
Call gorec(lRecNum)
```

Table 3-16: The Main Database outlining input (Green) and Output (Yellow) from L03 Breakaway Transfer Metres. RANGE(LogisticsMains) subroutine.

Code	Data Field Name	Units	Central\NE\DV\ MG101\17	Central\NE\DV\ MHNE\8	Central\NE\LW\ LW101\19
			Gate road Block	Mains Block	LW Block
	IC LoA Model				
mIMP	Imported Data Fields				
mIMP_NUMOFROADS	Number of Roadways		2	7	1
mIMP_ROADWIDTH	RoadWay Width		5.2	5.2	0
mIMP_CLINEOFFSET	RoadWay C/Line Offset		50	40	0
mIMP_CTHRUOFFSET	Cut-Through Offset		120	75	0
mIMP_BLOCKLENGTH	Block Length (Max)		151.87	75	100
mIMP_BLOCKWIDTH	Block Width (Max)		55.2	245.2	320
mIMP_AREAACT1	Area		1517	3815.76	0
mIMP_VOLACT1	Volume		0	0	0
mIMP_CENTXACT1	Centroid X		2,735	322	2,705
mIMP_CENTYACT1	Centroid Y		575	322	388
mIMP_MINDIRACT1	Mining Direction		90	45	90
mIMP_AREAACT2	Area		5107	14574.24	32000
mIMP_VOLACT2	Volume		0	0	0
mIMP_CENTXACT2	Centroid X		2721.65	312.89	2704.83
mIMP_CENTYACT2	Centroid Y		575.27	312.89	387.67
mIMP_MINDIRACT2	Mining Direction		270	225	270
mIMP_Seamthknss	Insitu Thickness		0	0	0
mPHYS	Physicals				
mPHYS_Metres	Metres				
mPHYS_LinMet	Linear Metres	m	152	75	100
mPHYS_TotMet	Total Metres	m	292	734	100
mSched	Scheduling				
mSched_BaseRate	BaseRate				
mSched_BaseRate_Dev	Development Productivity	m/week	150	100	
mSched_BaseRate_LW	LW Productivity	m/week			60
mSched_Rate	Rate				
mSched_Rate_Dev	Development Productivity	m/week	60	100	
mSched_Rate_LW	LW Productivity	m/week			60
mSched_Dates	Dates				
mSched_Dates_Start	Start Date		19/08/2023	11/12/2021	25/03/2025
mSched_Dates_End	End Date		22/09/2023	18/01/2022	6/04/2025
mSched_Dates_Resource	Resource Name		CM2	CM1	LW1
mSupport	Primary Support Zones				
mSupport_DV	Development Zones				
mSupport_DV_Green	Green primary support metres	m	0	733.8	0
mSupport_DV_Yellow	Yellow primary support metres	m	0	0	0
mSupport_DV_Orange	Orange Support primary support metres	m	0	0	0
mSupport_DV_Red	Red Support primary support metres	m	291.7307692	0	0
mSupport_DV_DoubleRed	Double Red primary support metres	m	0	0	0
mDelay	Delays				
mDelay_InPath	Inpath				
mDelay_InPath_Flit	CM Flits		0	0	0
mDelay_InPath_LWMove	LW Move		0	0	0
mCycle	Cycle Times				
mCycle_Dist	Distance Travelled				
mCycle_Dist_CumDist	Cumulative Distance	m	3371	450	3371
mCycle_Logst	Logistics				
mCycle_Logst_Duration	Duration within Block		34.04	38.69	11.67
mCycle_Logst_Total	Total Deliveries Per Block Required	deliveries	416.88	269.30	65.40
mCycle_Logst_LoadsPer	Total Deliveries per Day Required	deliveries	12.25	6.96	5.61
mCycle_Logst_optime	Material delivery cycle time Machine Driving	hours	0.67	0.09	0.67
mCycle_Logst_utiltime	Material delivery cycle time Machine Driving + Set Down	hours	1.17	0.59	1.17
mCycle_Logst_onroad	Supplies on road at any given time	Loaders	0.60	0.17	0.27

```

find_mains_headings

Next i
End Sub
'-------------------------------------------------------------------------------------------------------------------------------------
Sub find_mains_headings
Dim j As Integer
Dim lNumberofPanelsinProcess As Long
Dim sCurrentPanelName as String
' print "2nd Sub routine" & dBreakawayCentroidx
lNumberofPanelsinProcess = GetNumChildren(GetRecNum(CURRENT))
Call gorec(downfirst)

j = 1
For j = 1 To lNumberofPanelsinProcess ' You could have multiple sub mains that you need to find the minimum distance from portal for.
sCurrentPanelName = sAreaName & sPanelName

'print sCurrentPanelName

 If Left(sPanelName,2) = "MH" and sCurrentPanelName <> sBasePanelName Then ' filters out the GoRec(HOME) block from the min dist otherwise always 0 dist.
' Print "sPanelNum"& sPanelName & " " & GetRecNum(CURRENT)
  find_smallest_dist_to_mains 'go block by block to get the minimum distance


print "lMinDistRecNum" & lMinDistRecNum
print "dMinimumDistance" & dMinimumDistance

 End If
 Call GoREC(NXT)

 If j = 74 Then
  j = j
 End If

Next j

End Sub
'-------------------------------------------------------------------------------------------------------------------------------------
Sub find_smallest_dist_to_mains
Dim lNumBlocksInPanel As Long
Dim dDisttoCentroid As Double
Dim k As Integer
Dim lMainsCumMetres As Long
Dim lNumberofPanelsinProcess As Long
' print "3rd Sub routine" & dBreakawayCentroidx

lNumBlocksInPanel = GetNumChildren(GetRecNum(CURRENT))

k = 1
For k = 1 To lNumBlocksInPanel
 If k = 1 Then ' first record in Mains headings
  Call GoRec(DOWNFIRST)
  dDisttoCentroid = ((M(mIMP_CENTXACT1) - dBreakawayCentroidx)^2 + (M(mIMP_CENTYACT1)- dBreakawayCentroidy)^2)^0.5 'pythagoras between centroids
  If dDisttoCentroid < dMinimumDistance Then
   dMinimumDistance = dDisttoCentroid ' update minimum distance
   lMinDistRecNum = getrecnum(current)
  End If

 elseif k > 1 Then ' check lDisttoCentroid is less than previous
  Call GoRec(NXTSIB) ' sibling block

  dDisttoCentroid = ((M(mIMP_CENTXACT1) -dBreakawayCentroidx)^2 + (M(mIMP_CENTYACT1)- dBreakawayCentroidy)^2)^0.5 'pythagoras between centroids
  If dDisttoCentroid < dMinimumDistance Then
   dMinimumDistance = dDisttoCentroid ' update minimum distance
   lMinDistRecNum = getrecnum(current)
  End If

 End If
Next k


End Sub
```

It is first important to refresh the knowledge of Parent and Child hierarchy of an XPAC main database. Every record in a main database has a unique identification number all the way down to the scheduling block level that allows programs to navigate subroutines into and out of records. This hierarchy is shown in Figure 3-35: -

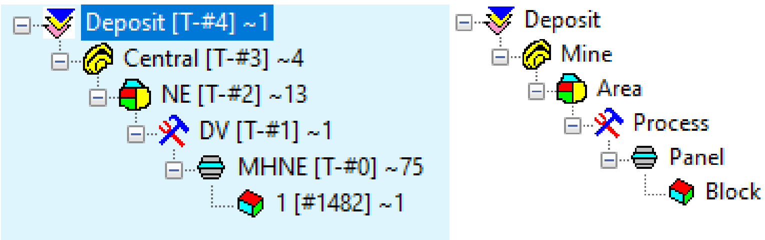


Figure 3-35: (LEFT) An example of the actual hierarchy for a specific scheduling block and (RIGHT): The generic hierarchy of the Main Database.

In Figure 3-35 (LEFT) scheduling block Central/NE/DV/MHNE/1 is filtered, where "Central" corresponds with the mine name, "NE" is the AREA/Domain, Process is either DV (for development) or LW for longwall and is in this case "DV", Panel is the "MHNE" and then "1" corresponds with the scheduling block number. In this case MHNE is the parent to child record Block 1, DV is the parent record to child record MHNE and so on and is the roadmap around and through the main database which in this thesis is very large at 13,529 records. L03 Breakaway Transfer Metres.bas utilises this roadmap to search for the closest block using multiple loops from other blocks.

Initially a starting minimum distance is set at 20,000 m (LINE17), this is because if the minimum variable was not set high it would remain zero and when searching for the minima it would never be less than zero and therefore the closest adjacent portal mains block would not be located. The first block of all mains blocks that do not have a portal are located firstly (LINE19). These are the only blocks that are considered in this subroutine. Centroid blocks for these blocks are then collected (LINES 22 and 23). LINE25 collects the AREA name (Grand Parent record of the scheduling block) and the Panel Name (Parent Record of a scheduling block) to locate the scheduling block in the future as the program must step away from this block to find the closest mains headings which has a scheduling block that is a portal no matter what part of the Mine/AREA it exists in.

An embedded subroutine "MainsHeadingsCumdist" is called (LINE27). The program then moves down to LINE71 where the program leaves the original block (first block of a mains headings panel that does not possess a portal) and goes to the very highest level of the database, identified through the string variable sMinePortal. LINE73 counts all AREAS / DOMAINS that exist under this which are used in a FOR/NEXT loop between LINES 75-82. The FOR/NEXT Loop steps into each AREA/DOMAIN LINE78 or LINE81 and then identifies the AREA in the database it has stepped down into (LINE84). LINE87 identifies the Child record in the AREA/Domain that is "DV", and the subroutine is then instructed to go to that record (LINE88). An embedded subroutine is then called known as "find_mains_headings".

The "find_mains_headings" subroutine searches for mains headings that exist in the Parent Record "DV". It starts at LINE100 which calculates how many children exist in the DV Parent record. This will be used as the limiting counter for the FOR/NEXT loop starting at LINE104. The subroutine goes down to the first child PANEL record (LINE101). The original scheduling block record (which is a mains headings record) must be discounted from the minimum distance algorithm otherwise the program will find itself and the minimum distance will be zero using the IF statement in LINE109 and if it a different set of mains headings then the subroutine calls a further embedded subroutine “find_smallest_distance_to_mains” (LINE111). LINE136 collects the number of children in the mains headings which are the scheduling blocks. Again, this is the limiting counter for the FOR/NEXT loop starting at LINE139. The loop cycles through every scheduling block in the mains headings to calculate the distance between the original block (where this entire program started) and the child record of the Mains determined by subroutine “find_mains_headings” (LINE142 for the first scheduling block, and LINE151 for all subsequent scheduling blocks) and if the distance is less than the previous distance remembering that the original dMinimumDistance variable was set to 20,000 m then dMinimumDistance is reset to the current distance (LINES 144, and 153). The record number of that block is stored for future reference (LINE145 and 154). The program now possesses a minimum distance from that set of Mains, this is not to say that this distance is the minimum as other Mains must be identified and this subroutine is repeated for every set of Mains in the AREA/DOMAIN by going back to the subroutine “find_headings_mains” (LINE95).

Once every Mains scheduling block within the AREA/DOMAIN is considered and tested to be the minimum distance from the original block, “find_mains_headings” subroutine ends and returns to within the FOR/NEXT loop of “MainsHeadingsCumDist” to find the next AREA/DOMAIN. This process is repeated finding mains headings and finding the Minimum distance from the original scheduling block until finally every other mains headings block distance is found and the singular minimum distance and the closest block is determined.

The flowchart of this subroutine is graphically displayed in Figure 3-36.

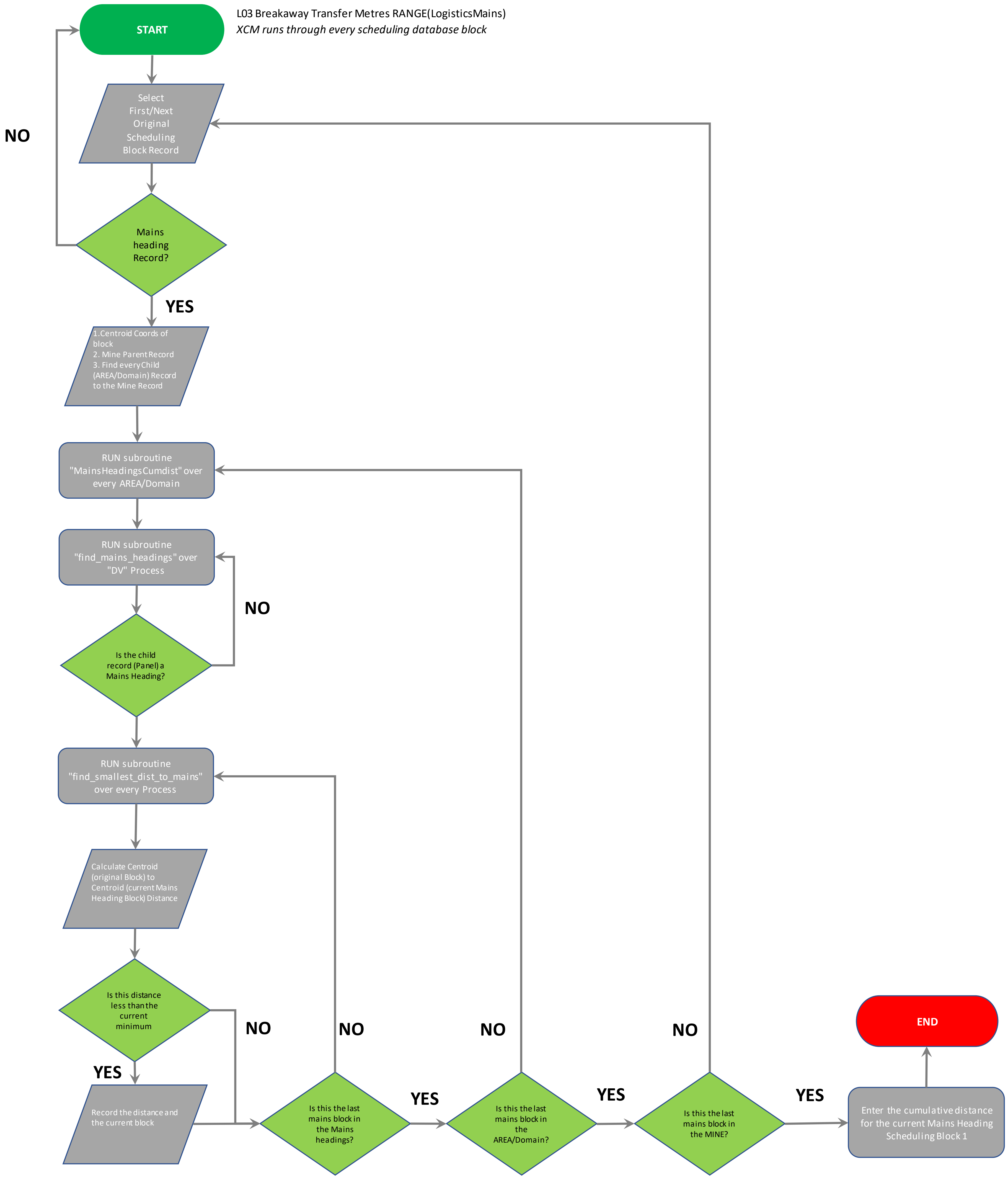


Figure 3-36: Flowchart of L03 Breakaway Transfer Metres RANGE(LogisticsMains)

3.4.3.4 L04 Cumulative dev metres RANGE(LogisticsMains)

The ‘L03 Breakaway Transfer Metres RANGE(LogisticsMains)’ subroutine only calculates the cumulative metres for the first block in a mains heading that does not contain a portal. For the remaining mains scheduling blocks subroutine ‘L04 Cumulative dev metres RANGE(LogisticsMains)’, abbreviated to L04, continues to cumulate the distance away from the portals working similarly to the algorithms in ‘L02 Cumulative dev metres PORTALS RANGE(ALL)’. It must be run only over the range “LogisticsMains” and only outputs to mCycle_Dist_CumDist as highlighted previously in yellow in Table 3-16.

```
'Script creation:L04 Cumulative dev metres RANGE(LogisticsMains)
 ' Author:  <David Walker>
 ' Position: <PhD Candidate UOW>
 ' Company: <University of Wollongong>
 '
 'Script description:
 ' Execution:
 '  Type:  Database
 '  Database: MAIN
 '  Trigger: NA
 '  Run type: Range
 '  Range:  LogisticsMains
 '
 ' Purpose: Finds the Scheduling Block that contains the portal and then cumulate distance in that Mains
Panel away from the portal
 ' Block by block
 'Script modification log:
 ' Date    Author/Company     Description of modifications

'~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
~~~~~~~~~~~~~~~~~~~~~~~~~~~~
 '      David Walker      First Write

'~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
~~~~~~~~~~~~~~~~~~~~~~~~~~~~
 '
 'Main subroutine
 Sub Main()
 'This is to cumulate linear advance metres per panel
 'Can do this via centroid but is then not governed by path
 'Getrecnum previous block
1  Dim lCurr_rec As Long
2  Dim lPrev_rec As Long
3  lCurr_rec = getrecnum(CURRENT)
4  lPrev_rec = getrecnum(PRVSIB)
5  Dim lPrev_dist As Long
6  Dim lPanel_dist As Long
7  If lPrev_rec > 0 Then 'block 2 and above
8   Call gorec(lPrev_rec)
9   lPrev_dist = M(mCycle_Dist_CumDist)
10  lPanel_dist = M(mPHYS_LinMet)
11  Call gorec(HOME)
12  If sProcessName = "DV" then 'development increases travel
13   If M(mCycle_Dist_CumDist)=0 and Not(isinrange("LogisticsPortal")) then
14    M(mCycle_Dist_CumDist) = lPrev_dist + lPanel_dist
15   End If
16   End If
17  End If
18  End If
19  'GoRec
20
21  End Sub
```

Prior to this subroutine being run, only scheduling block 1, which is the starting block of the new mains drivage has some cumulative metres. Therefore Block 2 and higher are the blocks that must be propagated. LINE4 will return either the previous scheduling block record number or if there is no previous block, will return the record number as -1. In LINE7 the IF statement ensures that a previous record exists and therefore Block 1 cannot be overwritten incorrectly. The subroutine then goes to the previous sibling where it collects the cumulative distance (LINE9) and incremental linear metres (LINE10) for that block remembering block 1's cumulative distance was from L03. LINE11 returns the subroutine to the original block. LINEs 12 and 13 qualify that the block is in DV (Development) process and is not mains headings that has a portal in it as these were already calculated in L02. LINE14 calculates the cumulative distance for the current block.

After executing L03 and L04 subroutines the Main database cumulative distance is now complete for all Mains. Figure 3-37 demonstrates the ongoing building of cumulative distance from the portals along the mains.

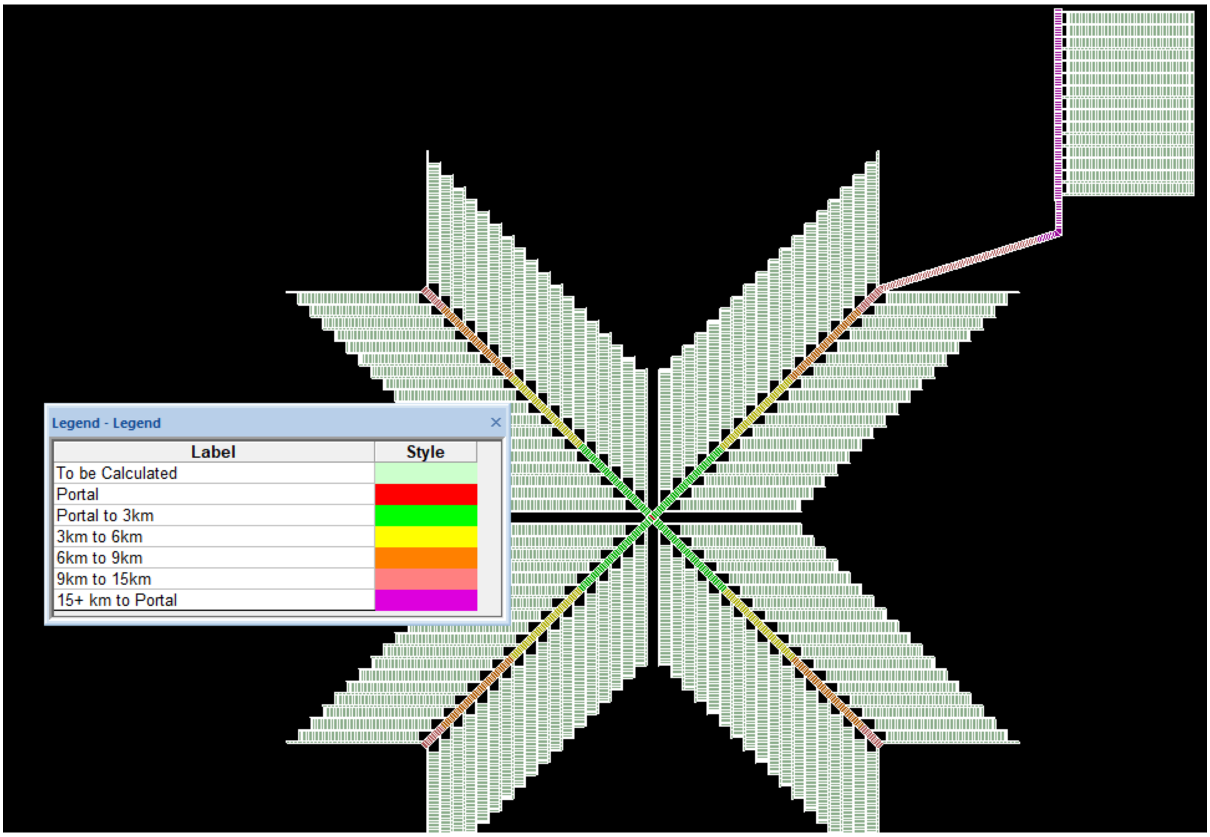


Figure 3-37: The impact of L03 and L04 on cumulative linear distance from a central portal for all mains headings.

3.4.3.5 L06 Breakaway Transfer Metres RANGE(LogisticsGates)

'L06 Breakaway Transfer Metres RANGE(LogisticsGates)' (abbreviated to L06) is the next subroutine to be executed. For speed it is run over only on maingate and tailgate panels. It takes the closest mains scheduling block cumulative distance calculated from L03 and L04 and adds that to block 1 of every maingate and tailgate. It should be noted that L06 and L08 are the same, but you cannot run the same program twice in XCM batch mode and therefore a duplicate L08 was created. In L08, the defined range changes from gateroads, to longwall and installation roads, and the first LW or installation road scheduling block looks for the closest gateroad scheduling block that would service it.

```
'Script creation:L06 Breakaway Transfer Metres RANGE(LogisticsGates)
' Author:  <David Walker>
' Position: <PhD Candidate UOW>
' Company: <University of Wollongong>
'
'Script description:
' Execution:
'  Type:  Database
'  Database: MAIN
'  Trigger: NA
'  Run type: Range
'  Range:  LogisticsMains
'
' Purpose: Writes the cumulative distance from calculated from L04 and then adds that to the first scheduling block for LW, or DV panels
' Date    Author/Company     Description of modifications
'~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
'      David Walker      First Write
'~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~

'Main subroutine
    Dim sParentPanel As String
    Dim sGateroadNumber As String
    Sub Main()
    If Left(sPanelName,2) = "MG" And lBlockNum = 1 Then

     sParentPanel = "MH"


    ElseIf (Left(sPanelName,2) = "IR" Or Left(sPanelName,2) = "LW") And lBlockNum = 1 Then

     sGateroadNumber = Right(sPanelName,3)
     sParentPanel = "MG" & sGateroadNumber


    End If
    GateroadCumdist

    End Sub
    '
    '~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
    Sub GateroadCumdist()
    Dim lNumBlocksInPanel As Long
    Dim i As Integer
    Dim p As String
    Dim sCurrentPanel As String
    'find the domains "Mains Headings"
    Dim dBreakawayCentroidx As Double
    Dim dBreakawayCentroidy As Double
    Dim dDisttoCentroid As Double
    Dim dMinimumDistance As Double

    Dim lPanelRec As Long
    Dim lMinDistRecNum As Long
    Dim lMainsCumMetres As Long

    'get centroid
    dBreakawayCentroidx=M(mIMP_CENTXACT1)
    dBreakawayCentroidy=M(mIMP_CENTYACT1)

    If sProcessName <> "LW" Then 'within the dev process so we only have to find the right MG/MH block
     Call GoRec(UP)
     Call GoRec(UP)
     Call GoRec(DOWNFIRST)
     If Left(sPanelName,2) = "MH" Then
      sCurrentPanel = Left(sPanelName,2)
     Else
      sCurrentPanel = sPanelName
     End If

    Else ' It is a longwall panel, and we have to find the right Maingate which is in development
     lPanelRec = getrecfromname(sMineName, sAreaName, "DV")
     Call GoRec(lPanelRec)
     Call GoRec(DOWNFIRST)
     sCurrentPanel = sPanelName
    End If

     Do Until sCurrentPanel = sParentPanel
      Call GoREC(NXT)
      If Left(sPanelName,2) = "MH" Then
       sCurrentPanel = Left(sPanelName,2)
      Else
       sCurrentPanel = sPanelName 'IR and MG have the same number suffix
      End If
     Loop
    ' we have now found the "Main Headings parent record" we need to find the closest block to the current record

    lNumBlocksInPanel = GetNumChildren(GetRecNum(CURRENT))
    i = 1
    For i = 1 To lNumBlocksInPanel
     If i = 1 Then ' first record in Main headings
      Call GoRec(DOWNFIRST)
      dDisttoCentroid = ((M(mIMP_CENTXACT1) - dBreakawayCentroidx)^2 + (M(mIMP_CENTYACT1)- dBreakawayCentroidy)^2)^0.5 'pythagoras between centroids
      dMinimumDistance = dDisttoCentroid
      lMinDistRecNum = getrecnum(current) ' block 1 could be the closest block
     elseif i > 1 Then ' check lDisttoCentroid is less than previous
      Call GoRec(NXTSIB) ' sibling block

      dDisttoCentroid = ((M(mIMP_CENTXACT1) -dBreakawayCentroidx)^2 + (M(mIMP_CENTYACT1)- dBreakawayCentroidy)^2)^0.5 'pythagoras between centroids
      If dDisttoCentroid < dMinimumDistance Then
       dMinimumDistance = dDisttoCentroid ' update minimum distance
       lMinDistRecNum = getrecnum(current)
      End If

      If i = 135 Then
       p = p
      End If
     End If
    Next i

    Call gorec(lMinDistRecNum) 'once we have the minimum block distance, we Get cumulative metres and add it to block cum metres in the gateroad
     lMainsCumMetres = M(mCycle_Dist_CumDist)
```

Table 3-17: The Main Database outlining input (Green) and Output (Yellow) from L06 Breakaway Transfer Metres. RANGE(LogisticsMains) subroutine

Code	Data Field Name	Units	Central\NE\DV\MG101\17	Central\NE\DV\MHNE\8	Central\NE\LW\LW101\19
			Gate road Block	Mains Block	LW Block
	IC LoA Model				
mIMP	**Imported Data Fields**				
mIMP_NUMOFROADS	*Number of Roadways*		*2*	*7*	*1*
mIMP_ROADWIDTH	*RoadWay Width*		*5.2*	*5.2*	*0*
mIMP_CLINEOFFSET	*RoadWay C/Line Offset*		*50*	*40*	*0*
mIMP_CTHRUOFFSET	*Cut-Through Offset*		*120*	*75*	*0*
mIMP_BLOCKLENGTH	*Block Length (Max)*		*151.87*	*75*	*100*
mIMP_BLOCKWIDTH	*Block Width (Max)*		*55.2*	*245.2*	*320*
mIMP_AREAACT1	*Area*		*1517*	*3815.76*	*0*
mIMP_VOLACT1	*Volume*		*0*	*0*	*0*
mIMP_CENTXACT1	*Centroid X*		*2,735*	*322*	*2,705*
mIMP_CENTYACT1	*Centroid Y*		*575*	*322*	*388*
mIMP_MINDIRACT1	*Mining Direction*		*90*	*45*	*90*
mIMP_AREAACT2	*Area*		*5107*	*14574.24*	*32000*
mIMP_VOLACT2	*Volume*		*0*	*0*	*0*
mIMP_CENTXACT2	*Centroid X*		*2721.65*	*312.89*	*2704.83*
mIMP_CENTYACT2	*Centroid Y*		*575.27*	*312.89*	*387.67*
mIMP_MINDIRACT2	*Mining Direction*		*270*	*225*	*270*
mIMP_Seamthknss	*Insitu Thickness*		*0*	*0*	*0*
mPHYS	**Physicals**				
mPHYS_Metres	**Metres**				
mPHYS_LinMet	Linear Metres	m	152	75	100
mPHYS_TotMet	Total Metres	m	292	734	100
mSched	**Scheduling**				
mSched_BaseRate	**BaseRate**				
mSched_BaseRate_Dev	Development Productivity	m/week	150	100	
mSched_BaseRate_LW	LW Productivity	m/week			60
mSched_Rate	**Rate**				
mSched_Rate_Dev	Development Productivity	m/week	60	100	
mSched_Rate_LW	LW Productivity	m/week			60
mSched_Dates	**Dates**				
mSched_Dates_Start	Start Date		19/08/2023	11/12/2021	25/03/2025
mSched_Dates_End	End Date		22/09/2023	18/01/2022	6/04/2025
mSched_Dates_Resource	Resource Name		CM2	CM1	LW1
mSupport	**Primary Support Zones**				
mSupport_DV	**Development Zones**				
mSupport_DV_Green	Green primary support metres	m	0	733.8	0
mSupport_DV_Yellow	Yellow primary support metres	m	0	0	0
mSupport_DV_Orange	Orange Support primary support metres	m	0	0	0
mSupport_DV_Red	Red Support primary support metres	m	291.7307692	0	0
mSupport_DV_DoubleRed	Double Red primary support metres	m	0	0	0
mDelay	**Delays**				
mDelay_InPath	**Inpath**				
mDelay_InPath_Flit	CM Flits		0	0	0
mDelay_InPath_LWMove	LW Move		0	0	0
mCycle	**Cycle Times**				
mCycle_Dist	**Distance Travelled**				
mCycle_Dist_CumDist	Cumulative Distance	m	3371	450	3371
mCycle_Logst	**Logistics**				
mCycle_Logst_Duration	Duration within Block		34.04	38.69	11.67
mCycle_Logst_Total	Total Deliveries Per Block Required	deliveries	416.88	269.30	65.40
mCycle_Logst_LoadsPer	Total Deliveries per Day Required	deliveries	12.25	6.96	5.61
mCycle_Logst_optime	Material delivery cycle time Machine Driving	hours	0.67	0.09	0.67
mCycle_Logst_utiltime	Material delivery cycle time Machine Driving + Set Down	hours	1.17	0.59	1.17
mCycle_Logst_onroad	Supplies on road at any given time	Loaders	0.60	0.17	0.27

```
92  Call gorec(home)
93   M(mCycle_Dist_CumDist) = lMainsCumMetres
94
95
96  End Sub
```

The IF statement (LINE4) defines the parent panel and will only proceed if the current block is Block number 1. A parent panel is the panel that the logistics system must travel through prior to entry. For a maingate or tailgate it will be Mains (LINE6), for an install road and longwall it is the gateroad (LINE11). Once parent panels are established, the embedded subroutine “GateroadCumdist” is executed (LINE16).

The centroid coordinates for the current scheduling block are collected as variables (LINEs 37 and 38). The scheduling block needs to then find its parent panel. For development panels, which can also be defined as “<>LW” or not equal to a Longwall Panel (LINE40) the program goes up to the Process level (LINE41 and 42). Below this level are all development panels in the same domain. Unlike L03, the subroutine L06 references parent panels that are in the same AREA/Domain whereas L03 had to search the entire model for the closest block. It then steps back down to the first development panel (LINE43).

For longwall panels the right gateroad parent must be found, and so the process is changed to “DV” (LINE51). The program then goes to the first development panel (LINEs 52-53) in the same domain as the longwall and arrives at the same place in the database as LINE4 which is the first development panel of the AREA/Domain.

A Do Loop is introduced in LINE57. This loop will move through every development panel until the Parent Panel is found (LINES 58-64). Once the parent panel is located, the loop is exited, and the number of scheduling block children is found (LINE67). This is used as the upper limit for the FOR/NEXT loop commencing on LINE69. The loop looks for the minimum distance between all the parent scheduling blocks and block 1, gateroads for L06, and installation roads and longwall roads in L08.

The flowchart logic of L06 is shown in Figure 3-38.

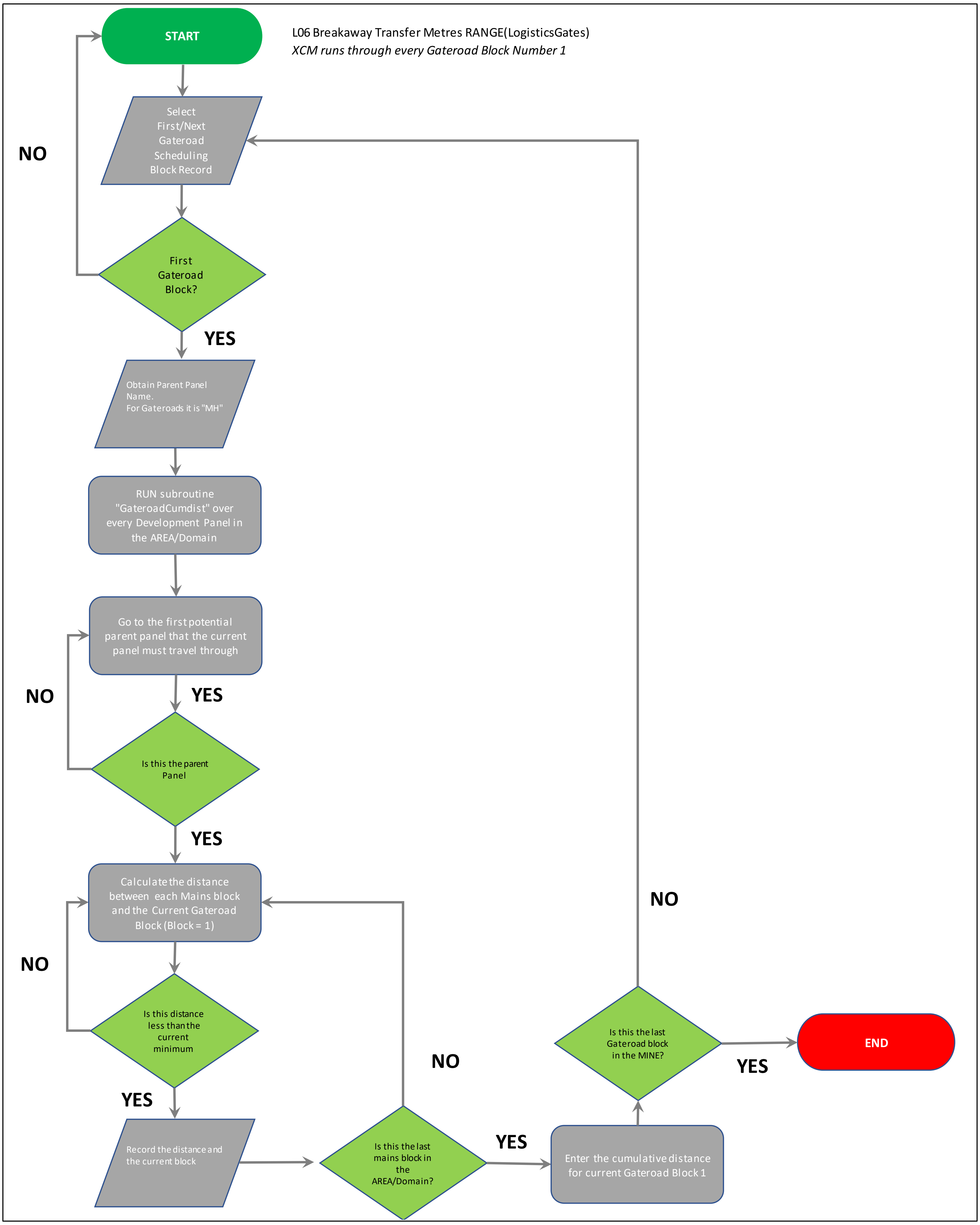


Figure 3-38: Flowchart of L06 Breakaway Transfer Metres RANGE(LogisticsGates)

3.4.3.6 L07 Cumulative dev metres (LogisticsGates)

L07 Cumulative dev metres (LogisticsGates), abbreviated to L07, propagates the cumulative distance from the Gateroad scheduling block 2 and higher. It is designed to be run only over gateroad panels for speed of calculation. L07 is very similar to L04 except for the range it is executed over and L04 and has a triple nested IF statement whereas L07 has only a double IF statement. It reads and writes to the same main database variables as what L04 does.

```
'Script creation:L07 Cumulative dev metres (LogisticsGates)
 ' Author:  <David Walker>
 ' Position: <PhD Candidate UOW>
 ' Company: <University of Wollongong>
 '
 'Script description:
 ' Execution:
 '  Type:  Database
 '  Database: MAIN
 '  Trigger: NA
 '  Run type: Range
 '  Range:  LogisticsGates
 '
 ' Purpose: Propagates cumulative distance along a gateroad after block 1 is calculated from L06
 ' Date    Author/Company     Description of modifications

'~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
 '       David Walker      First Write

'~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~

Sub Main()
'This is to cumulative linear advance metres per panel
'Can do this via centroid but is then not governed by path
'Getrecnum previous block
1 Dim lCurr_rec As Long
2 Dim lPrev_rec As Long
3 lCurr_rec = getrecnum(CURRENT)
4 lPrev_rec = getrecnum(PRVSIB)
5 Dim lPrev_dist As Long
6 Dim lPanel_dist As Long
7 if lPrev_rec >0 then 'a previous record exists
8  Call gorec(lPrev_rec)
9  lPrev_dist = M(mCycle_Dist_CumDist)
10 lPanel_dist = M(mPHYS_LinMet)
11 Call gorec(HOME)
12 if sProcessName = "DV" then 'development increases travel
13  M(mCycle_Dist_CumDist) = lPrev_dist + lPanel_dist
14 else 'LW rereat decreases travel back to Mains
15  M(mCycle_Dist_CumDist) = lPrev_dist - lPanel_dist
16 end if
17 end if
18 End Sub
```

Essentially L07 starts by finding all gateroads block number 2 (LINE7). It then goes to the previous record and gets the cumulative metres from the portal remembering Block 1 was calculated from L06. It then adds the previous cumulative distance and the linear metres (Block length) of the of the previous block and writes this into block 2 as cumulative distance (LINE13). It then repeats this process for Block 3, Block 4 all the way to the end of each gateroad panel.

After running L01 to L07 cumulative distances are calculated from the portals, along all mains and then inbye to gateroad driveage. This can be seen in Figure 3-39 where distances have now been formed out along the gateroads.

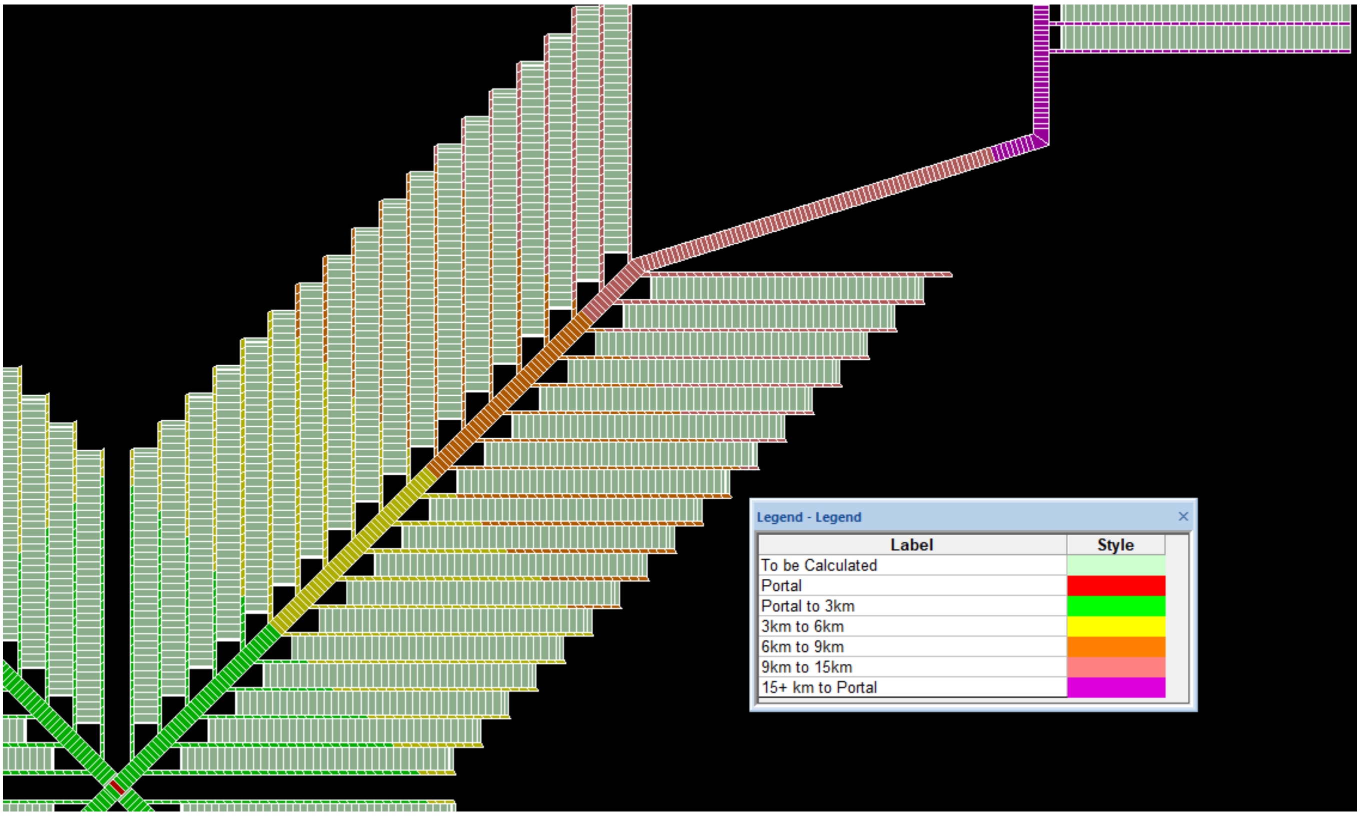


Figure 3-39: Impact of L06 and L07 on the Cumulative distance from the portal.

3.4.3.7 L08 Breakaway Transfer Metres RANGE(LogisticsIR_LW)

L08 Breakaway Transfer Metres RANGE(LogisticsIR_LW), abbreviated to L08, as previously mentioned is a duplicate of L06 but runs over a different range known as "LogisticsIR_LW". Its purpose is to find the closest maingate scheduling block which has a cumulative distance calculated from L07. The programming currently assumes travel to the longwall and installation road is through the maingate but could be adjusted if necessary to supply from the tailgate side. The main difference between L06 and L08 is that L06 only found the first block cumulative distance from a mains scheduling block. This is not the case for L08. L08 finds the closest gateroad block cumulative distance for every longwall or installation roadblock and uses that distance. As the longwall retreats towards the mains the longwall the cumulative distance from the portals over time decreases, until a longwall changeout occurs when the longwall cumulative distance will rise again. The output of this process is shown in Figure 3-40.

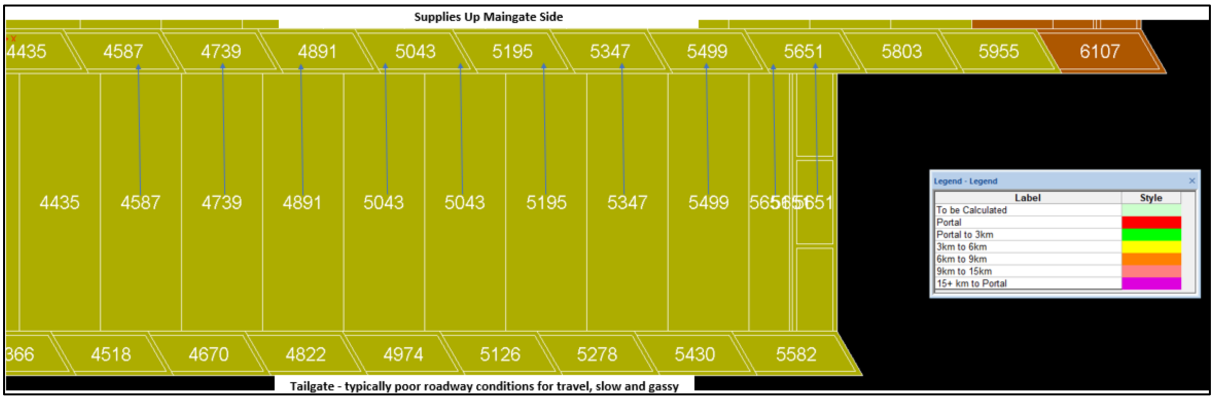


Figure 3-40: Close up view of LW01 in the North-East Domain with cumulative distances annotated

Figure 3-40 has cumulative distance annotated, and since longwall supplies are typically taken to the adjacent scheduling block maingate corner, it is reasonable to use the same cumulative distance as where the maingate corner would be. The relationship between the maingate cumulative distance and that of each longwall and installation road scheduling block is shown using the arrows. Whichever maingate scheduling block centroid is closer, its cumulative distance is written to the corresponding longwall block. The flowchart logic of L06 is shown in Figure 3-41.

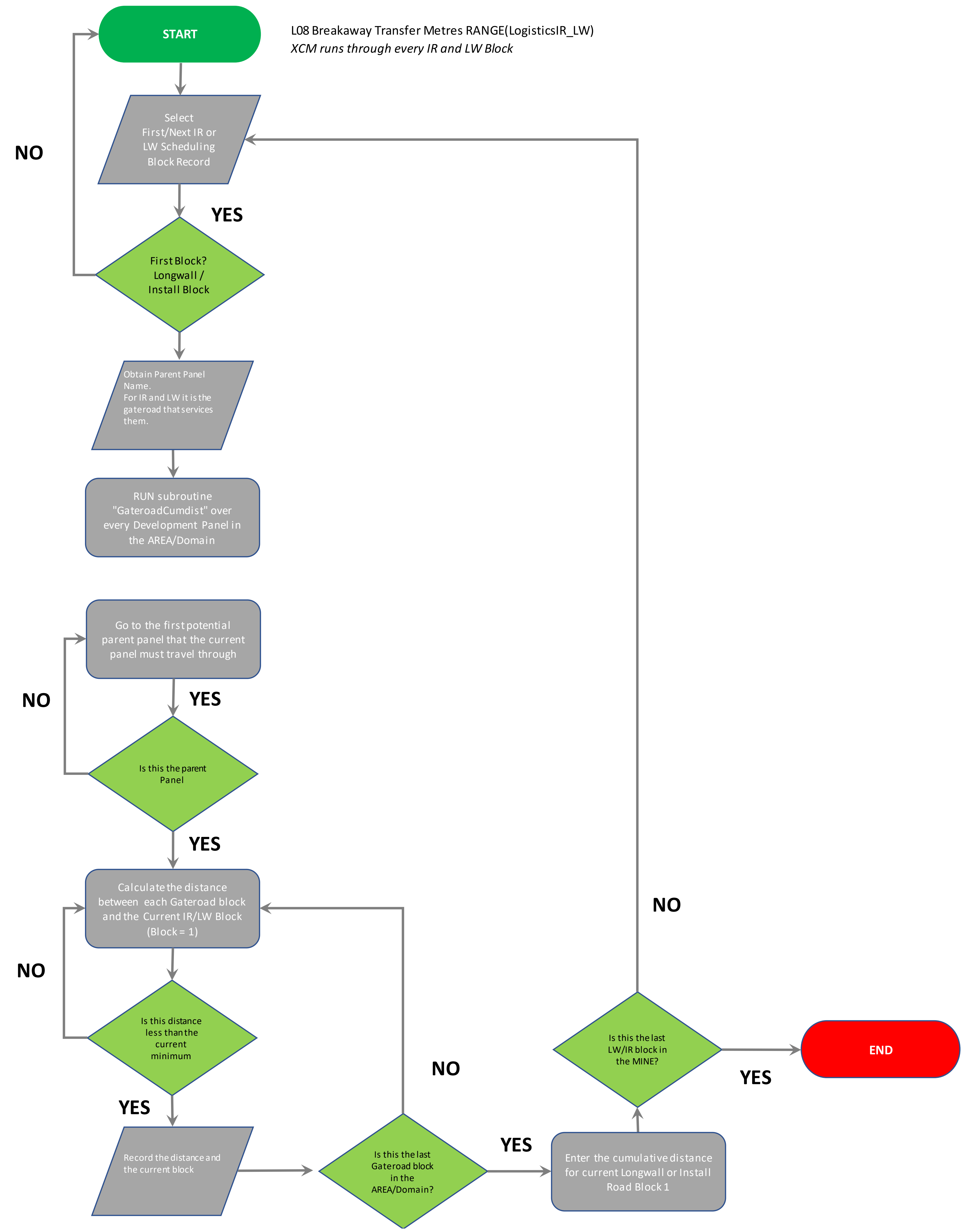


Figure 3-41: Flowchart of L08 Breakaway Transfer Metres RANGE(LogisticsIR_LW)

After running L01-L08, all cumulative distances are calculated for the entire reserve database. From the portals, along all mains, inbye along gateroad driveage and to LW and installation panel distances from the portal . This is illustrated in Figure 3-42 and shows the contrast of distance from the original radiating method of Figure 3-26.

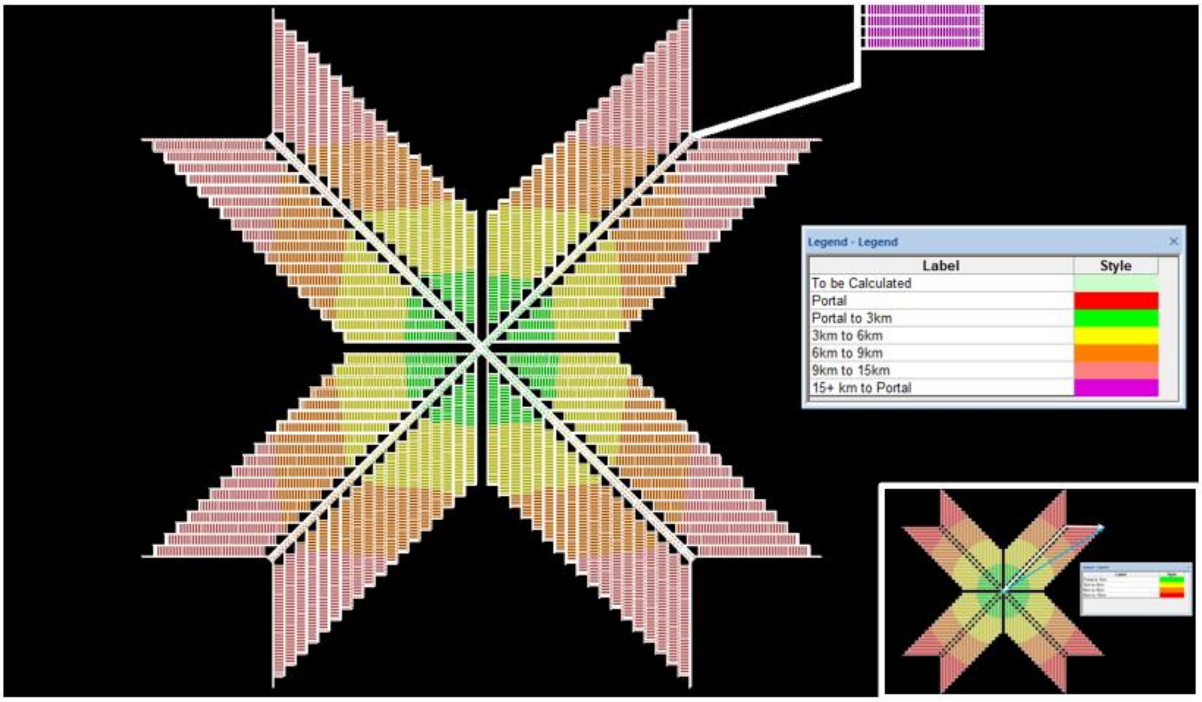


Figure 3-42: All cumulative distances for every scheduling block calculated. Inset redundant and incorrect centroid to centroid distances (Previous: Figure 3-26)

Figure 3-42 highlights the difference between a simplistic radiating "as the crow flies" distance and that of a travel road that logistics supply would follow. It shows as expected, that the travel path route is a more accurate and conservative estimation of cumulative distance from portals which in turn will give a better estimation of logistics strain over time and at any time.

After running L08, all cumulative scheduling blocks now have cumulative distances from the portal. The time to run the batch consecutive subroutines is 8 minutes and 50secs with an extremely large database, given that computer specification also will contribute to speed variability.

3.4.4 Scheduling

Upon completion of L08, the schedule is executed. The schedule must be checked for validity and may take some iterations as per any mine schedule to get the desired result. As the schedule runs a subroutine is executed at the completion of every scheduling step known as –UP03 - Post–Step - Write Block Start and Finish Dates.bas', abbreviated to UP03. Scheduling steps can be defined since every productive and non-productive step that each machine must undertake as it works through its path throughout a schedule to completion are accounted for. Currently, the largest main database used in this thesis has 13,529 scheduling blocks. One schedule that was run, based on the input paths, reserve size, calendar database and resource/ machine productivities required 16,835 scheduling steps and therefore UP03 is run 16,835 times during the scheduling run. The number of steps changes every time a path, calendar, reserve size or productivity changes.

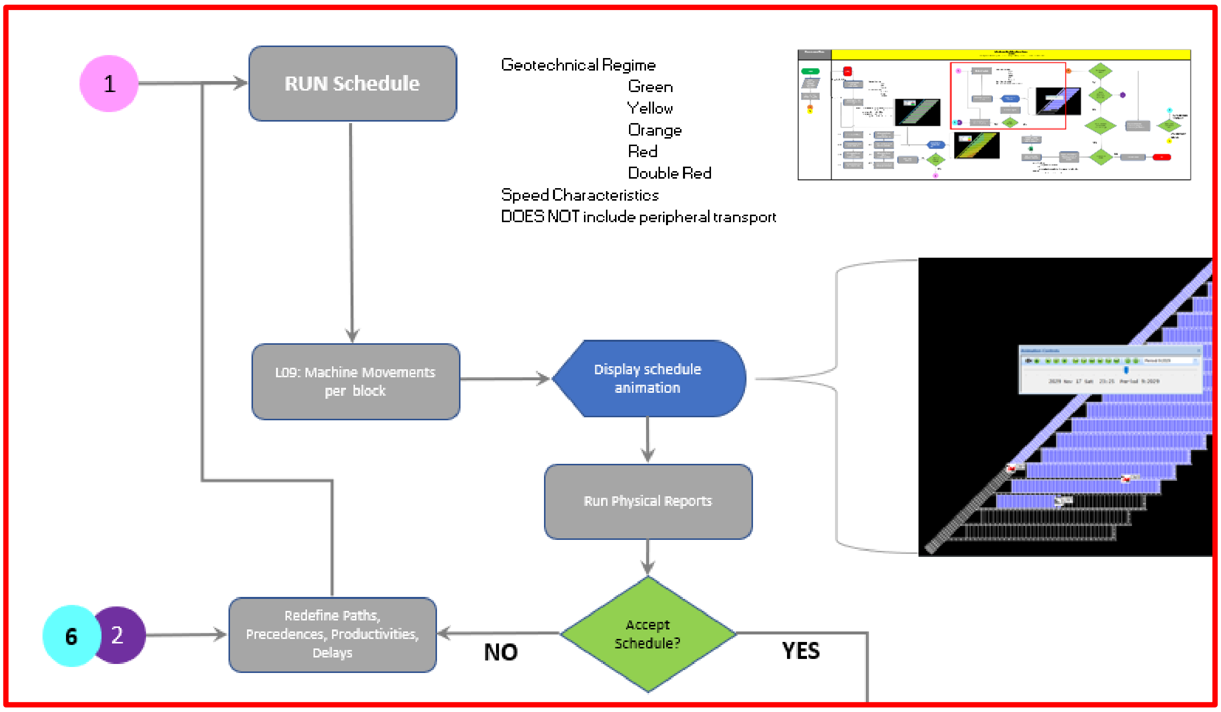


Figure 3-43*: Stage 3 scheduling in the process–UP03 - Post–Step - Write Block Start and Finish Dates.bas*

Upon completion of L08, the schedule is executed. The schedule must be checked for validity and may take some iterations as per any mine schedule to get the desired result. As the schedule runs a subroutine is executed at the completion of every scheduling step known as–UP03 - Post–Step - Write Block Start and Finish Dates.bas, abbreviated to UP03.

This subroutine must be attached to every resource/machine to ensure that all blocks' start, and finish date is captured. The subroutine also known as a Trigger XCM is shown: -

```
'Script description: Checks at the completion of every scheduling step if a block has been completed
' Then writes back to Main DB as a basevalue, the start and finish dates of that particular block.
'  Execution:
'    Type:    Trigger
'    Trigger:  All resources (Post Step)
'    Run type:  Current
'    Range:   All/Deposit
'
'  Purpose:
'    This script writes the resource name, start date, and finish date of the scheduling block in each
panel.
_'Main subroutine
Sub Main()
1   Dim curOutStep As OutputPathStep
2   Call GetCurrentOutputStep(curOutStep)
3   If curOutStep.StepType = PE_PROD Then
4     If ReadBaseValue(ACTIVE_MAIN, curOutStep.TaskId, "mSched_Dates_Start") <= 0 Then
5               Call   WriteBaseValue(ACTIVE_MAIN,   curOutStep.TaskId,   "mSched_Dates_Resource",
curOutStep.ResourceName, True)
6       Call WriteBaseValue(ACTIVE_MAIN, curOutStep.TaskId, "mSched_Dates_Start", curOutStep.StartDate,
True)
7     End If
8
9    'If curOutStep.RemainingPct = 0 Then
10      Call WriteBaseValue(ACTIVE_MAIN, curOutStep.TaskId, "mSched_Dates_End", curOutStep.FinishDate,
True)
11    'End If
12  End If
End Sub
```

LINE3 filters only the type of steps that mine the scheduling blocks, also known as a productive step (. StepType = PE_PROD), are considered. LINE4 checks if the scheduling block is about to be mined and obtains and enters the resource /machine name into the main database that is about to mine it (LINE5) and the start date that the scheduling block is scheduled to commence mining (LINE6). At the completion of the block being mined the date from the schedule is entered (LINE10). The variables in the main database written to executing the UP03 subroutine are shown in Figure 3-44 and Table 3-18: The block start and finish dates output from subroutine UP03.: -

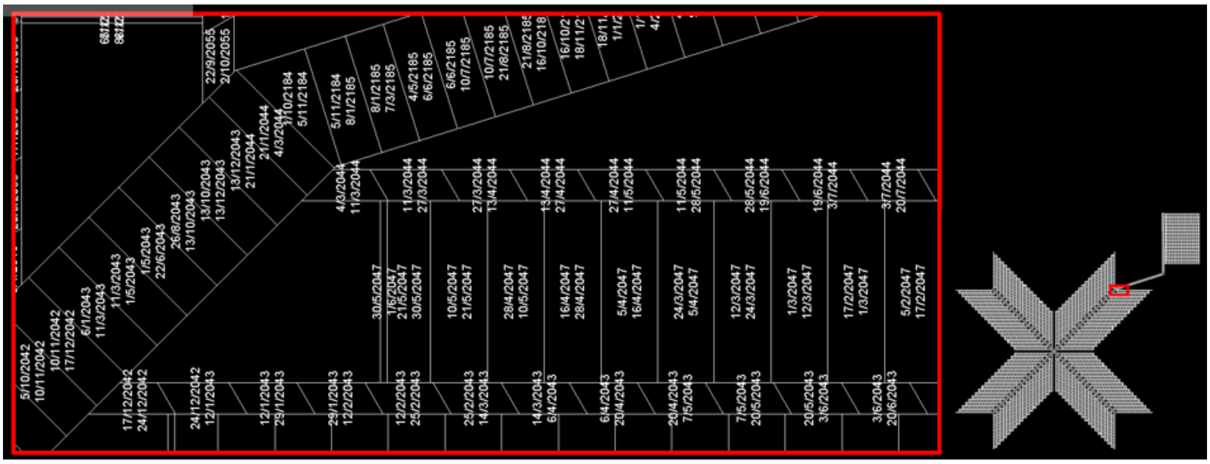


Figure 3-44: Start and finish dates of NE AREA/Domain scheduling blocks for panels MG117, LW118 and MG118 and MHNE and MHNE_Ext.

Table 3-18: The block start and finish dates output from subroutine UP03.

Code	Data Field Name	Units	Central\NE\DV\ MG101\17	Central\NE\DV\ MHNE\8	Central\NE\LW\ LW101\19
			Gate road Block	Mains Block	LW Block
	IC LoA Model				
mIMP	Imported Data Fields				
mIMP_NUMOFROADS	Number of Roadways		2	7	1
mIMP_ROADWIDTH	RoadWay Width		5.2	5.2	0
mIMP_CLINEOFFSET	RoadWay C/Line Offset		50	40	0
mIMP_CTHRUOFFSET	Cut-Through Offset		120	75	0
mIMP_BLOCKLENGTH	Block Length (Max)		151.87	75	100
mIMP_BLOCKWIDTH	Block Width (Max)		55.2	245.2	320
mIMP_AREAACT1	Area		1517	3815.76	0
mIMP_VOLACT1	Volume		0	0	0
mIMP_CENTXACT1	Centroid X		2,735	322	2,705
mIMP_CENTYACT1	Centroid Y		575	322	388
mIMP_MINDIRACT1	Mining Direction		90	45	90
mIMP_AREAACT2	Area		5107	14574.24	32000
mIMP_VOLACT2	Volume		0	0	0
mIMP_CENTXACT2	Centroid X		2721.65	312.89	2704.83
mIMP_CENTYACT2	Centroid Y		575.27	312.89	387.67
mIMP_MINDIRACT2	Mining Direction		270	225	270
mIMP_Seamthknss	Insitu Thickness		0	0	0
mPHYS	Physicals				
mPHYS_Metres	Metres				
mPHYS_LinMet	Linear Metres	m	152	75	100
mPHYS_TotMet	Total Metres	m	292	734	100
mSched	Scheduling				
mSched_BaseRate	BaseRate				
mSched_BaseRate_Dev	Development Productivity	m/week	150	100	
mSched_BaseRate_LW	LW Productivity	m/week			60
mSched_Rate	Rate				
mSched_Rate_Dev	Development Productivity	m/week	60	100	
mSched_Rate_LW	LW Productivity	m/week			60
mSched_Dates	Dates				
mSched_Dates_Start	Start Date		19/08/2023	11/12/2021	25/03/2025
mSched_Dates_End	End Date		22/09/2023	18/01/2022	6/04/2025
mSched_Dates_Resource	Resource Name		CM2	CM1	LW1
mSupport	Primary Support Zones				
mSupport_DV	Development Zones				
mSupport_DV_Green	Green primary support metres	m	0	733.8	0
mSupport_DV_Yellow	Yellow primary support metres	m	0	0	0
mSupport_DV_Orange	Orange Support primary support metres	m	0	0	0
mSupport_DV_Red	Red Support primary support metres	m	291.7307692	0	0
mSupport_DV_DoubleRed	Double Red primary support metres	m	0	0	0
mDelay	Delays				
mDelay_InPath	Inpath				
mDelay_InPath_Flit	CM Flits		0	0	0
mDelay_InPath_LWMove	LW Move		0	0	0
mCycle	Cycle Times				
mCycle_Dist	Distance Travelled				
mCycle_Dist_CumDist	Cumulative Distance	m	3371	450	3371
mCycle_Logst	Logistics				
mCycle_Logst_Duration	Duration within Block		34.04	38.69	11.67
mCycle_Logst_Total	Total Deliveries Per Block Required	deliveries	416.88	269.30	65.40
mCycle_Logst_LoadsPer	Total Deliveries per Day Required	deliveries	12.25	6.96	5.61
mCycle_Logst_optime	Material delivery cycle time Machine Driving	hours	0.67	0.09	0.67
mCycle_Logst_utiltime	Material delivery cycle time Machine Driving + Set Down	hours	1.17	0.59	1.17
mCycle_Logst_onroad	Supplies on road at any given time	Loaders	0.60	0.17	0.27

UP03 is critical because if duration per block is combined with deliveries per block, deliveries per day can be calculated which is a critical indicator of logistics strain at any point in time from the start to finish of any schedule.

3.4.4.1 L09 Post Schedule Supplies per day

The remainder of Logistics strain key performance indicators (KPIs) are calculated by executing the subroutine 'L09 Post Schedule Supplies per day.bas', abbreviated to L09. Unlike L01 through to L08 which can be run at any time pre- or post- schedule, L09 can only be executed on completion or approval of a satisfactory schedule being completely acceptable.

```
'Script creation:L09 Post Schedule Supplies per day
' Author:  <David Walker>
' Position: <PhD Candidate UOW>
' Company: <University of Wollongong>
'
'Script description:
' Execution:
'  Type:  Database
'  Database: MAIN
'  Trigger: NA
'  Run type: Range
'  Range:  ALL
'
' Purpose: Finds breakaway blocks that that are closest to Maingate drivage then adds the cumulative distance
'for Longwall and Install Roads.
'Script modification log:
' Date    Author/Company     Description of modifications
'~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
'       David Walker      First Write
'~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
'
'Main subroutine
Sub Main()
1 dim dDuration as double
2 dDuration = M(mSched_Dates_End) - M(mSched_Dates_Start)
3 M(mCycle_Logst_Duration) = dDuration
4
5 M(mCycle_Logst_LoadsPerDay) = safedivide(M(mCycle_Logst_Total), dDuration)
6 M(mCycle_Logst_optime) = safedivide(M(mCycle_Dist_CumDist) * 2/1000 , gSpeedofLoader) 'wheels rotating time
7 M(mCycle_Logst_utiltime) = M(mCycle_Logst_optime) + gSetDownTime' drive time in and out + set down time
8 M(mCycle_Logst_onroad) = M(mCycle_Logst_LoadsPerDay) * M(mCycle_Logst_utiltime) / gDedicatedTravelWindowTime
9
10 End Sub
```

In this subroutine, global variables have been introduced. These are signified by the prefix "g" prior to the variable name. Global variables are entered in a dedicated XPAC menu to quickly change their respective values. Accurate cycle time prediction is critical in understanding machine requirements at any given time (Chanda & Gardiner, 2010). Programs L01-L08 calculate the cumulative distance from a nominated position (usually pit bottom) speed has a higher degree of variability. It was therefore vital that speeds could be easily adjusted and updated, based on historical information. It was also important to provide a model where a range of speeds could be applied or a most probable speed could be stochastically determined which Nasri et al. (2018) have presented. The global variables that are referred to in this XCM are for machine average speed (gSpeedofLoader) in kilometres per hour and represent, in this case, a most probable speed for the duration of the journey, the average time between loading and unloading or set down time at the production district delivery point (gSetDownTime) measured in hours, and dDedicatedTravelWindowTime being the window of time per day in hours that LHD may travel. LINE2 calculates the duration in days from the commencement to the completion of the scheduling block. LINE3 outputs the duration of mining the scheduling block.

Duration(days) = Scheduling Block End Date – Scheduling Block Start Date

Where: Dates are calculated from–UP03 - Post–Step - Write Block Start and Finish Dates.bas

LINE5 calculates the deliveries per day, which is the total deliveries required for the scheduling block divided by the mining duration.

Machine deliveries per day = Total Loads for the scheduling block / Duration(days)

Where: Total loads per block are calculated from: M02 Main DB.bas

Operating time is defined as the time when the delivery LHDs are underground and underway. LINE6 calculates this as Cumulative Distance from the Portal multiplied by two for a round trip to the portal divided by the average speed of the LHD.

Machine Operating Time = Block Distance from Portal x 2 / (1000 x average speed of LHD underway)

Where: average speed of the LHD is a global variable

Block distance from the portal is calculated from L01 to L08

Distance is in metres

Speed is in km/hr

Utilised time is typically defined as total time when a LHD may have its engine on but may or may not be moving. LINE7 calculates the utilised time which is the time the LHDs are underground and therefore may be travelling or maybe setting down a load or can also include any other delay.

Machine Utilised Time = Machine Operating Time + gSetDownTime

Where: gSetDownTime is a global variable and can include unloading and backload loading time but may also include other discrete delays (traffic lights etc) that have not been considered in the average speed of the machine

Time is in hours

LINE8 calculates the number of machines on road in the process of delivery during the window of time that deliveries are allowed (gDedicatedTRavelTimeWindow in hours). Some operations may have deliveries as priority, if the mine is logistics constrained, or there may be dedicated heavy haulage travel roads which prevent delivery interruption. Other mines on the other hand may only have dedicated windows on less busy shifts such as afternoon shift or night shift, or that deliveries can only occur at specific times of the day.

$$\text{Machines on road at a point in time} = \frac{\text{Machine deliveries per day x Utilised Time}}{\text{gDedicatedTravelTimeWindow}}$$

Machine deliveries per day x Utilised Time equates to Total Machine hours underground in a single day.

The variables in the main database written to executing the UP03 subroutine are shown in Table 3-19.

Table 3-19: The main database outlining input (green) and output (yellow) from L09 post schedule supplies per day.bas

Code	Data Field Name	Units	Central\NE\DV\ MG101\17	Central\NE\DV\ MHNE\8	Central\NE\LW\ LW101\19
			Gate road Block	Mains Block	LW Block
	IC LoA Model				
mIMP	**Imported Data Fields**				
mIMP_NUMOFROADS	*Number of Roadways*		*2*	*7*	*1*
mIMP_ROADWIDTH	*RoadWay Width*		*5.2*	*5.2*	*0*
mIMP_CLINEOFFSET	*RoadWay C/Line Offset*		*50*	*40*	*0*
mIMP_CTHRUOFFSET	*Cut-Through Offset*		*120*	*75*	*0*
mIMP_BLOCKLENGTH	*Block Length (Max)*		*151.87*	*75*	*100*
mIMP_BLOCKWIDTH	*Block Width (Max)*		*55.2*	*245.2*	*320*
mIMP_AREAACT1	*Area*		*1517*	*3815.76*	*0*
mIMP_VOLACT1	*Volume*		*0*	*0*	*0*
mIMP_CENTXACT1	*Centroid X*		*2,735*	*322*	*2,705*
mIMP_CENTYACT1	*Centroid Y*		*575*	*322*	*388*
mIMP_MINDIRACT1	*Mining Direction*		*90*	*45*	*90*
mIMP_AREAACT2	*Area*		*5107*	*14574.24*	*32000*
mIMP_VOLACT2	*Volume*		*0*	*0*	*0*
mIMP_CENTXACT2	*Centroid X*		*2721.65*	*312.89*	*2704.83*
mIMP_CENTYACT2	*Centroid Y*		*575.27*	*312.89*	*387.67*
mIMP_MINDIRACT2	*Mining Direction*		*270*	*225*	*270*
mIMP_Seamthknss	*Insitu Thickness*		*0*	*0*	*0*
mPHYS	**Physicals**				
mPHYS_Metres	**Metres**				
mPHYS_LinMet	Linear Metres	m	152	75	100
mPHYS_TotMet	Total Metres	m	292	734	100
mSched	**Scheduling**				
mSched_BaseRate	**BaseRate**				
mSched_BaseRate_Dev	Development Productivity	m/week	150	100	
mSched_BaseRate_LW	LW Productivity	m/week			60
mSched_Rate	**Rate**				
mSched_Rate_Dev	Development Productivity	m/week	60	100	
mSched_Rate_LW	LW Productivity	m/week			60
mSched_Dates	**Dates**				
mSched_Dates_Start	Start Date		19/08/2023	11/12/2021	25/03/2025
mSched_Dates_End	End Date		22/09/2023	18/01/2022	6/04/2025
mSched_Dates_Resource	Resource Name		CM2	CM1	LW1
mSupport	**Primary Support Zones**				
mSupport_DV	**Development Zones**				
mSupport_DV_Green	Green primary support metres	m	0	733.8	0
mSupport_DV_Yellow	Yellow primary support metres	m	0	0	0
mSupport_DV_Orange	Orange Support primary support metres	m	0	0	0
mSupport_DV_Red	Red Support primary support metres	m	291.7307692	0	0
mSupport_DV_DoubleRed	Double Red primary support metres	m	0	0	0
mDelay	**Delays**				
mDelay_InPath	**Inpath**				
mDelay_InPath_Flit	CM Flits		0	0	0
mDelay_InPath_LWMove	LW Move		0	0	0
mCycle	**Cycle Times**				
mCycle_Dist	**Distance Travelled**				
mCycle_Dist_CumDist	Cumulative Distance	m	3371	450	3371
mCycle_Logst	**Logistics**				
mCycle_Logst_Duration	Duration within Block		34.04	38.69	11.67
mCycle_Logst_Total	Total Deliveries Per Block Required	deliveries	416.88	269.30	65.40
mCycle_Logst_LoadsPer	Total Deliveries per Day Required	deliveries	12.25	6.96	5.61
mCycle_Logst_optime	Material delivery cycle time Machine Driving	hours	0.67	0.09	0.67
mCycle_Logst_utiltime	Material delivery cycle time Machine Driving + Set Down	hours	1.17	0.59	1.17
mCycle_Logst_onroad	Supplies on road at any given time	Loaders	0.60	0.17	0.27

For example. Using Table 3-19, LW101 Block 19 commences on the 25/3/2025 at 6:32PM and is completed on the 6/4/2025 at 10:32AM which equates to a duration of 11.67 days to complete mining of this block. The total deliveries required for this block are 65.4 deliveries and the block is 3371 m from the portal and the average speed of the LHD is 10 km/hr. Unloading time is 15 mins, communication to control for panel entry 5 mins and light section delays = 10 mins. Deliveries have priority and can operate without interruption for 24 hours per day.

Duration(days) = Scheduling Block End Date – Scheduling Block Start Date

= 6/4/2025@10:32 – 25/3/2025 @18:32

= 11.67 days

Machine deliveries per day = Total Loads for the scheduling block / Duration(days)

= 65.40 / 11.67

= 5.61

Machine Operating Time = Block Distance from Portal x 2 / (1000 x average speed of LHD underway)

= 3371 x 2 / (1000x 10)

= 0.674 hours or 40 mins

gSetDownTime (hours) = sum of all discrete delays (mins)/ 60

= Unloading time + communication time + light section delays

= (15 + 5 + 10) /60

= 0.5 hours

Machine Utilised Time = Machine Operating Time + gSetDownTime

= 0.674 + 0.5

= 1.174 hours

Machines on road at a point in time = $\frac{\text{Machine deliveries per day x Utilised Time}}{\text{gDedicatedTravelTimeWindow}}$

= 5.61 x 1.174 / 24

= 0.27 machines at any given time

3.4.5 Reporting

The flowchart of logistics bottleneck identification and rectification is now reaching its completion. At this stage the data is ready for export to be further manipulated in Microsoft Excel, allowing analysis of whether logistics strain is tolerable, and therefore, if the strategic mine plan and its value proposition is valid.

To understand logistics strain over time, three key performance indicators of logistics strain are reported daily being cumulative total distance, deliveries per day and loads on road for the LoM schedule for the combined production panels for any given day. Recalling from Chapter 1 and to replicate from Figure 3-46, the logistics breaking strain of the mine occurs when it is impossible to continue at the rate of delivery. This will typically be a nominated maximum number of LHDs determined by key mining staff and will consider LHD fleet availability, ventilation considerations, rate of roadway deterioration, and pedestrian / vehicular interaction that can be safely and practically operated.

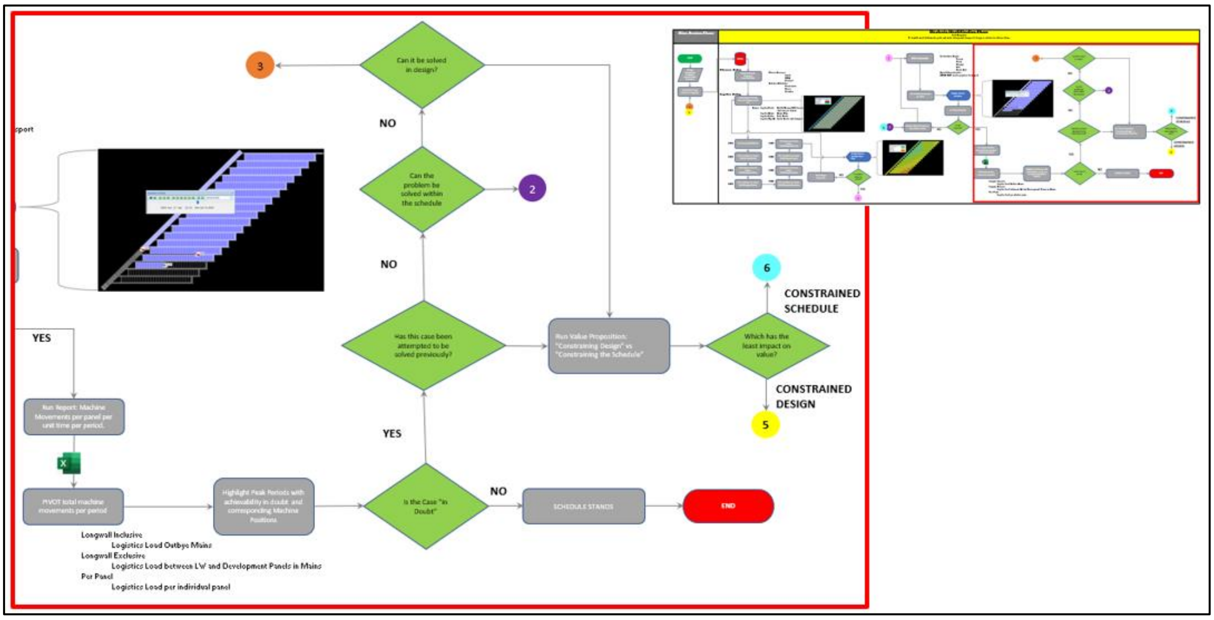


Figure 3-45: Reminder of Figure 3-9 highlighting the reporting phase.

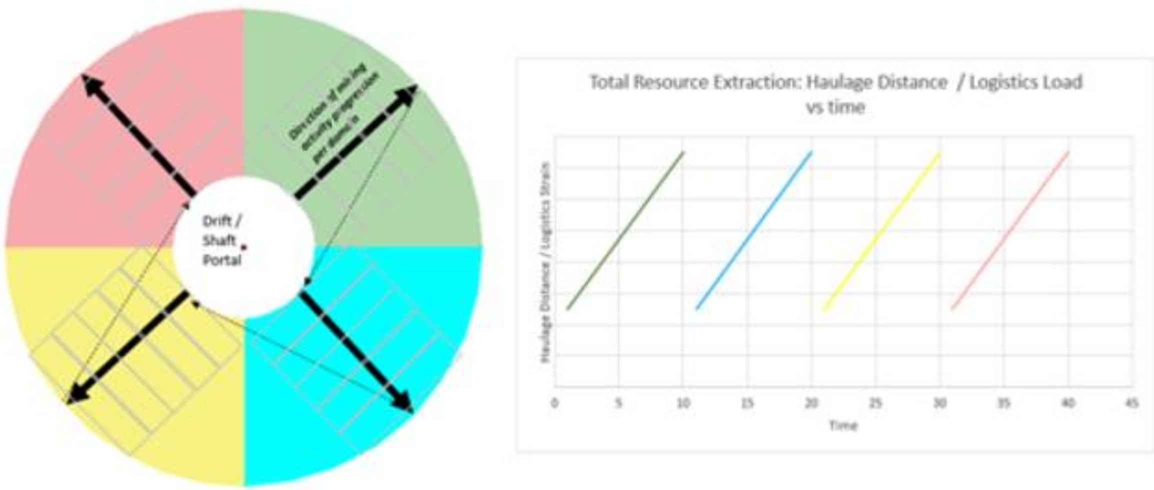


Figure 3-46: Chapter 1 (Figure 1-3) theoretical graph of logistics strain over time.

If logistics breaking strain is identified and can be rectified, the schedule remains valid. There are many ways to alleviate such strain, for example a change in path, upgrade of machinery or increasing payload per delivery, better lighting and road conditions, reduction in delivery delay, dedicated haulage roads additional interim portals installed closer to face operations or even more drastic changes such as complete design overhaul. The earlier these issues are identified, the easier it is to execute a solution and to encompass it inside a value proposition. Retrospectively addressing a logistics constraint (as with any constraint) will require unplanned expense not to mention distraction, possibly a sub-optimal quick fix that will reduce the value proposition of the mine that was never considered in the justification of the operation. Consider, for example, that to achieve daily delivery requirements the only immediate solution is to retrospectively concrete all travel roads as fast as possible which may lead to transport interruptions and complexity compared to early identification and planning where concreting is part of routine face production operation where a systemised approach is adopted, and standards are monitored and benchmarked.

Eventually even with all available mitigation strategies employed, logistics breaking strain may still occur (albeit usually deferred) which then requires a downgrading of the schedule itself. Early identification of logistics breaking strain may have deferred a downgrade in productivity so that the NPV impact is close to minimal and strategic decision makers have a more accurate value proposition. Otherwise, the schedule would be considered capped by the logistics breaking strain.

3.4.5.1 External Export, L10 ExcelOutput of MainDB

The remaining analysis is undertaken in Microsoft Excel. Post schedule, if acceptable, requires XPAC outputs and variables of each scheduling block to be dumped in. This is done using the subroutine L10 ExcelOutput of MainDB.bas, abbreviated to L10.

```
'Script creation:L10 Excel Output of MainDB
' Author:  <David Walker>
' Position: <PhD Candidate UOW>
' Company: <University of Wollongong>
'
'Script description:
' Execution:
'  Type:  Database/Trigger
'  Database: MAIN
'  Trigger: NA
'  Run type: Range
'  Range:  LogisticsIR_LW
'
' Purpose: Dumps key variables from the schedule and MainDB into an Excel Spreadsheet
'Script modification log:
' Date     Author/Company      Description of modifications
'~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
'        David Walker      First Write
'~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
  'Main subroutine
Sub Main()

If IsFirstInRange() Then

 Dim excel As Object
 Set excel = CreateObject("Excel.Application")
 'Set excelvba = CreateObject("Excel.vba")
 excel.Visible = True
 Dim wbk As Object
Set wbk = excel.Workbooks.Add
Set sCurrSheet = excel.Worksheets
wbk.Activate

Dim i As Long
Dim lCurrRec As Long

excel.cells(1, 1) = "Mine"
excel.cells(1, 2) = "Area"
excel.cells(1, 3) = "Process"
excel.cells(1, 4) = "Panel"
excel.cells(1, 5) = "Block #"
excel.cells(1, 6) = "Record #"
excel.cells(1, 7) = "Green m"
excel.cells(1, 8) = "Yellow m"
excel.cells(1, 9) = "Orange m"
excel.cells(1, 10) ="Red m"
excel.cells(1, 11) ="Double Red m"
excel.cells(1, 12) = "Start Date"
excel.cells(1, 13) = "End Date"
excel.cells(1, 14) = "Cum Dist from Shaft"
```

```
31 excel.cells(1, 15) ="Mining Duration in Block"
32 excel.cells(1, 16) ="Total Loads"
33 excel.cells(1, 17) ="Loads per Day"
34 excel.cells(1, 18) ="Operating Time - Wheels Turning"
35 excel.cells(1, 19) ="Utilised Time - Engine On"
36 excel.cells(1, 20) ="Loads on Road"
37
38
39 lCurrRec = GetRecNum(CURRENT)
40 i = 2
41 Do While lCurrRec > 0
42
43  If lBlockNum <> "" Then
44  excel.cells(i, 1) = sMineName
45  excel.cells(i, 2) = sAreaName
46  excel.cells(i, 3) = sProcessName
47  excel.cells(i, 4) = sPanelName
48  excel.cells(i, 5) = lBlockNum
49  excel.cells(i, 6) = lCurrRec
50  excel.cells(i, 7) = M(mSupport_DV_Green)
51  excel.cells(i, 8) = M(mSupport_DV_Yellow)
52  excel.cells(i, 9) = M(mSupport_DV_Orange)
53  excel.cells(i, 10) = M(mSupport_DV_Red)
54  excel.cells(i, 11) = M(mSupport_DV_DoubleRed)
55  excel.cells(i, 12) = M(mSched_Dates_Start)
56  excel.cells(i, 13) = M(mSched_Dates_End)
57  excel.cells(i, 14) = M(mCycle_Dist_CumDist)
58  excel.cells(i, 15) = M(mCycle_Logst_Duration)
59  excel.cells(i, 16) = M(mCycle_Logst_Total)
60  excel.cells(i, 17) = M(mCycle_Logst_LoadsPerDay)
61  excel.cells(i, 18) = M(mCycle_Logst_optime)
62  excel.cells(i, 19) = M(mCycle_Logst_utiltime)
63  excel.cells(i, 20) = M(mCycle_Logst_onroad)
64
65 i = i + 1
66
67 End If
68
69
70
71 lCurrRec = GetRecNum(NXT)
72 If lCurrRec <0 Then
73  GoTo 1000
74 End If
75
76 Call GoRec(lCurrRec)
77 Loop
78
79
80
81 1000 Stop
82
83 End If
84
85 End Sub
```

LINEs 5-12 remotely open an Excel spreadsheet. LINEs 17-36 then write in headers for the data export. LINEs 17-22 are scheduling block identifiers and LINEs 23-36 are MainDB variables posts schedule execution. LINE39 sets the first record, and the row number is then set to two in LINE40, directly below the headers. A dump of every valid scheduling block into Excel occurs using a Do Loop between LINEs 41 and 67. Once all valid blocks are dumped, the record number will revert to (-1) (LINE72) which triggers the subroutine to stop (LINE 73 and LINE81). An example of the Excel dump is shown in Table 3-20.

Table 3-20: Table of data for each scheduling block dumped from XPAC into Excel.

Mine	Area	Process	Panel	Block #	Record #	Green m	Yellow m	Orange m	Red m	Double Red m	Start Date	End Date	Cum Dist from Shaft	Mining Duration in Block	Total Loads	Loads per Day	Operating Time - Wheels Turning	Utilised Time - Engine On	Loads on Road
Central	NE	DV	IR101	1	6	729.6	0	0	0	0	13/02/2024	4/04/2024	5651	51.072	267.7632	5.242857	1.1302	1.6302	0.356121
Central	NE	DV	IR101	2	7	203.0769	0	0	0	0	4/04/2024	18/04/2024	5651	14.21538	74.52923	5.242857	1.1302	1.6302	0.356121
Central	NE	DV	IR102	1	9	729.6	0	0	0	0	12/06/2025	2/08/2025	6176	51.072	267.7632	5.242857	1.2352	1.7352	0.379059
Central	NE	DV	IR102	2	10	203.0769	0	0	0	0	2/08/2025	16/08/2025	6176	14.21538	74.52923	5.242857	1.2352	1.7352	0.379059
Central	NE	DV	IR103	1	12	729.6	0	0	0	0	24/11/2026	16/01/2027	6701	53.072	267.7632	5.045282	1.3402	1.8402	0.386847
Central	NE	DV	IR103	2	13	203.0769	0	0	0	0	16/01/2027	30/01/2027	6701	14.21538	74.52923	5.242857	1.3402	1.8402	0.401996
Central	NE	DV	IR104	1	15	729.6	0	0	0	0	8/04/2028	29/05/2028	7226	51.072	267.7632	5.242857	1.4452	1.9452	0.424934
Central	NE	DV	IR104	2	16	203.0769	0	0	0	0	29/05/2028	12/06/2028	7226	14.21538	74.52923	5.242857	1.4452	1.9452	0.424934
Central	NE	DV	IR105	1	18	729.6	0	0	0	0	4/08/2029	24/09/2029	7751	51.072	267.7632	5.242857	1.5502	2.0502	0.447871
Central	NE	DV	IR105	2	19	203.0769	0	0	0	0	24/09/2029	8/10/2029	7751	14.21538	74.52923	5.242857	1.5502	2.0502	0.447871
Central	NE	DV	IR106	1	21	729.6	0	0	0	0	15/12/2030	6/02/2031	8276	53.072	267.7632	5.045282	1.6552	2.1552	0.453066
Central	NE	DV	IR106	2	22	203.0769	0	0	0	0	6/02/2031	21/02/2031	8276	14.21538	74.52923	5.242857	1.6552	2.1552	0.470809
Central	NE	DV	IR107	1	24	729.6	0	0	0	0	9/05/2032	29/06/2032	8801	51.072	267.7632	5.242857	1.7602	2.2602	0.493746
Central	NE	DV	IR107	2	25	203.0769	0	0	0	0	29/06/2032	14/07/2032	8801	14.21538	74.52923	5.242857	1.7602	2.2602	0.493746
Central	NE	DV	IR108	1	27	729.6	0	0	0	0	21/08/2033	11/10/2033	9326	51.072	267.7632	5.242857	1.8652	2.3652	0.516684
Central	NE	DV	IR108	2	28	203.0769	0	0	0	0	11/10/2033	26/10/2033	9326	14.21538	74.52923	5.242857	1.8652	2.3652	0.516684

3.4.5.2 Additional Manipulation and Reporting

In Table 3-20 the key logistics variables for each scheduling block exist over a date range. To build this output table for the large generic database with five domains takes 18 minutes. To study the effect of the combined logistics outputs (cumulative distance, loads per day, loads on road etc.) these variables must be summed daily for each production panel. For example, consider the loads per day, for a given day, for the longwall, development panels 1, 2 and 3 is 5, 7, 13, 8 loads per day respectively. The daily total loads per day is 33 loads per day. Daily numbers are critical for understanding logistics strain; therefore, the dump must be split down into daily figures so that the accumulation of logistics KPIs can be undertaken. This is achieved using the Excel VBA macro as shown below: -

```
Sub RunDaily2()

Application.ScreenUpdating = False
k = 2
i = 2
'read in first and last date for the line
Worksheets("ExportData").Activate
dDay = Application.WorksheetFunction.RoundDown(Cells(i, 12), 0) ' this rounds up to almost midnight
' to minimise adjacent block crossover on a particular day: And dDay <
' Worksheets("ExportData").Cells(k, 13) find the last date
Do Until Cells(i, 1) = ""
      LastDay = Application.WorksheetFunction.RoundDown(Cells(i, 13), 0)
      'rowstopaste = Application.WorksheetFunction.RoundDown

      rowstopaste = LastDay - 1 - dDay 'prevents double counting of machinery in the same panel
      Range(Cells(i, 1), Cells(i, 20)).Select
      Selection.Copy
      Worksheets("Daily Data").Activate
      Range(Cells(j, 2), Cells(j + rowstopaste, 2)).Select
      ActiveSheet.Paste

      Do Until Cells(j, 2) = ""
              Cells(j, 1) = dDay
              j = j + 1
              dDay = dDay + 1
      Loop
      i = i + 1
      Worksheets("ExportData").Activate
      dDay = Application.WorksheetFunction.RoundDown(Cells(i, 12), 0)
Loop

```

```
30
31
32
33 Worksheets("Daily Data").Activate
34 Columns("A:U").Select
35 ActiveWorkbook.Worksheets("ExportData").Sort.SortFields.Clear
36 ActiveWorkbook.Worksheets("ExportData").Sort.SortFields.Add2 Key:=Range( _
37 "A2:A900000"), SortOn:=xlSortOnValues, Order:=xlAscending, DataOption:= _
38 xlSortNormal
39 With ActiveWorkbook.Worksheets("ExportData").Sort
40     .SetRange Range("A1:U900000")
41     .Header = xlYes
42     .MatchCase = False
43     .Orientation = xlTopToBottom
44     .SortMethod = xlPinYin
45     .Apply
46 End With
47
48
49
50 End Sub
```

The macro works line by line down through the XPAC dump to create a new daily report. Firstly, the scheduling block start, and end dates are rounded back to midnight (LINE 6, LINE 10 respectively) because scheduling blocks will be started through any 24-hour period and therefore on any given day there would otherwise be a risk of double counting logistics KPIs for a single production machine/unit. Each line of the XPAC dump is copied (LINE 14). The duration in days is the number of lines that each line must be pasted to (LINE 13) with each row being a new day within the start and finish dates (LINE 17). The individual days are infilled into the pasted block using the Do Loop in LINEs 20-24. For example, if a development unit operated from 1st March to the 7th of March in a particular scheduling block, the one line from the XPAC dump will be copied and pasted to seven lines, with the first line being 1st March, the second line being 2nd March and so on until the last and seventh line being 7th March. All other data is duplicated for each day. LINEs 33 to 46 sort the entire daily spreadsheet just created by ascending date. An example of the daily report is shown in Table 3-21.

The XPAC dump for the very large generic scheduling database inclusive of NE, NW, SE, SW, and Northeast Extended Domains exports the start and end dates of 13,022 scheduling instances. Out of these instances there are 260,420 individual database variables reported. Once expanded to a daily report, this increases to 228,322 lines of data and 5,023,084 database variables and takes ten minutes to process with the ultrabook computer used in this thesis. The daily report is then pivoted to a sum per day for key logistics indicators, distance from portal, total loads per day and loads on road as a sum per day of all machines/resources.

Table 3-21: Daily logistics report in MS Excel from XPAC dump.

Date	Mine	Area	Process	Panel	Block #	Record #	Green m	Yellow m	Orange m	Red m	Double Red m	Start Date	End Date	Cum Dist from Shaft	Mining Duration in Block	Total Loads	Loads per Day	Operating Time - Wheels Turning	Utilised Time - Engine On	Loads on Road
16/03/2024	Central	NE	DV	IR101	1	6	729.6	0	0	0	0	45335.0421	45386.1141	5651	51.072	267.7632	5.242857	1.1302	1.6302	0.356121
16/03/2024	Central	NE	DV	MG101	34	183	291.7308	0	0	0	0	45355.2361	45368.8502	5955	13.6141	107.0652	7.864286	1.191	1.691	0.554104
16/03/2024	Central	NE	DV	MHNE	22	1503	733.8	0	0	0	0	45320.105	45371.471	1500	51.366	269.3046	5.242857	0.3	0.8	0.174762
17/03/2024	Central	NE	DV	IR101	1	6	729.6	0	0	0	0	45335.0421	45386.1141	5651	51.072	267.7632	5.242857	1.1302	1.6302	0.356121
17/03/2024	Central	NE	DV	MG101	35	184	310.7058	0	0	0	0	45368.8502	45383.3498	6107	14.4996	114.029	7.864286	1.2214	1.7214	0.564066
17/03/2024	Central	NE	DV	MHNE	22	1503	733.8	0	0	0	0	45320.105	45371.471	1500	51.366	269.3046	5.242857	0.3	0.8	0.174762
18/03/2024	Central	NE	DV	IR101	1	6	729.6	0	0	0	0	45335.0421	45386.1141	5651	51.072	267.7632	5.242857	1.1302	1.6302	0.356121
18/03/2024	Central	NE	DV	MG101	35	184	310.7058	0	0	0	0	45368.8502	45383.3498	6107	14.4996	114.029	7.864286	1.2214	1.7214	0.564066
18/03/2024	Central	NE	DV	MHNE	22	1503	733.8	0	0	0	0	45320.105	45371.471	1500	51.366	269.3046	5.242857	0.3	0.8	0.174762
19/03/2024	Central	NE	DV	IR101	1	6	729.6	0	0	0	0	45335.0421	45386.1141	5651	51.072	267.7632	5.242857	1.1302	1.6302	0.356121
19/03/2024	Central	NE	DV	MG101	35	184	310.7058	0	0	0	0	45368.8502	45383.3498	6107	14.4996	114.029	7.864286	1.2214	1.7214	0.564066
19/03/2024	Central	NE	DV	MHNE	22	1503	733.8	0	0	0	0	45320.105	45371.471	1500	51.366	269.3046	5.242857	0.3	0.8	0.174762
20/03/2024	Central	NE	DV	IR101	1	6	729.6	0	0	0	0	45335.0421	45386.1141	5651	51.072	267.7632	5.242857	1.1302	1.6302	0.356121
20/03/2024	Central	NE	DV	MG101	35	184	310.7058	0	0	0	0	45368.8502	45383.3498	6107	14.4996	114.029	7.864286	1.2214	1.7214	0.564066
20/03/2024	Central	NE	DV	MG201	26	859	291.7308	0	0	0	0	45371.471	45385.0851	4739	13.6141	107.0652	7.864286	0.9478	1.4478	0.474413
21/03/2024	Central	NE	DV	IR101	1	6	729.6	0	0	0	0	45335.0421	45386.1141	5651	51.072	267.7632	5.242857	1.1302	1.6302	0.356121

The system for high-speed identification of logistics bottlenecks throughout the entire life of mine daily, whilst not mature, is certainly benchmarked to be able to be built upon as differing demands are identified. It is important to note that once an acceptable schedule has been achieved, sensitivities of speed and/or payload can be achieved without any modification to schedule using L01-L10 and VBA manipulation in around a total of 50 minutes processing time.

3.5 Case-by-Case Isolation and Experimentation

The next phase of the research methodology is to use the system developed in this thesis for high-speed strategic identification of logistics bottlenecks to demonstrate case-by-case isolation of changes to the strategic mine plan. This is done through building cases for varying schedules and changing a single parameter between a new case and its predecessor. By changing a single variable between each case, the impact of a single variable change on logistics strain can be isolated. It is imperative that only a single variable is changed at each step to not "muddy the waters" that two or more variable changes could do. The case-by-case "build" is shown in Figure 3-47 and demonstrates how each case is derived from the previous for isolation of logistics impact to properly be evaluated.

As can be seen the case build is a tree structure with arrows from preceding cases and with a single variable change between each case. The case build can be summarised in Table 3-22.

Whilst most of these cases in Table 3-22 and Figure 3-47 are self-explanatory important cases within the build should be elaborated upon. For this purpose, Cases 1, 2, 3, 4, 5 and 6 will be explained in more detail. The remaining cases will be discussed further in Chapter 4.

Table 3-22: Case build highlighting isolators studied (note mpw = metres per week).

CASE	Predecessor	Comment	Case Isolator
1	NIL	Homogeneous Primary Support and Baseline Development Rate, 4 domains. Each successive LW is on the other side of Mains, Central Shaft	BASE CASE
2	1	Case 1 + Extended NE domain	Impact of NE Extended domain including a step change in distance from portals
3	2	Case 2: With variable primary support	Variable primary supports and development rates
4	3	Case 3 + change in path stay on same side of Mains then return.	Impact of faster advancement away from the portal as only one side of the Mains is extracted by LW at a time
5	4	Case 4 + Additonal Inbye Shaft as well as central shaft	Impact on Logistics by adding portals closer to workings faces as the pit progresses
6	4	Case 4 + only NE and NE Extended Domain	Domain extension to replicate Adit / Box Cut / Cut and Cover Mine
7	6	Case 6 + Faster Speeds	Impact of Speed variance
8	7	Case 7 + Increase Payload	Impact of Payload variance
9	6	Case 6 + Reduction in delivery window	Change to intensity of deliveries
11	6	Case 6 + Dev headline rate of 220mpw	Change to intensity with change to development rate

Figure 3-47: Case build utilising system for high-speed identification of logistics bottlenecks.

3.5.1 Case 1 (Base Case): Migration Away and Return to a Central Portal

Case 1 or the Base Case is to understand the most simplified mine schedule to replicate the migration away and return to a central portal as an extension of Design 1 and is shown in Figure 3-48. The impact of the number of development units is simplified with only entering and exiting the schedule as development inventory in advance needs to be built or retracted. There are also only two development rates which are baseline green support rates for gateroads and mains headings only to understand the impact of migration away from the portal. Case 1 comprises only four AREAS/Domains Northeast, Northwest, Southeast and Southwest and are extracted in this order. Within each AREA/Domain development and longwall progression is incrementally moving from one side of the mains to the other, slowly advancing out to the end of domain. This requires the longwall to be rehanded, where the tailgate and maingate drives, and the beam stage loader are reversed and therefore a set of these for each "hand" are required for each longwall change out.

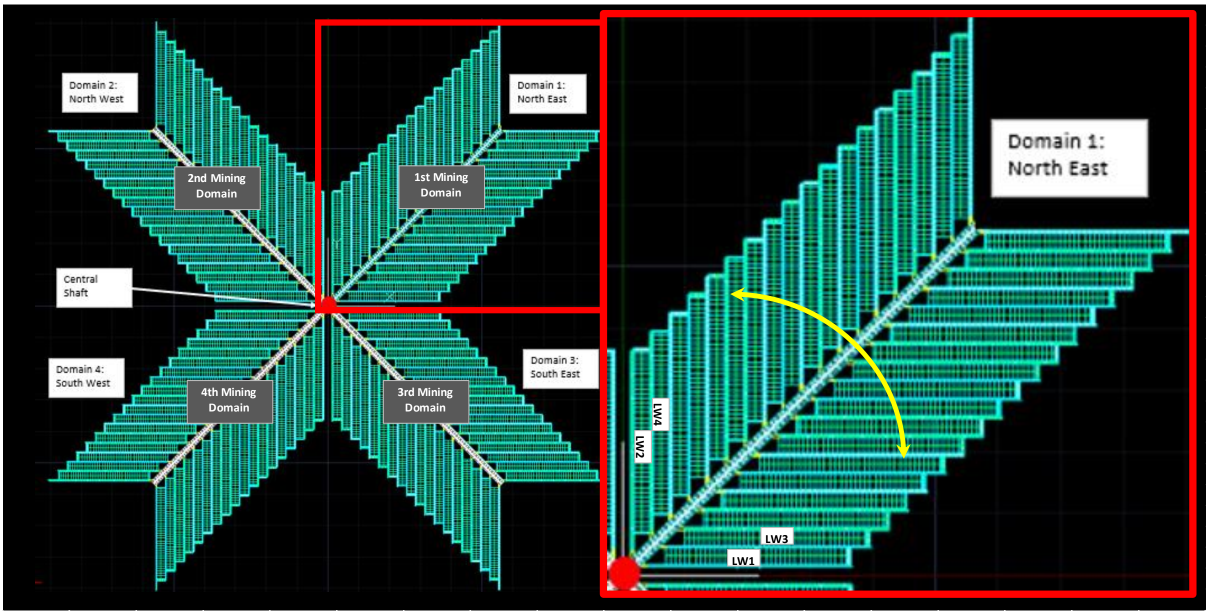


Figure 3-48: Case 1 progression of AREA/Domains and longwall progression within the AREA/Domain.

3.5.2 Case 2: Extended Domain Introduction

Case 2 has no changes to rate nor sequences. Rather it incorporates the Northeast Extension Domain to allow the study of exhausted reserves nearby a portal and the operation must then step away. Case 2 is shown in Figure 3-49 with the inclusion of the additional step away 5th Mining domain.

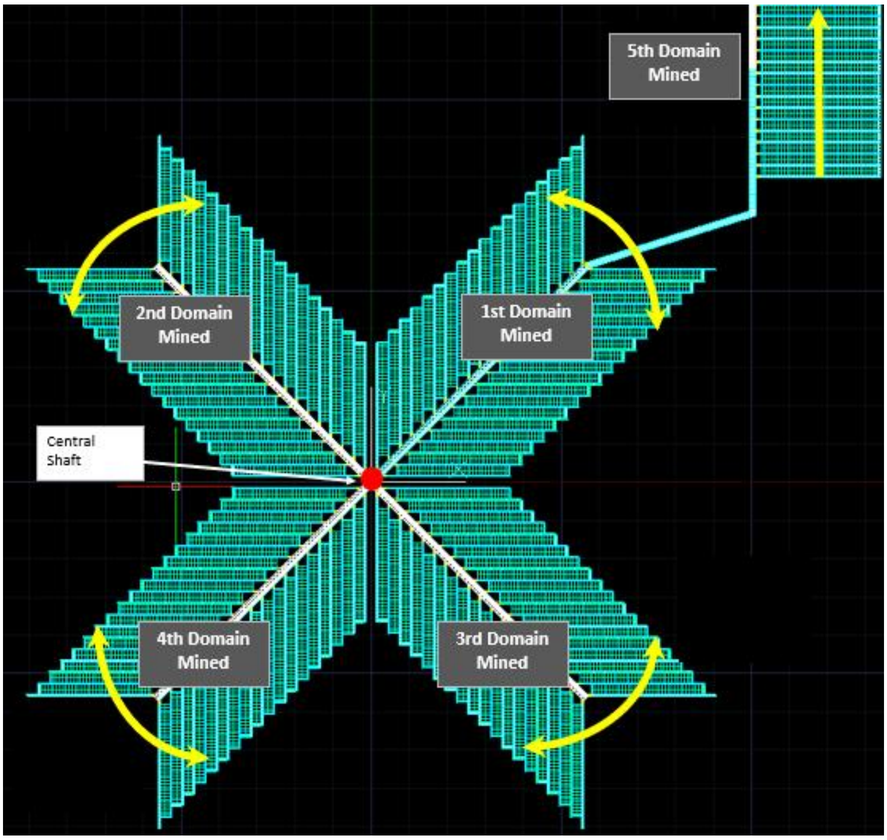


Figure 3-49: Case 2 Progression of AREA/Domains

3.5.3 Case 3: Varying Primary Support and Rate. Case 4: Impact of Sequence

Both Case 3 and Case 4 introduce variable support and rates as discussed in Section 3.4.1.3 and summarised in Table 3-7. Case 4 builds on from Case 3 by changing the mining sequence. Rather than rehanding the longwall each time, Case 4 progresses down one side of the mains and then returns and progresses down the other side. Rehanding a longwall from side to side apart for the second set of longwall equipment, defers the rate of mains advance and therefore should increase NPV for the operation as associated costs of mains advance are deferred. The first thought for Cases 1,2, and 3 is that compared to Case 4 they are closer to the portals for a longer period and therefore defer logistics strain, but what is the ramification of this deferral later into the schedule? Figure 3-50 shows the difference in advance between Case 3 and Case 4 within the Northeast AREA/Domain. There is no change to sequencing in NE_EXT AREA/Domain as all longwalls are on one side of the mains.

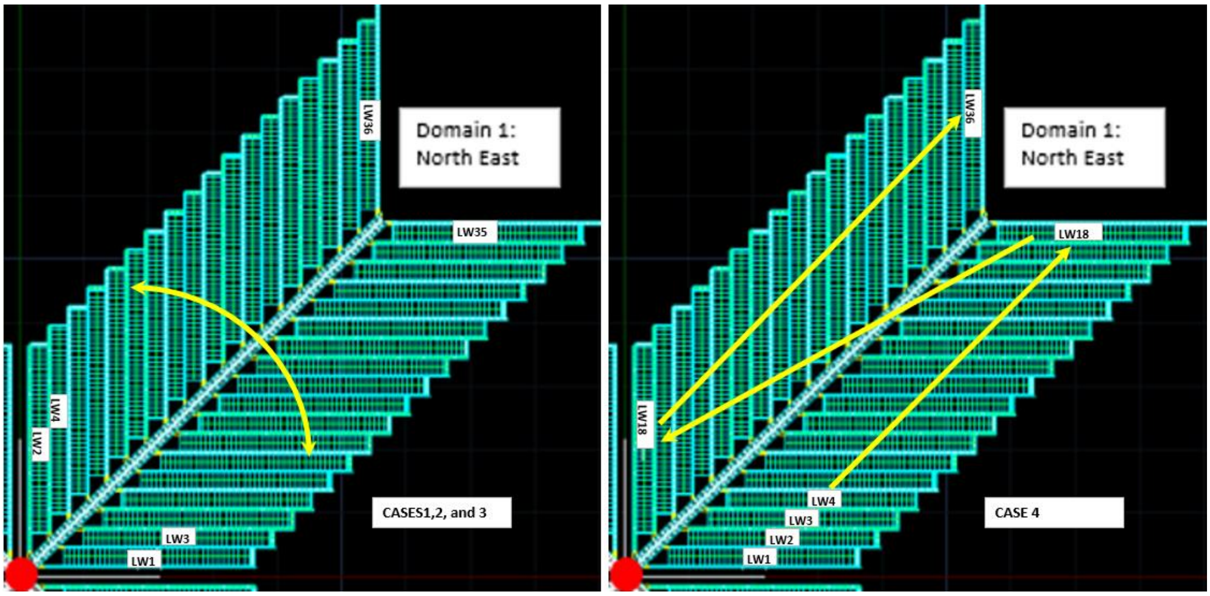


Figure 3-50: The comparison of sequencing between Cases 1,2 and 3 (left) and Case 4 (right)

3.5.3.1 Case 5: Additional Portal Infrastructure

Case 5 has no change to Case 4 with respect to scheduling. Using the subroutines L01-L10, new mid-mains shafts are introduced into the mine. These are to demonstrate the impact of closer portals on logistics strain because cumulative distance is reset with the commissioning of the inbye shaft. These shaft locations are shown in Figure 3-51: -

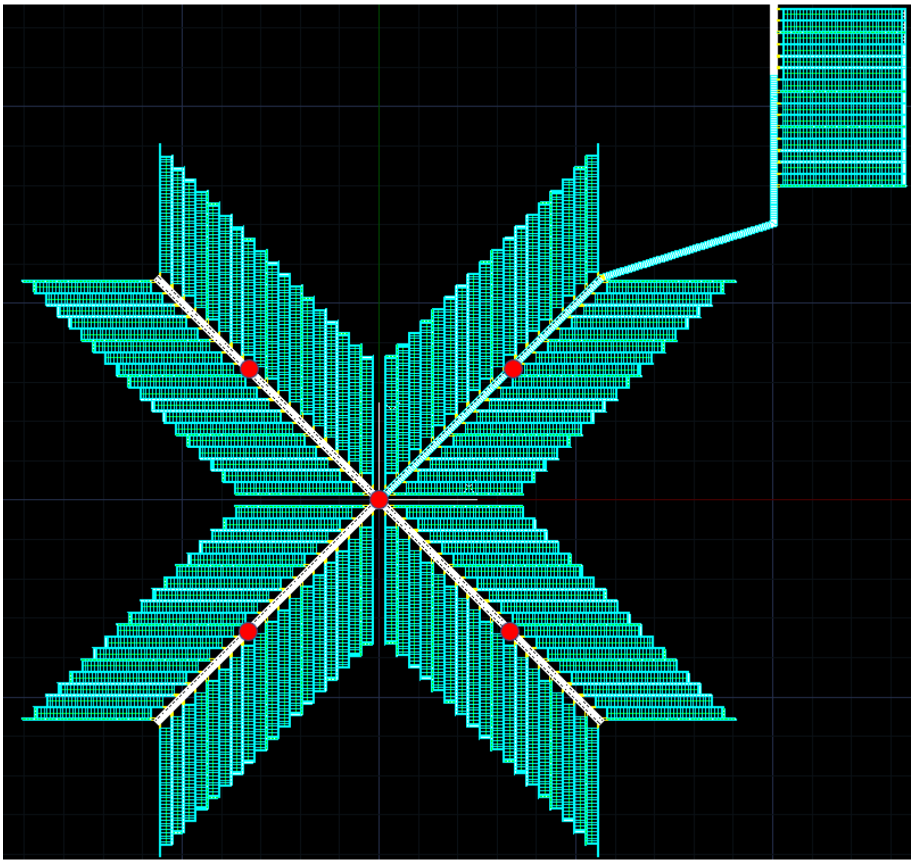


Figure 3-51: Shaft locations for Case 5.

3.5.4 Case 6: Adit / Box Cut / Cut and Cover Mine

Case 6 focusses on AREA/Domains NE and NE_EXT, which are extracted consecutively without the remaining domains. It allows more detailed changes to logistics strain that may be lost in the larger mine schedules. It is designed to replicate the adit / box cut / cut and cover mine design impacts on logistics strain. Case 6 is the basis for Case 7 to Case 11 and schedule progression is illustrated in Figure 3-52:-

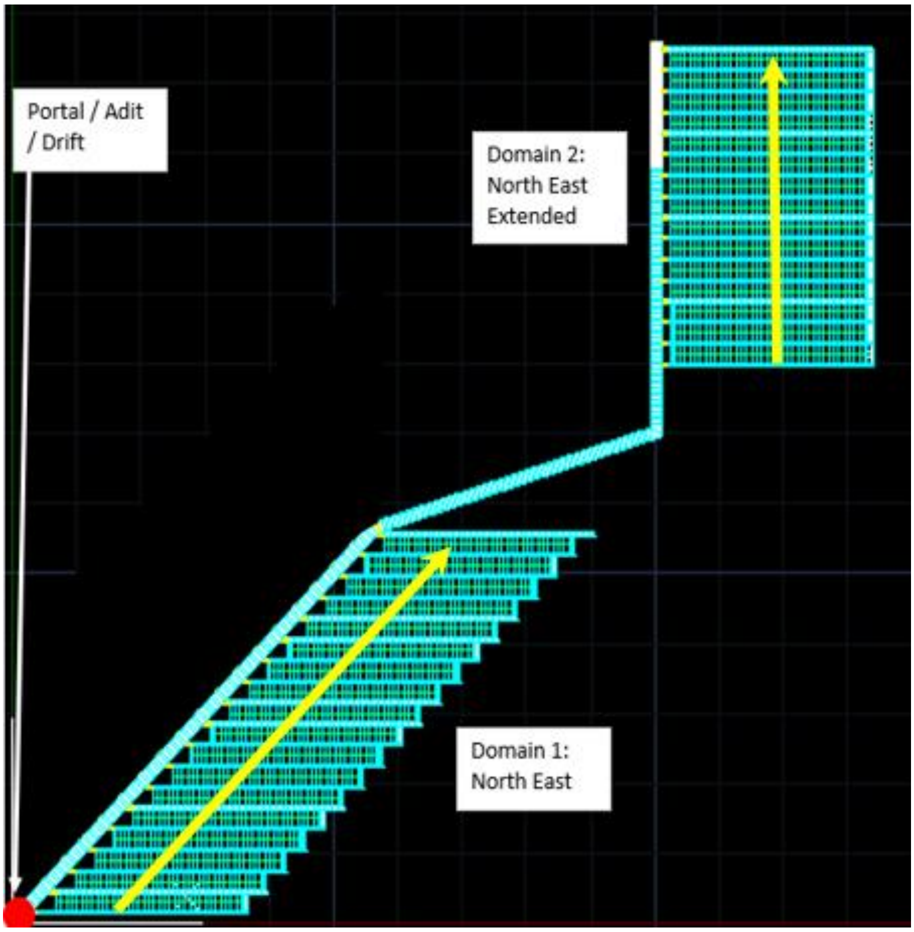


Figure 3-52: Cases 6 – 11 schedule sequencing.

3.6 The Tactical Identification Phase – FlexSim

XPAC is employed at a macroscopic level to understand trends and shifts in logistics strain for a timeframe up to the entire LoM. However, on a day-to-day basis XPAC cannot at a very detailed level provide information to analyse if logistics strain can be alleviated through finer adjustments. Finer adjustments that can be identified and rectified, have the potential to transform and alleviate logistics strain back at a strategic level by taking these adjustments and changing baseline strategic assumptions within the XPAC model. This cyclical relationship is demonstrated in Figure 3-53 where a problematic trend in logistics strain is identified within XPAC, a specific day is identified within XPAC and the face positions, deliveries required, and the number of delivery LHDs available are transferred into FlexSim. FlexSim enables closer examination of the travel path, and potentially allows planners to address superfluous delays which can reduce cycle time and be subsequently transferred back up to XPAC to recalibrate the model.

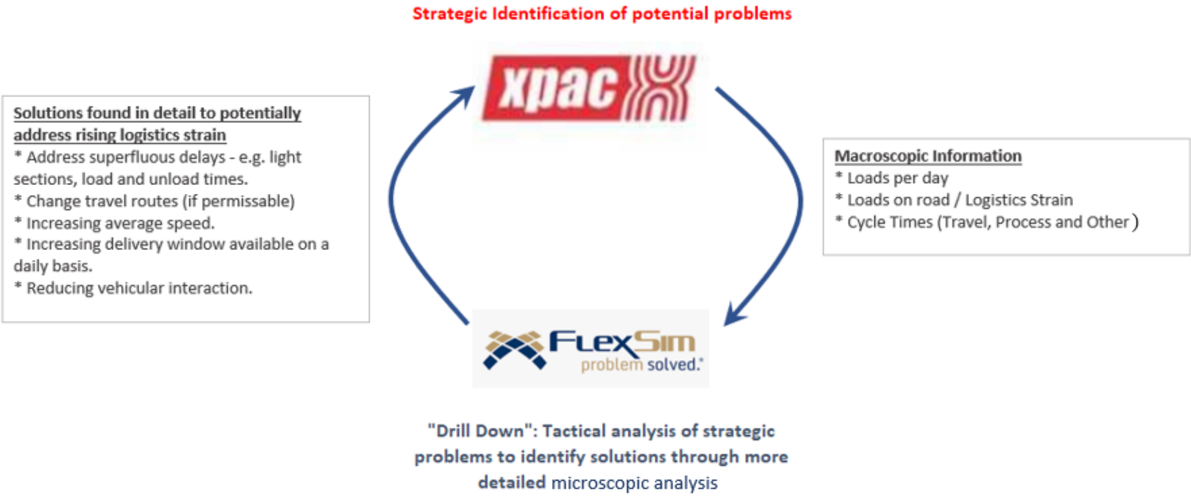


Figure 3-53: The cyclical relationship between the use of XPAC and FlexSim

The XPAC and FlexSim software for the purposes of this thesis can be employed in four ways. Firstly identification, secondly confirmation, thirdly alleviation and lastly verification. Up until now logistics breaking strain has relied on a consultative approach with a key stakeholder such as the mining logistics department, FlexSim allows the planner to independently assess the impact of logistics strain on an operation well before a problem is realised.

3.6.1 Identification

FlexSim can be employed to identify a logistics problem, in doing so the planner can see if the productivity rates can be achieved. Identification of logistics breaking strain is difficult if there is insufficient data of logistics performance especially when the operation is in either pre-construction or early execution stages or phases. There may also be an absence of expertise, particularly in “value proposition project phases” to be able to provide a feel for what is an acceptable threshold for logistics breaking strain.

For example, a mine plan has large distances between domains and does not have approval to install portals inbye. The mine has productivities that have been assigned nominal rates. FlexSim in this circumstance can prove if there is a risk to being able to achieve these productivities based on the loads required to be delivered on a peak day highlighted by XPAC within the plan.

3.6.2 Confirmation

FlexSim can be used to confirm the threshold of logistics breaking strain. The mining logistics department may, in this example, be only thinking of the logistics system within its current parameters or may simply be wrong in what the logistics breaking strain threshold for that the operation ought to be. Simulation in this case can either increase total operation value if the logistics breaking strain has been conservatively estimated (too low in reality), leading to undervaluing of the project. The project can also be overvalued by aggressively overestimating the logistics breaking strain by being too impractical. Therefore, FlexSim is a useful tool for key stakeholders to visually understand vehicular interaction for anecdotal estimation of logistics breaking strain.

For example, 15 years after commencing operations, a new domain has been designed in the annual life of mine plan. It is looking likely that the "Loads on road" required to meet projected productivity is 6.5. After consultation with the mining logistics department and senior mine management there is an impasse between them with the mining logistics department stating they can only achieve five "Loads on road" and the senior mine management stating that eight loads on road is feasible. FlexSim allows visualisation of solutions through analysing 'what if' scenarios, and after the application of several of these it is found that concrete roads, lighting, and heavy haulage mean that six loads on road is the logistics breaking strain, meaning a: -

- Benchmarking of a more efficient logistics system.
- Earlier and typically cheaper changes to the mine plan rather than retrospective or reactive changes.
- Buy-in from two opposing key stakeholders.
- A smaller downgrade in value than if the mining logistics department had capped the plan but more reflective of reality.

3.6.3 Alleviation

FlexSim, as previously discussed, can be used to alleviate logistics strain as already discussed in the example above by "drilling down" into the day-to-day detail where XPAC cannot. Short-term spikes may be discovered in the 12-week rolling average loads on road that are above the logistics breaking strain threshold. Whilst individual days can often be managed on a week-to-week basis by building materials inventories prior to the spike, it is very unlikely that a 12-week rolling average above logistics breaking strain would have the storage capacity in the panel to meet planned production for such a long period of time.

For example, logistics breaking strain has been identified to be six loads on road. Three development units in yellow support and a longwall have an estimated loads on road of seven for a period of 14 weeks and then reduces to four thereafter. In the first instance XPAC could change the input paths of the machines or stand down some development for that time if longwall float allows it, or the development units are redeployed to another area that requires less loads on road. FlexSim provides the option that can be used to reduce loads on road through exploring alternative solutions such as examining delays due to pedestrian or vehicle interaction or opportunities such as fewer light sections, more dedicated roadways, and priority access between supply vehicles and other vehicles.

3.6.4 Verification

XPAC and FlexSim are completely independent applications. The XPAC model can therefore be verified by replication in FlexSim for specific time stamps noted in XPAC. Once a particular day within the XPAC schedule is singled out it will output three unique KPIs, the distance from the portal, the "loads per day" (deliveries per day) and the "loads on road" (machines operating underground). FlexSim through simulation of that specific day will then, through inputs of speeds and varying the number of delivery LHDs, be able to determine the number of deliveries each production panel receives and give a visual representation of movements throughout that day.

For example, on a specific day within the XPAC strategic schedule the deliveries per day are 40 deliveries spread between:

- 13 deliveries in MG102.
- 13 deliveries in MG103.

- Six deliveries in LW101.
- and six deliveries required in the mains headings.

XPAC also outputs based on 10 km/hr maximum speed and a 15-minute load and 15-minute unload time that 6.5 delivery LHDs (loads on road) are required to operate throughout that day. The face positions are input into FlexSim as are the machine speed and delay parameters, as well as the proportion of deliveries to each panel. A FlexSim simulation is then run for a 24-hour period with nominally six delivery LHDs available. This results in the following deliveries:

- 12 deliveries in MG102.
- 13 deliveries in MG103.
- Five deliveries in LW101.
- and six deliveries required in the mains headings.

Therefore six “loads on road” delivery LHDs operating in that specific day’s 24-hour window will fail to deliver the quota required for MG102, and LW101 meaning that if only six delivery LHDs are available and there is no inventory management from a previous stockpile of supplies in the panel for such an event, logistics breaking strain will occur because the panel will run out of supplies for the planned development rate of the day.

Now if another FlexSim simulation is then run for a 24-hour period with nominally seven delivery LHDs available. This results in the following deliveries:

- 13 deliveries in MG102.
- 14 deliveries in MG103.
- Six deliveries in LW101.
- and six deliveries required in the mains headings.

All the loads per the daily quota are satisfied, which in turn verifies the XPAC model prediction of 6.5 loads on road.

3.6.5 <u>FlexSim Inputs</u>

To study the above, XPAC will output peak points within the life of mine schedule that are perceived as an executable risk, as an instant in time of a specific day. An instant in the LoM schedule from XPAC is replicated in FlexSim as shown in Figure 3-54.

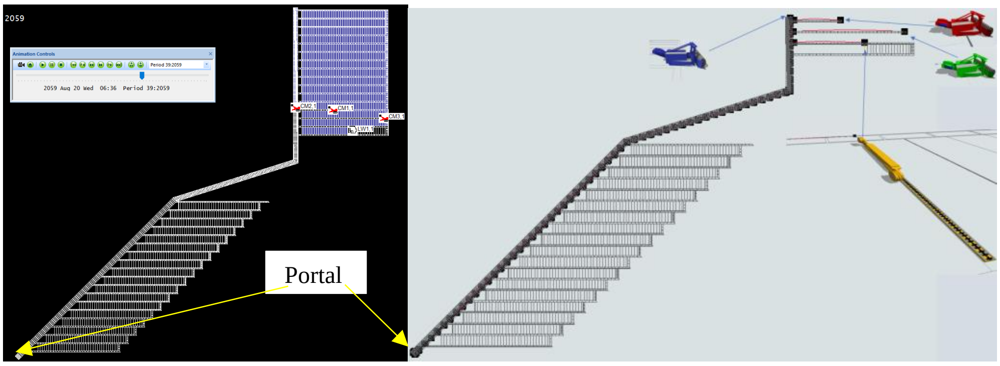


Figure 3-54: Production face positions determined to be a peak day from XPAC (left) are replicated in FlexSim (right).

In FlexSim, delivery LHDs must acquire the load at the portal, travel from there to the productive face, unload and then return to the portal. Speeds, acceleration, loading times, vehicle interaction are all required inputs.

3.6.5.1 Loads

Loads are assumed to have been previously delivered to the bottom of the portal / pit bottom area prior to the start of that day. This ensures there are no delays to delivery from surface to pit bottom which would delay the transport of the load and is outside the scope of this thesis but identified as another potential bottleneck for future analysis. The loads are created in FlexSim and are colour coded to reflect the machine they are designated to be delivered to with red for CM1, blue for CM2, green for CM3 and yellow for longwall. The pit bottom area in FlexSim is shown in Figure 3-55:

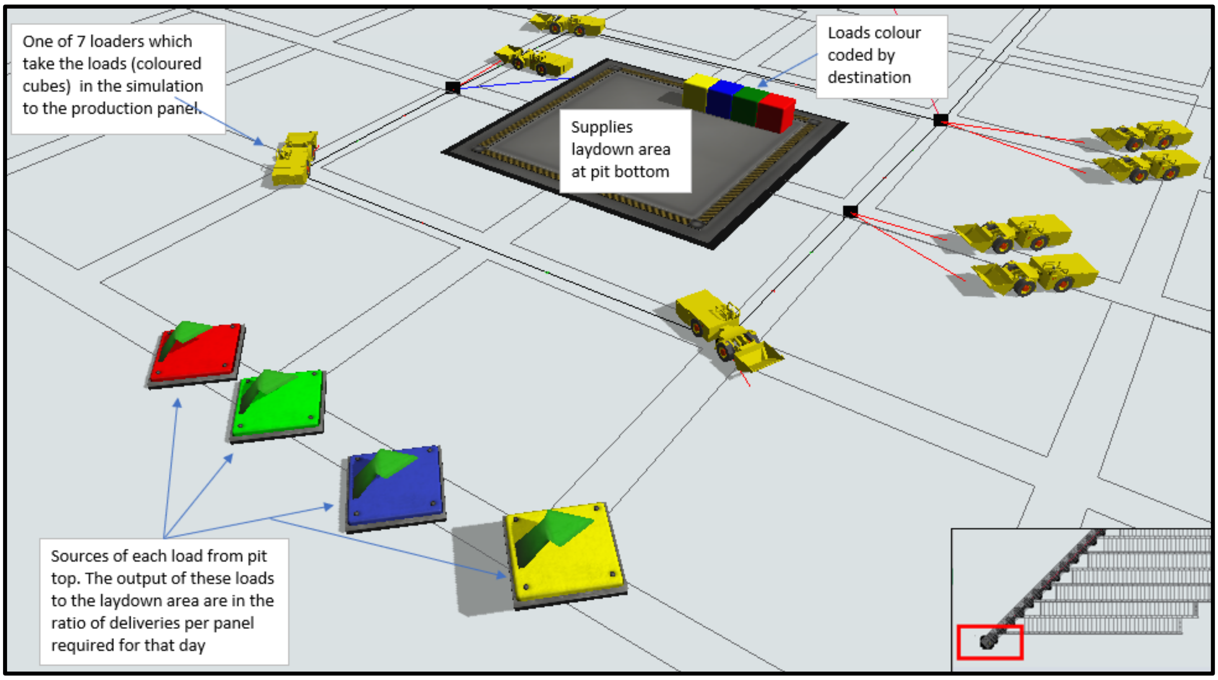


Figure 3-55: Pit Bottom Supplies laydown area. Colours of loads and sources of each load reflect their destination.

Each load per panel delivered is based upon the ratio of deliveries required for that panel and is determined by the primary support for each panel on that day and therefore is variable but can be either calculated manually for each productive unit's geographic position and corresponding expected geotechnical regime or given through schedule output reports. For example, if deliveries per panel on this day are MG102 at 13, MG103 at 13, LW101 at six and mains headings at six deliveries, the ratio of delivery is 2.17, 2.17, 1, and 1, meaning that for every load that is delivered to pit bottom ready for transport for the longwall, a mains headings load is delivered, and 2.17 loads are delivered to pit bottom for both MG102 and MG103.

3.6.5.2 LHDs

The LHDs take the colour coded loads to their respective production panel. The LHD key inputs are consistent with XPAC LHD parameters but with finer detail including acceleration and deceleration and using normal distribution for load and unload times ranges to reflect better on reality. The initial key inputs for each LHD are:

- Capacity = one load one per trip from the portal to the productive face and return.
- Maximum speed = 10 km/hr or 2.78 m/s.

- Acceleration and deceleration = 0.5 m/s^2 or 5.56 seconds to reach 10 km/hr.
- Load and unload times = normal distribution with a mean of 900 seconds and a standard deviation of 200 seconds.

These key inputs are entered in the FlexSim menu shown in Figure 3-56.

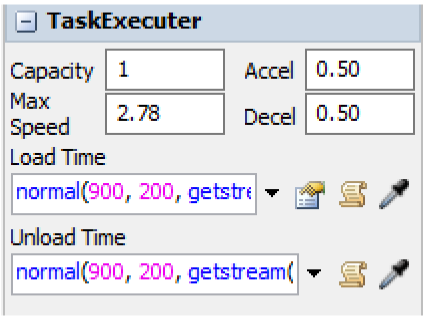


Figure 3-56: The LHD key inputs menu in FlexSim. Speed is in m/s and acceleration is in m/s^2.

It is important to note that the above parameters can be changed when addressing an occurrence of logistics breaking strain by changing the speed, the number of loads, or the time to load and unload if evidence exists that current or planned infrastructure can do so. Each mine will be able to obtain these parameters through time-motion studies, but lighting and concreting will affect speed and issues arising such as operator competence or pit bottom layout will affect load and unload time variability on a mine by mine (or even crew by crew) basis.

3.6.5.3 Vehicular Interaction and Traffic Control

Traffic control is set up to either prevent vehicle interactions in a section of roadway or to set a flow direction for traffic such as areas which are one way. There are three major scenarios where traffic control is set up over the delivery route, which are mains headings, gateroads and controlling direction of flow of traffic.

In main headings, LHD operators will shunt out of the way if oncoming lights are seen, and therefore only one LHD could occupy a section of road at any given time whilst the other LHD would shunt into a cut through and wait for the machine already in the section to pass. In the FlexSim simulations in this thesis, if a single transport route using a single roadway has been applied then the first machine to occupy the controlled section receives right of way status and the other machine must wait and shunt. Figure 3-57 highlights the application of traffic control to enforce no passing along the roadway with shunting occurring every four pillars which would simulate a conservative recognition of a LHD in the section and time to shunt. Shorter sections may underestimate the delay to shunt, and longer sections may block the road for too long a time and overestimate delay for each LHD and provide a pessimistic view of total average cycle time.

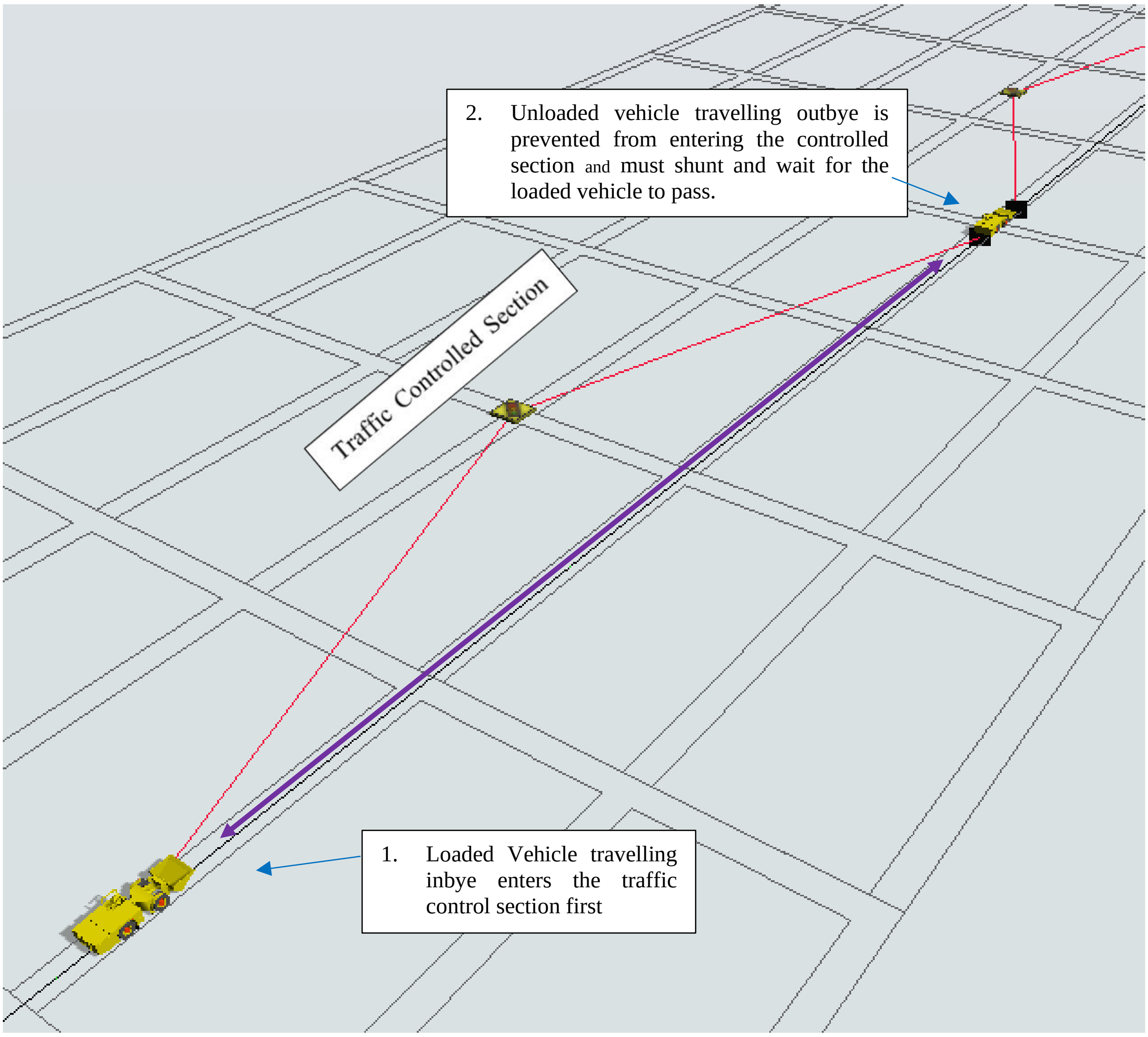


Figure 3-57:Traffic control preventing passing in roadways and forcing vehicles to give way and shunt.

In FlexSim, a traffic-controlled section is signalled by a traffic light symbol. The physical extent of the section is bound by two black travel network nodes along the roadway which are connected to the traffic light symbol using a RED object connection line as shown in Figure 3-58.

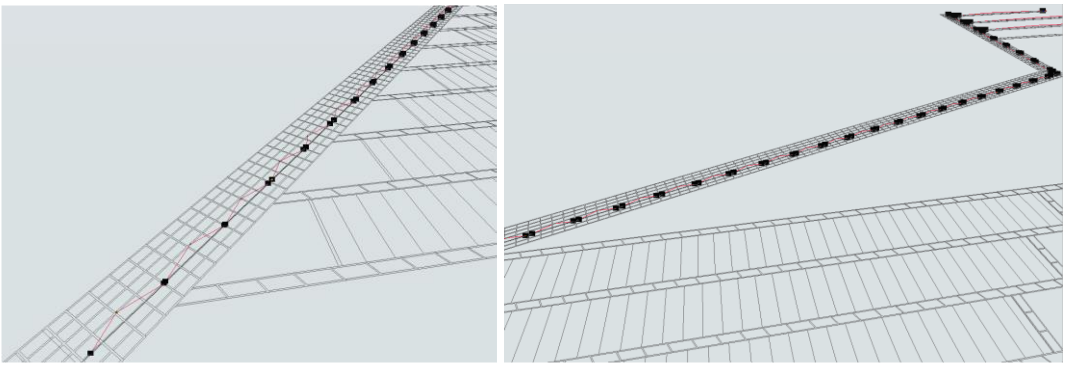


Figure 3-58: Traffic control sections connected by red object connection lines for outbye (left) and inbye(right) mains that define multiple traffic-controlled sections limiting passing t^o every ^4th pillar.

Adjacent network nodes which are not connected are designated passing shunt areas.

Recalling from Section 3.3.2, ventilation is limited to a single large delivery LHD for development. Therefore, unlike mains, a single traffic-controlled section is defined from gateroad entrance through to the continuous miner which prevents more than one unit from travelling down a gateroad in the same ventilation circuit and breaching diesel particulate matter threshold limit values. If there was a convoy of two units then the second unit would wait at cut through # 1 until the delivery unit exited the panel or shutdown whilst unloading inbye as shown in Figure 3-59.

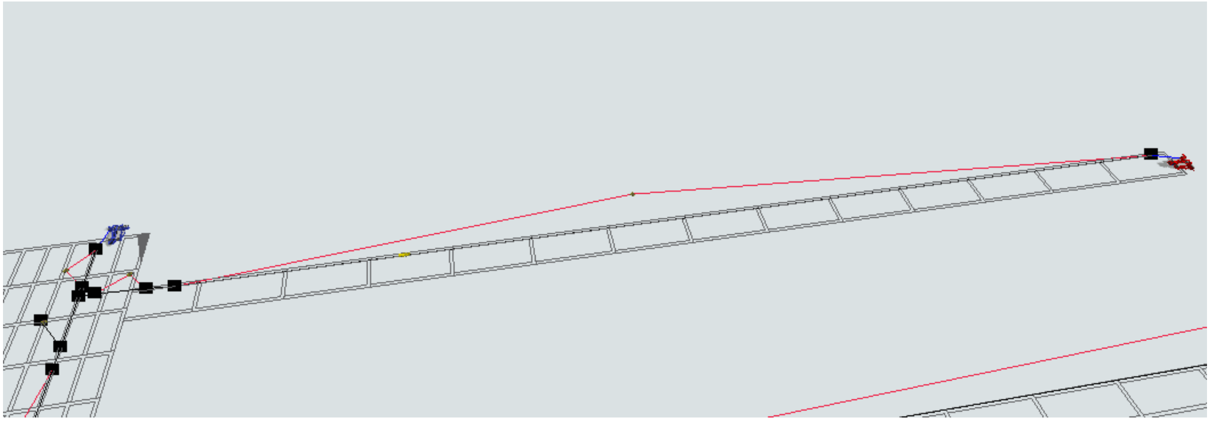


Figure 3-59: A single gateroad traffic control section to allow only one large diesel delivery LHD to travel down it.

Traffic can be controlled to only travel in a single direction in certain circumstances such as travelling around pit bottom or when utilising a dedicated inbye and outbye travel road. Controlling direction of flow will mostly prevent vehicle shunting as no passing of inbye and outbye vehicles occurs. Single direction roadways are shown in Figure 3-60 with a green arrow showing the direction of forced travel and a red arrow showing the impassable direction.

3.6.5.4 Interference of Other Machines

Depending on the scenario, other machines such as faster personnel transport (Driftrunners, etc) during shift change or other itinerant vehicles can be encountered during the delivery cycle of a supply machine. The philosophy adopted in this thesis is consistent with mines visited and is that these other vehicles give the delivery LHD priority and that deliveries during this period follow in the incoming shift and shunt for the outgoing shift leading to minimal interruption. A FlexSim case has been studied in Chapter 4 where the impact of interaction during shift change has been considered by reducing the window of operating times for delivery vehicles for single travel/ haulage roads. Inbye and outbye one-way travel roads would see significantly less delay due to interaction except for LHDs needing to shunt if a faster personnel transport wishes to overtake.

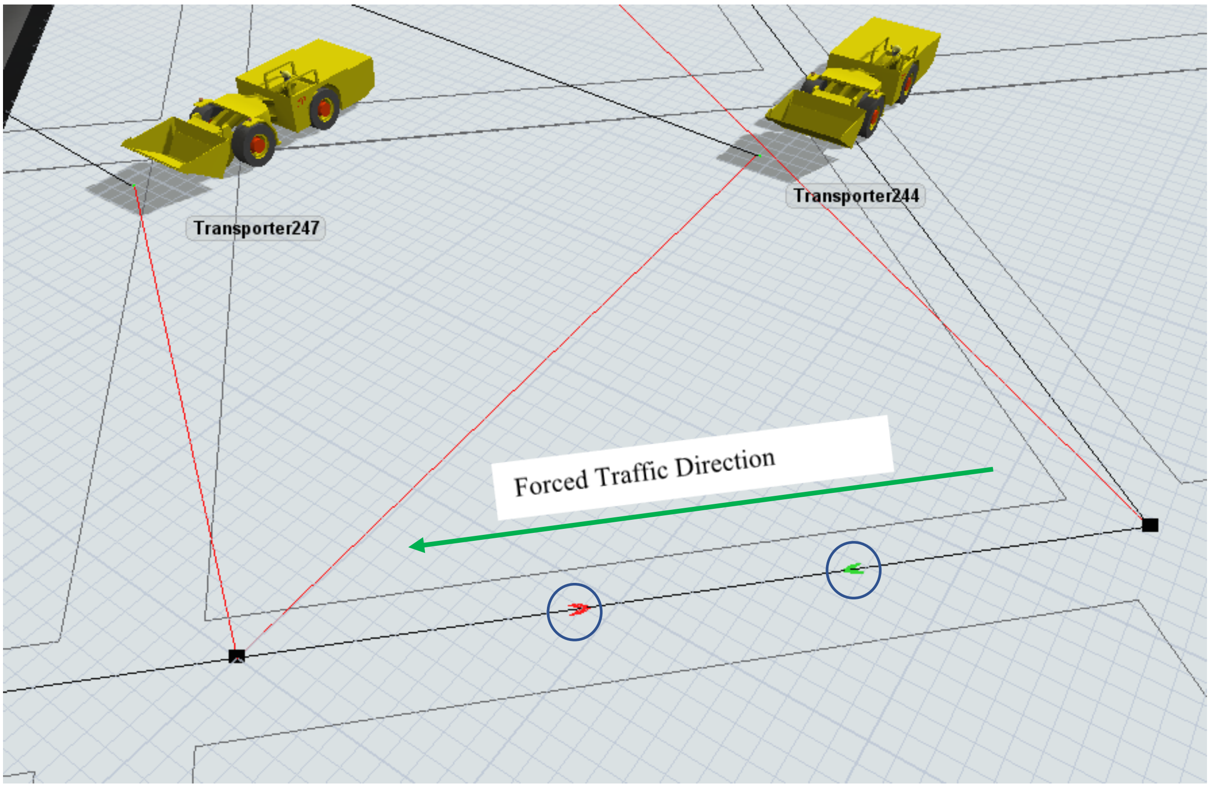


Figure 3-60: Traffic direction. A red arrow means you cannot travel in that direction. (LHD = Transporter in FlexSim)

3.7 Chapter Conclusion

This thesis has developed a system to attempt to identify early logistics bottlenecks and therefore give the mine planner the best opportunity to proactively address unacceptable logistics strain. This system will allow speedy sensitivity analysis to either remove or defer logistics breaking strain. In the case that neither deferral or removal of logistics breaking strain can occur, the system is able to identify the cap and schedules are run that are downgraded and will reflect the future reality. This allows the planner and strategic decision makers to understand the revised value of the mine plan that will closer reflect reality.

The second phase of this thesis is the setup of the application using this system. Multiple mine plans, schedules, productivities, and logistic variables have been set up for analysis. These have been done using a "case build" where a single variable is changed between cases to isolate incremental changes in logistics strain impacts. The experimentation of the model and its detailed outcomes are discussed in Chapter 4.

Chapter 4

RESULTS AND DISCUSSION

4.1 Introduction

To understand the logistics strain upon a strategic mine plan, multiple scenarios within Chapter 3 had been identified. Each case as shown in Figure 4-1 has a single variable change built on from the case before to isolate the logistics impact. This was done to confirm the hypothesis of logistics strain over time raised in Chapter 1 by evaluating the impact on logistics strain:

- With migration away and return to a portal.
- If a new domain that has a large step around migrating away from the portal.
- If migration away from a portal in a general direction from an adit/box cut/ cut and cover mine.
- With variability of primary support.
- With changes to machine path philosophy.
- With additional portal/shafts closer to the productive faces as the mine progresses.
- With higher speeds.
- With larger delivery payloads.
- With higher productivity of development units.
- If delivery windows of time were restricted.

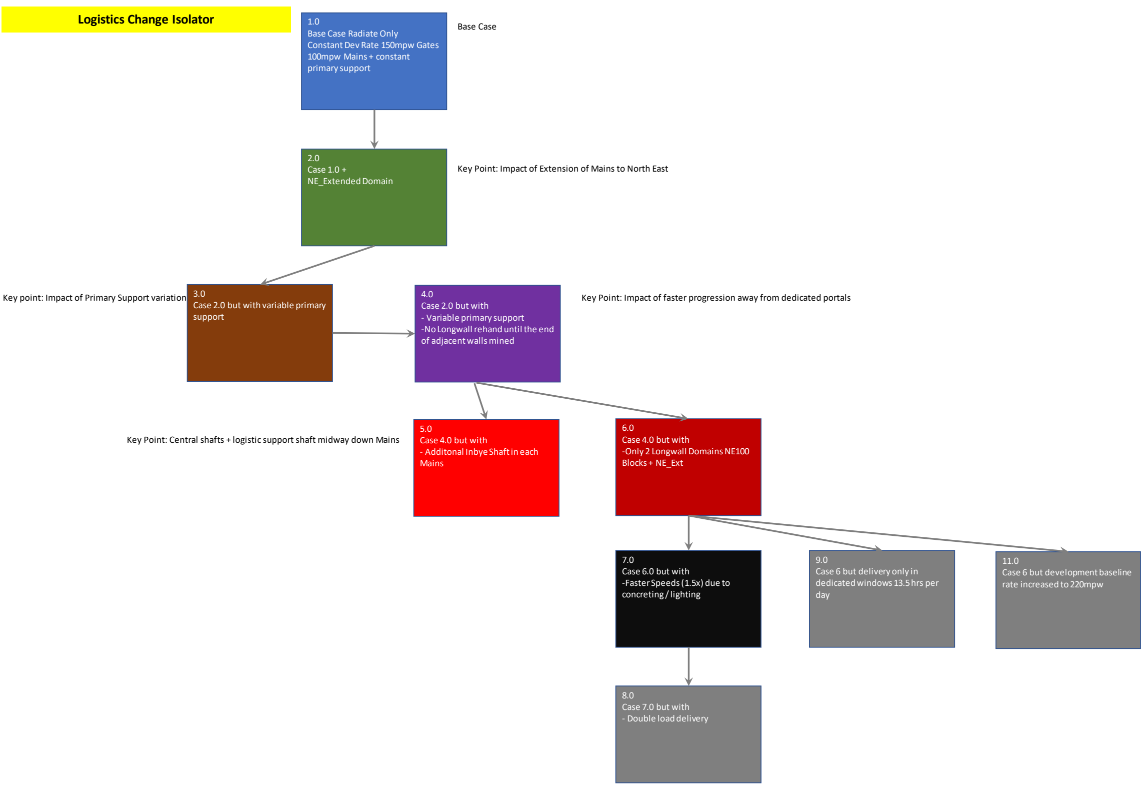


Figure 4-1: Reminder Figure 3-47 (page 116). Case build utilising system for high-speed identification of logistics bottlenecks.

In this chapter each case will be presented with a suite of standard figures and graphs. Some of the cases have no change to a particular KPI and therefore such a graph if there is no benefit to present this may be removed and only be commented upon. For any case that has a different schedule a period plot (as shown in Figure 4-2) is presented. This will show the timing of each scheduling block and when it is mined according to the schedule. This will show the general path of the schedule and the rate of progress through the schedule. The colour schemes for period ranges are consistent across all cases.

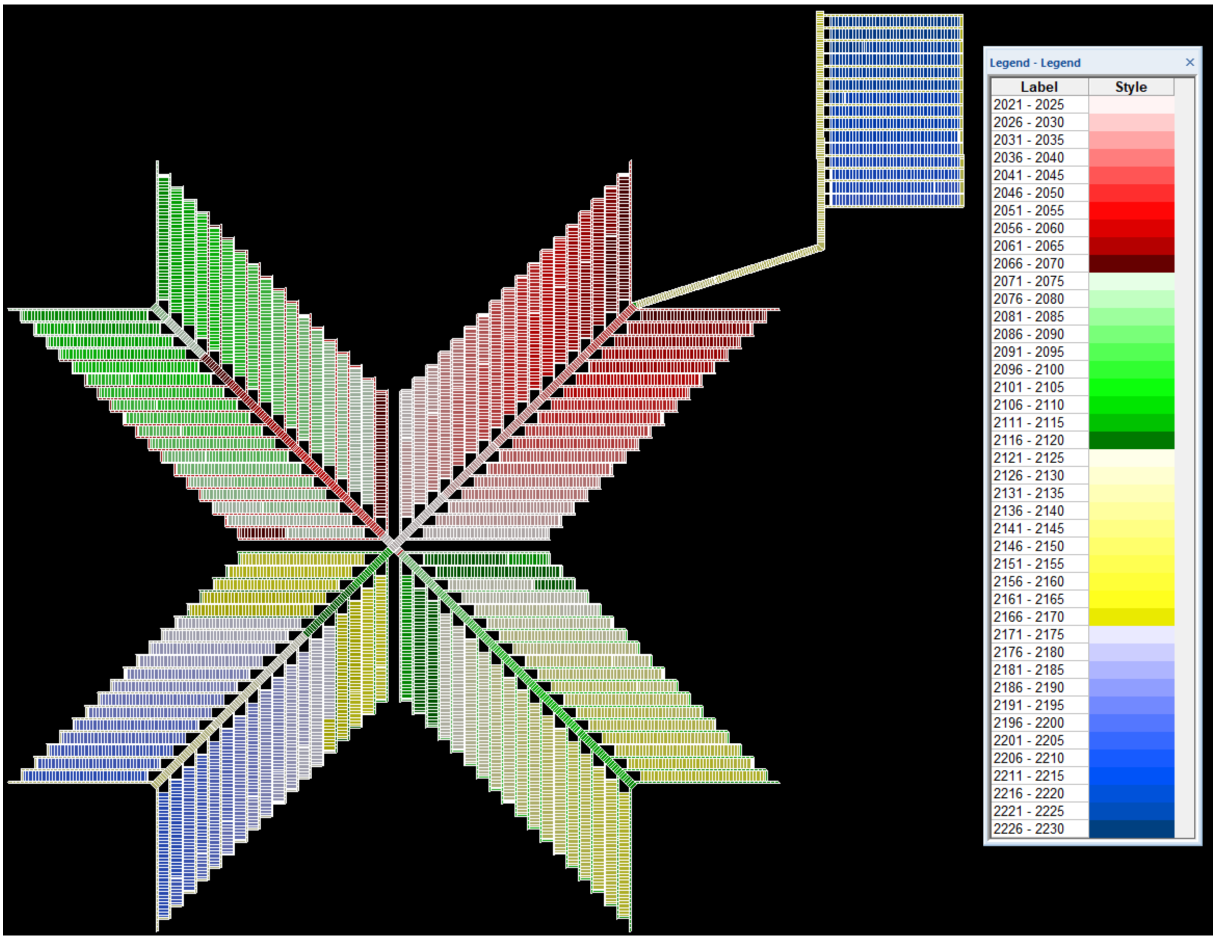


Figure 4-2: Period plot.

Four graphs are typically presented for each case. Except for the base case (Case 1) there is a comparison of the previous case (in grey) that the presented case (red, purple, or orange depending on the metric) has been built upon. Combined distance point data in Figure 4-3 is the first graph shown. Combined distance is the additional of each productive unit's distance from the portal to the productive face on any given day within the entire schedule.

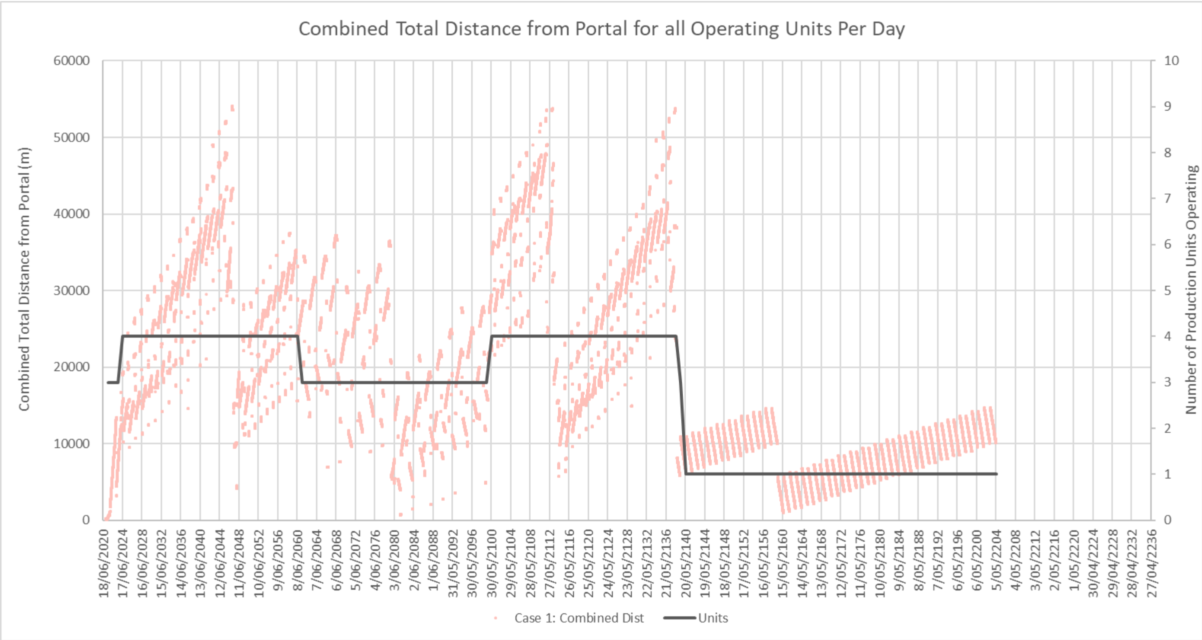


Figure 4-3: Combined distance point data

As peaks and troughs can be managed and smoothed the second graph is the 12-week (84-day) rolling average which is considered the likely peak and trough for an operation if some form of logistics planning were to take place as shown in Figure 4-4.

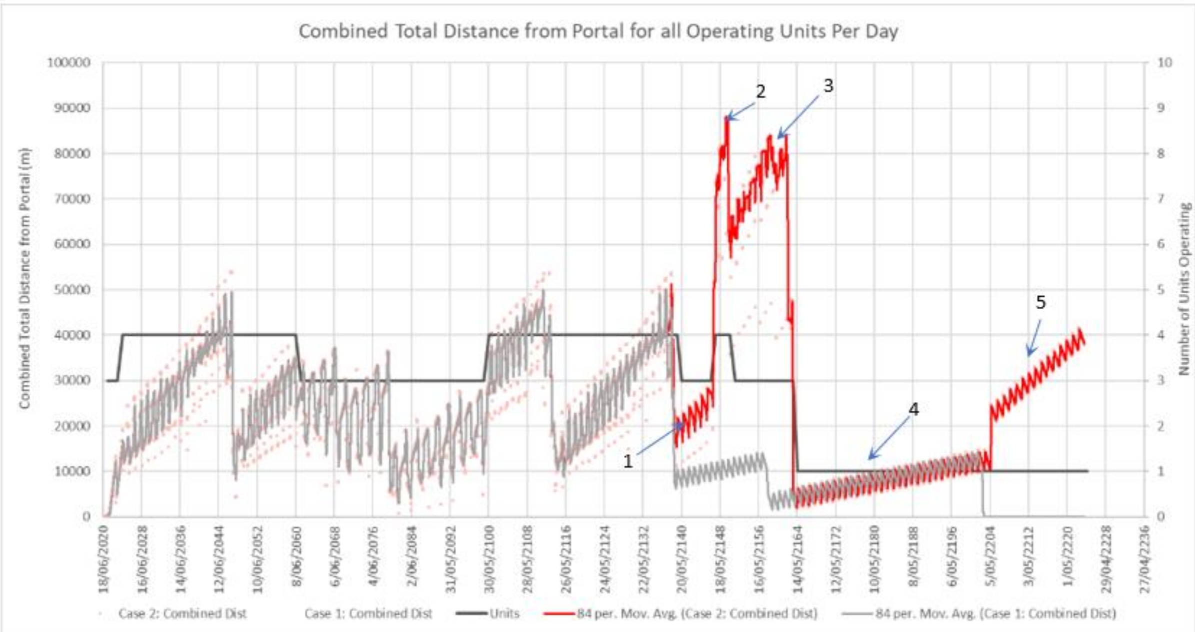


Figure 4-4: Current vs previous case 12-week rolling average for combined distance with key milestones

Key milestones may be highlighted on these graphs to explain differences between cases. These milestones may be explained using comparison status plots of the schedule as shown in Figure 4-5. Blue signifies what is left to be mined whereas transparent/black is what has previously been mined for now in the schedule.

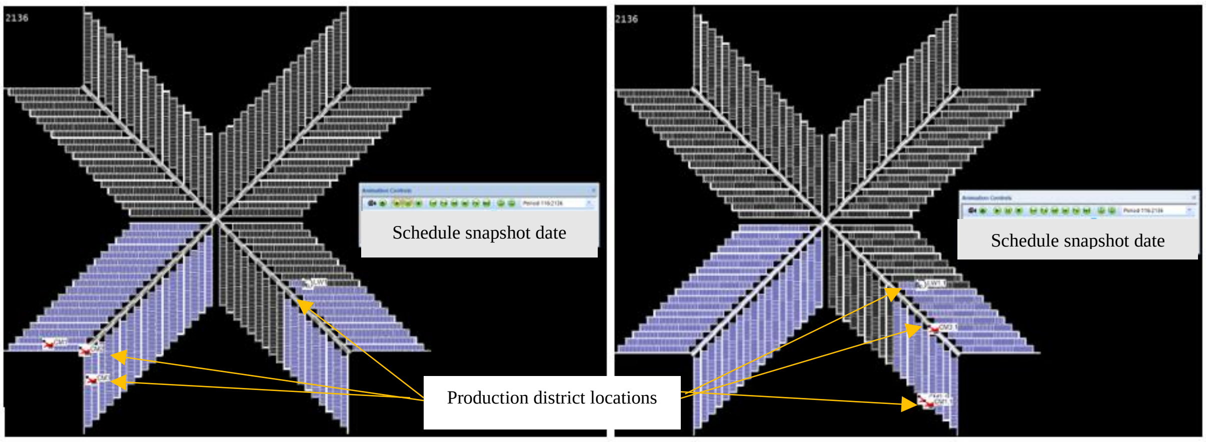


Figure 4-5: Current vs previous case status plots that correspond to milestones on graphs to assist in explaining changes.

Whilst status plots can be used on any of the suite of graphs, they are usually utilised to explain combined distance graph changes between cases as schedule changes are reflective of combined distance and are most easily explained with a status plot.

Loads per day is the next graph and includes a 12-week rolling average, and individual point data and the previous case for comparison purposes. It is the combined number of deliveries for all productive panels per day. Loads per day is independent of distance from the portal and is only concerned with the materials that are required per day to not interrupt the productive activity. Loads per day should be considered as how many times a delivery machine delivers to the laydown area for the productive panels and therefore if a machine is capable of a double payload, then loads per day will be halved.

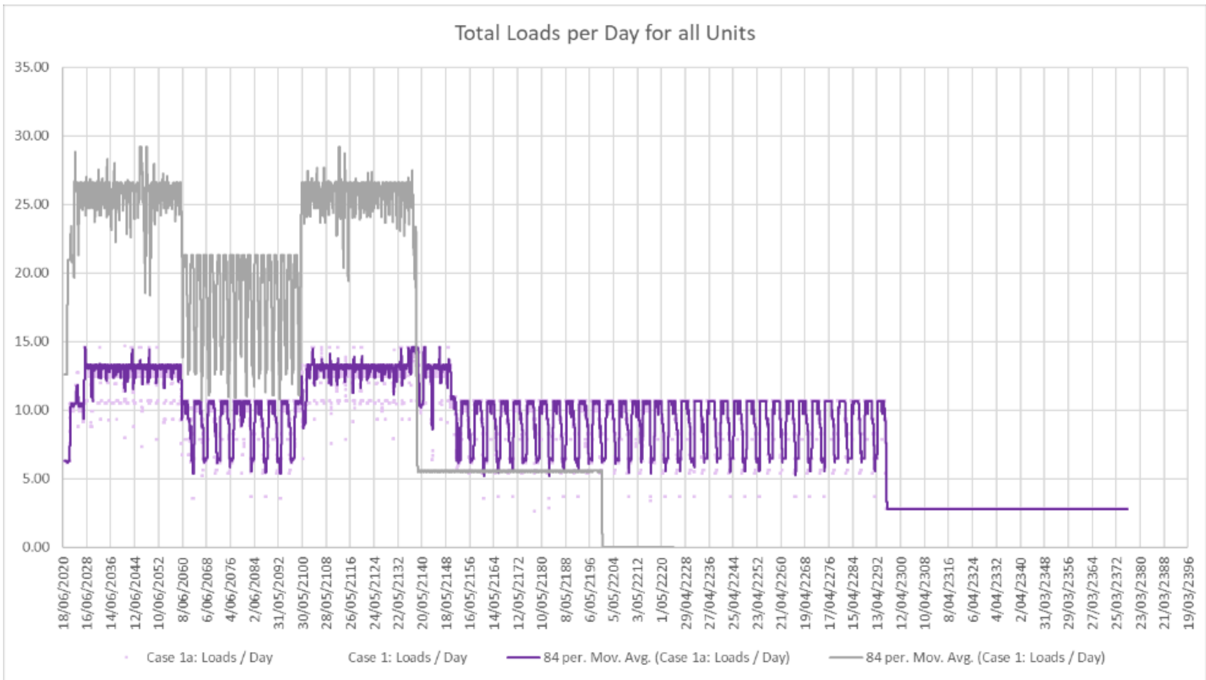


Figure 4-6: Loads per day

Loads on road is a colloquial term to mean how many delivery machines are on the road at any given instant. Unlike combined distance and loads per day that are important components of logistics strain, loads on road is the combined effect of these and is the most accurate reflection of logistics strain at a strategic level. Therefore, the term is interchanged with logistics strain or sometimes "loads on road / logistics strain". It is very important to note that loads on road includes both loaded and returning units.

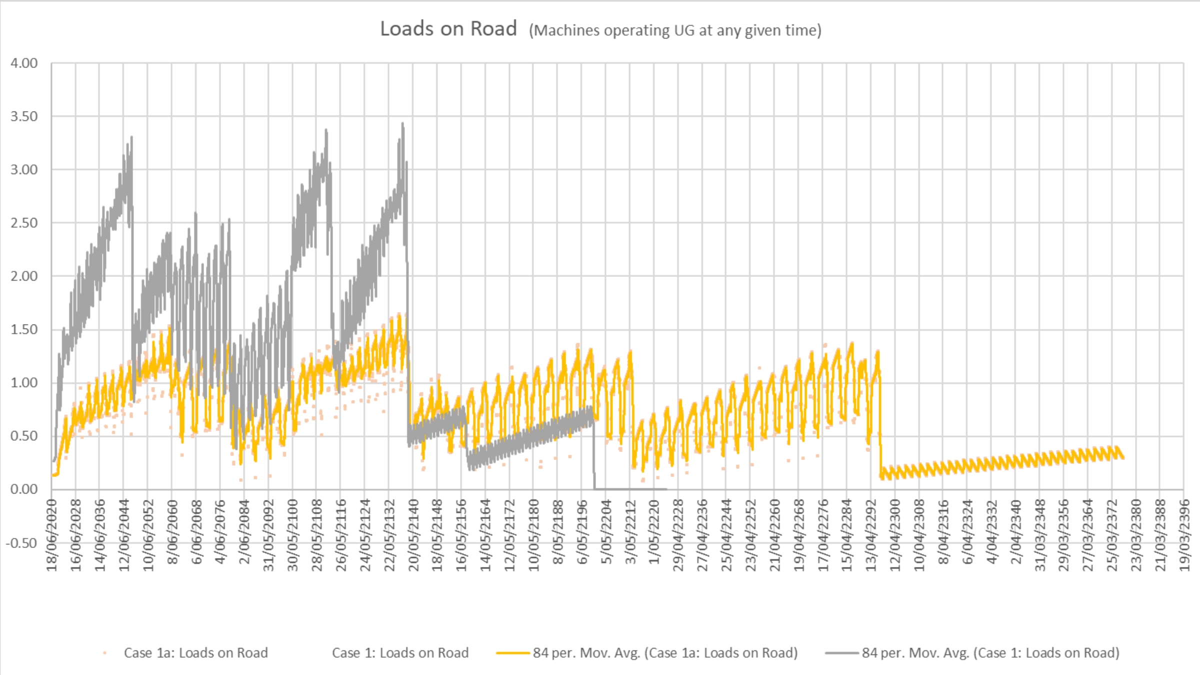


Figure 4-7: Current vs previous case loads on road / logistics strain.

Loads on road is designed to be the reality checker where the mine planner can have a conversation with management or the mining logistics department, who are also known as the manager of supplies to the productive faces for the reality check that the actual mine plan is achievable from a logistics perspective.

The following standardised colour scheme is used for consistency across all cases for the graphs presented: -

- Red data points: Current case daily point data of combined distance to the portal.
- Red solid line: 84-day / 12-week moving average of the combined distance to the portal.
- Black line in combined distance charts: Number of productive units that time.
- Purple data points: Current case daily point data of total loads per day.
- Purple solid line: 84-day / 12-week rolling average of the total loads per day.
- Orange data points: Current case daily point data of loads on road. Loads on road is also the combined indicator of logistics strain.
- Orange solid line: 84-day / 12-week rolling average of the total loads on road / logistics strain.
- Grey Solid Line: Previous comparison case 84-day / 12-week rolling average of the respective indicator of either combined distance, loads per day or loads on road.

4.2 Case 1 – Radiate away from portal and return constant productivity

This is the base case where development is set to 100 metres per week for development in main headings and 150 metres per week in gateroads with the longwall retreating at 60 linear metres per week. The period plot for Case 1 is shown in Figure 4-8. It shows the rehanding of longwalls each side of the mains for each of them. When a domain is completed the next new domain back closer to the shaft is developed and extracted.

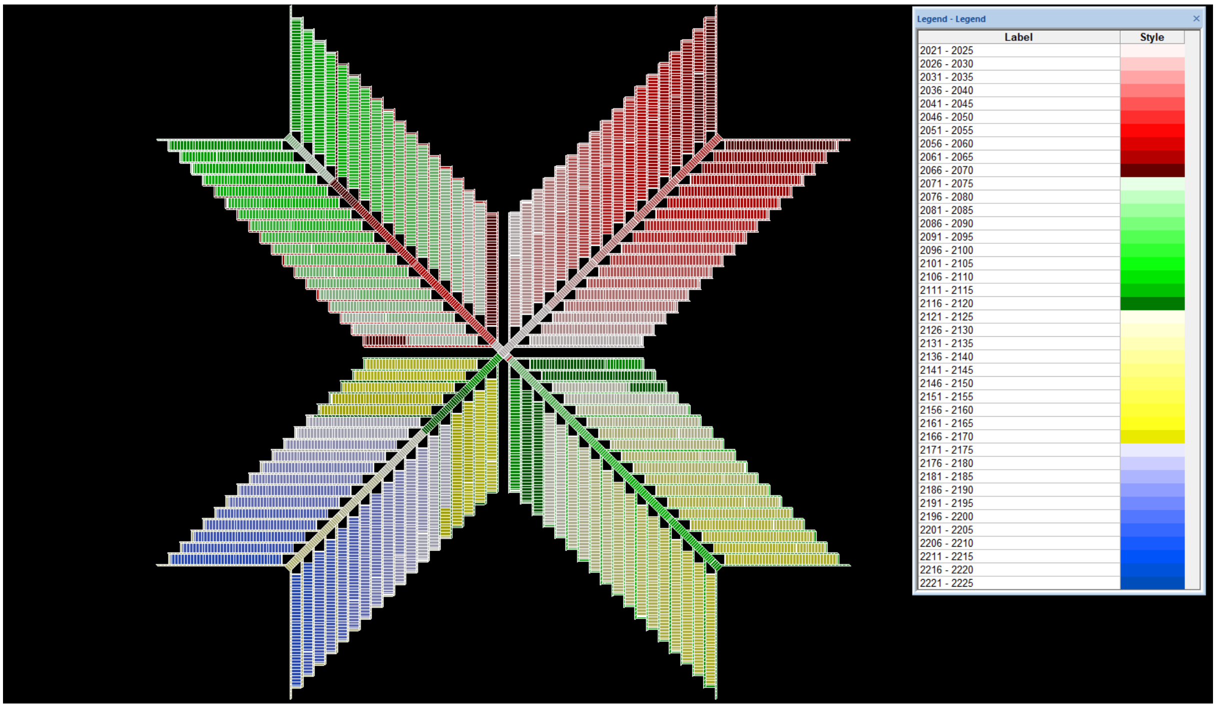


Figure 4-8: Period plot of Case 1

The duration of the Case 1 schedule is 184 years with each domain taking slightly over 40 years each. As can be seen the longwall must rehand from one side of the mains to the other meaning that reaching the outer extremities of the longwall domain is deferred. The case includes three development units and the longwall operation requiring supply. Between the years 2061 and 2100, a development unit is dropped as development inventory is sufficiently ahead to sustain longwall operations with two development units operating during this time.

4.2.1 Combined Distance

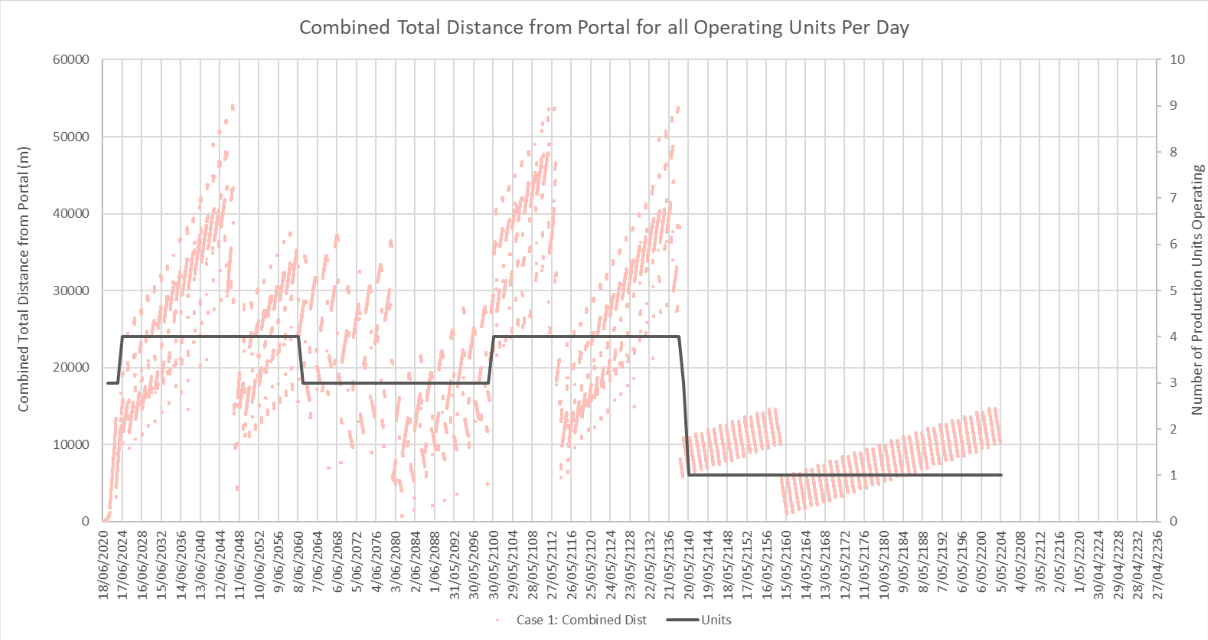


Figure 4-9 : Case 1 daily combined total distance from the portal (red point data) for all productive units

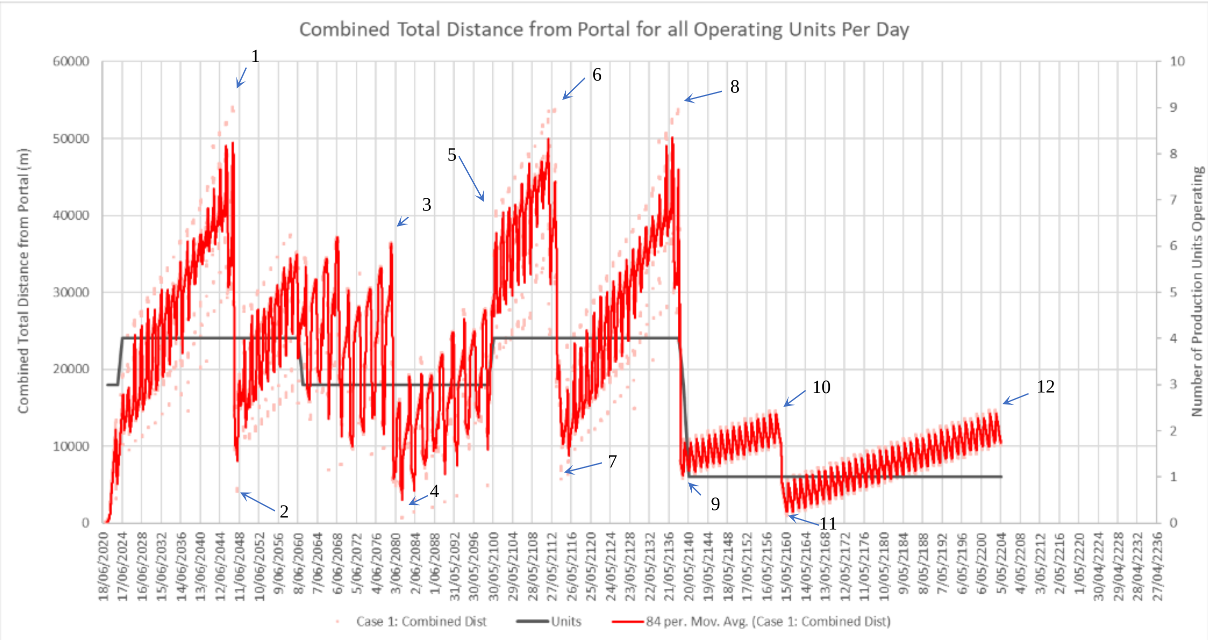


Figure 4-10: Case 1 daily combined total distance from portal for all productive units (in red) with a 12-week rolling average trendline and key milestones.

Figure 4-9 monitors the combined distance from each productive face to the portal daily (point data) and the number of units operating each day. Figure 4-10 includes the 12-week rolling average of the daily combined distance. As can be seen from 2140 onwards the combined distance falls. This signals development has been completed for this schedule leaving only the longwall in need of supply. Distance maxima and minima have been highlighted. These milestones are examined against the schedule timeline.

MILESTONE 1 MAXIMA. The Quarter 1 2047 milestone is illustrated in the schedule status in Figure 4-11. It represents a peak in logistics strain for this case. As can be seen all the productive units are at a combined maximum distance from the central supply portal. This does not mean that all the development units and longwall are at their maximum distance, rather the combination of each individual distance from the portal is at a maximum distance. In this case it is when the longwall is just beyond halfway through the Northeast Domain at LW110 and close to the start line, or the most inbye position and therefore furthest away from the portal for that longwall panel. CMs 1 and 2 are at the extremities of the Northeast Domain (MG218 and MG118 respectively) and CM3 is relatively close to the portal in NW domain tailgate.

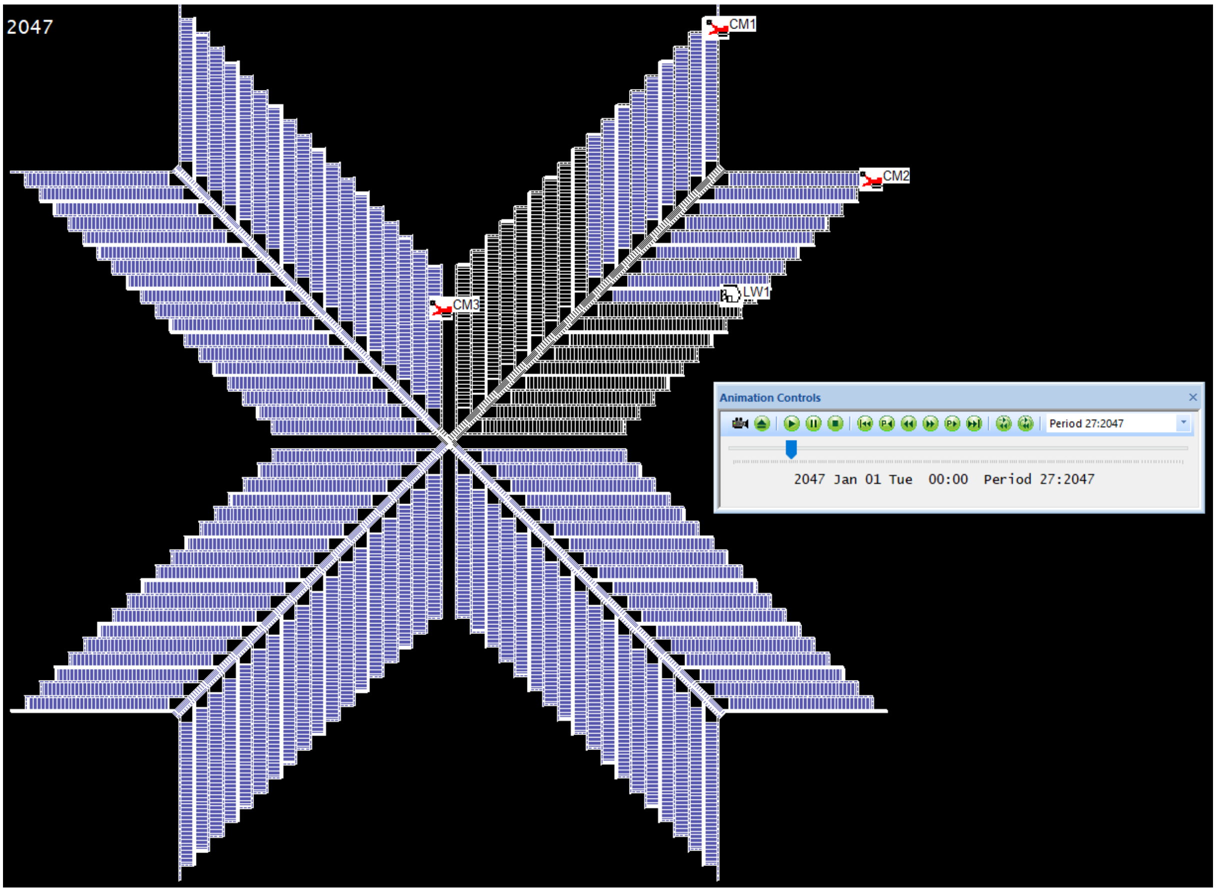


Figure 4-11: Schedule status for Milestone 1 in Quarter 1 2047 for Case 1.

MILESTONE 2 MINIMA. In Quarter 4 2047, shown in Figure 4-12, the longwall is completing LW110 and is therefore closer to the portal compared to Milestone 1. CMs 1, 2 and 3 are all very close to the portal in the NW domain. This is an important confirmation of Figure 1-3 in Chapter 1 of logistics strain with the migration away and return hypothesis as shown in Figure 4-13. As can be seen between Milestone 1 and Milestone 2 there is a collective migration away and return to the central portal but importantly not every productive unit has to be at their maximum or minimum distance for each milestone to occur.

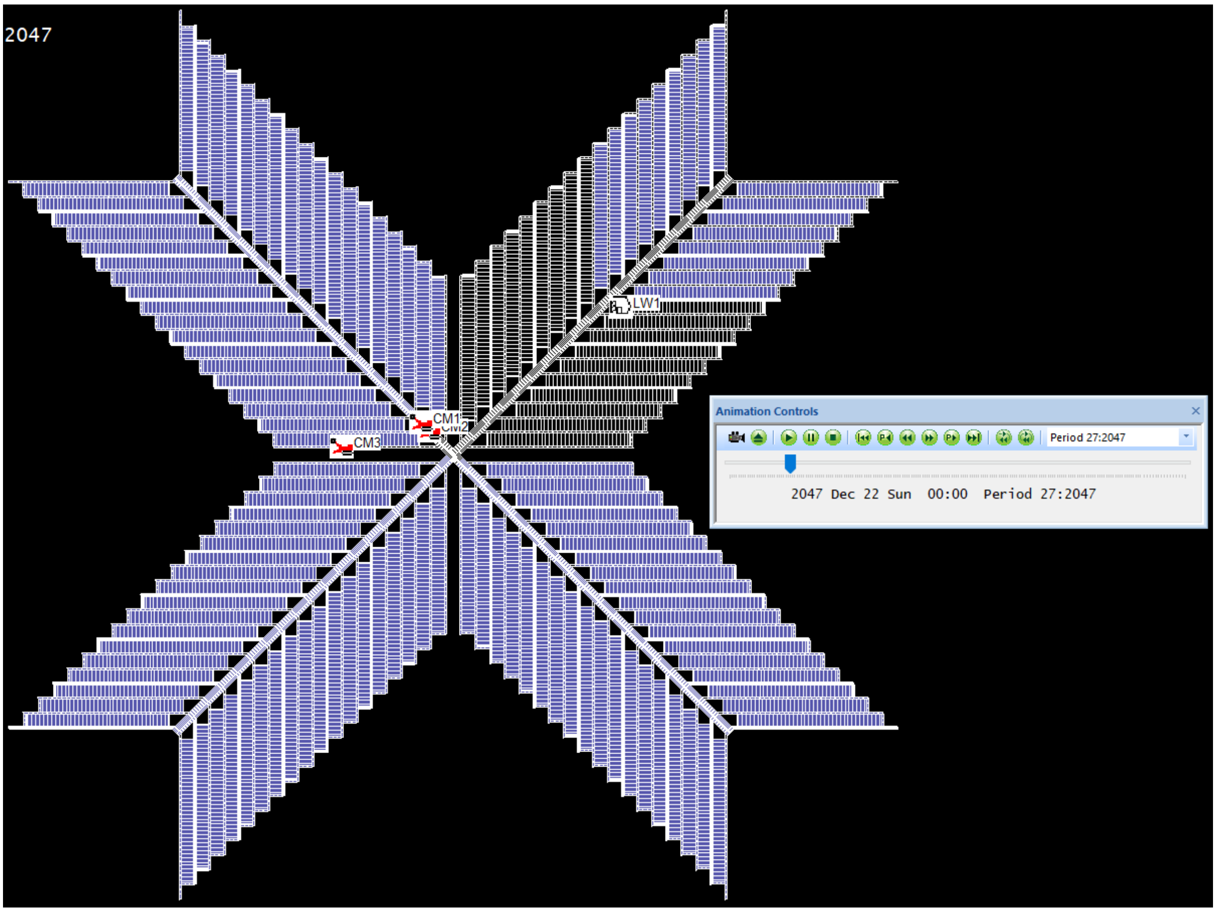


Figure 4-12: Schedule status for Milestone 2 in Quarter 2 2047 for Case 1.

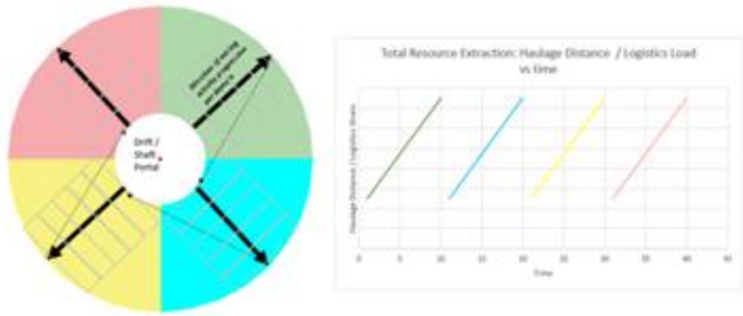


Figure 4-13: Reminder of the question posed on logistics supply strain in Chapter 1.

MILESTONE 3 Slight MAXIMA: Milestone 3 (Qtr3 2079) shown in Figure 4-14 occurs when only CM1 and CM2 can sustain the longwall and therefore logistics strain is significantly less than Milestone 1 simply because there are only three productive units operating instead of four. The maxima occur with both development units at the extremities of the Northwest Panel, but the longwall is only at Longwall 204 and is most inbye. As can be seen the development inventory in advance is significant but very much done on purpose to highlight differences in logistics strain. As previously stated these schedules are not considered realistic but rather extremes in overall duration and development inventory to amplify the impact of logistics strain and confirm the Chapter 1 hypothesis.

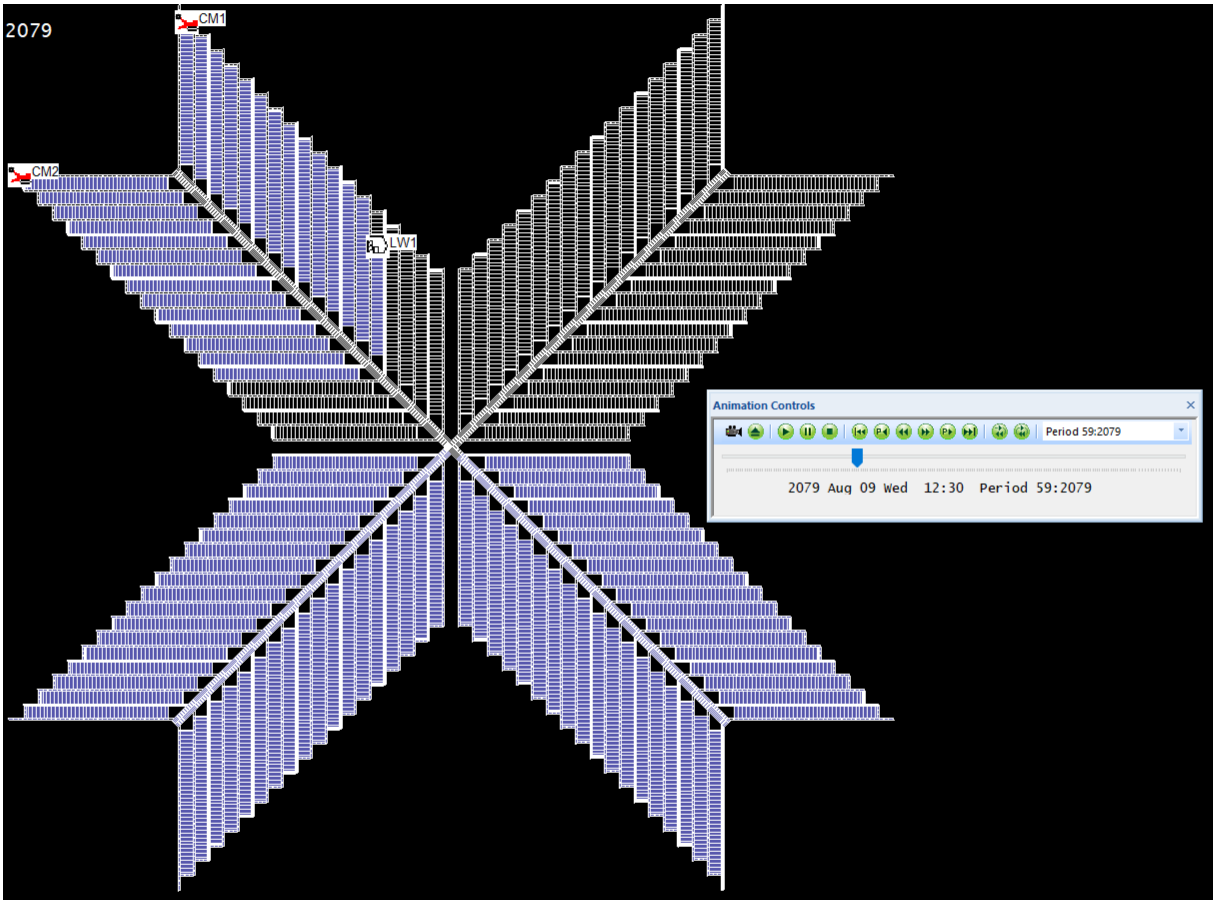


Figure 4-14: Schedule status for Milestone 3 in Quarter 3 2079 for Case 1.

MILESTONE 4 MINIMA. Milestone 4 (QTR 3 2081), shown in Figure 4-15, continues to have only two development units operating in the Southeast Area/Domain as a super unit configuration near the portal and the longwall is approaching the take off point nearest the mains headings. The total combined distance from the portal sharply increases by 4.2 km with any longwall changeout.

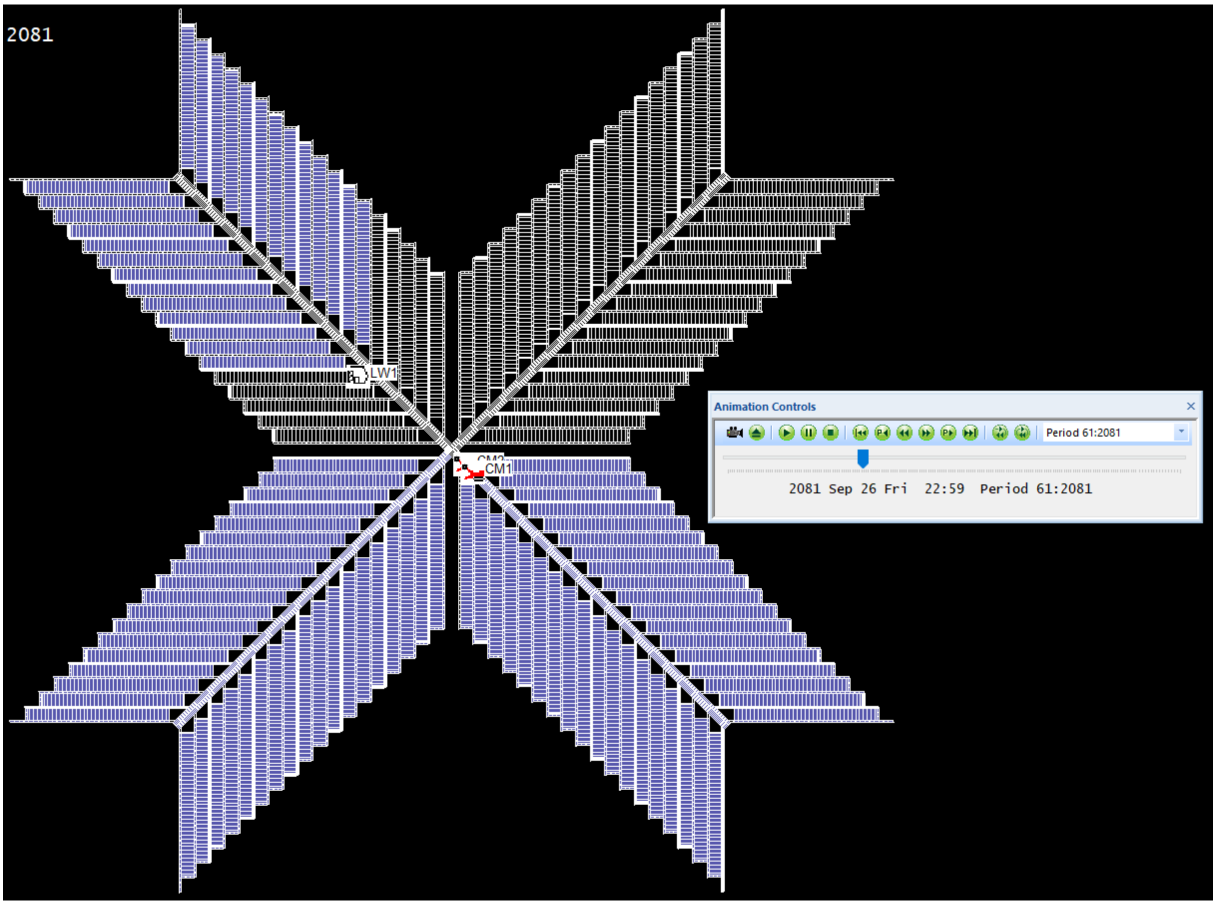


Figure 4-15: Schedule status for Milestone 4 in Quarter 3 2081 for Case 1.

Milestone 4 is one of the lowest logistics strains since operational commencement due to the proximity to the portal of both development and longwall, and that there are only two productive development units.

MILESTONE 5 STEP CHANGE. Milestone 5 (QTR 1 2100) highlights the instantaneous impact on logistics strain by adding in another productive unit. It is an immediate step change in logistics strain with the re-entry of a third continuous miner. The miner commences production 5208 metres from the portal which immediately adds this distance to the combined distance. This with additional short-term planning complexity certainly would contribute to diseconomies of scale operating mines experience when adding additional continuous miners to an operation and when reversed and a continuous miner is removed a step change in relative productivity.

MILESTONE 6 MAXIMA. Milestone 6 (QTR 1 2112), shown in Figure 4-16, again confirms the radiate away and return hypothesis on logistics strain with all units at a maximum distance away from the portal albeit in different areas/ domains. The longwall is at its most inbye longwall of the Northeast Domain and CM1, CM2 and CM3 are at the extremities of development in the Southeast Domain leading to a maximum in cumulative distance.

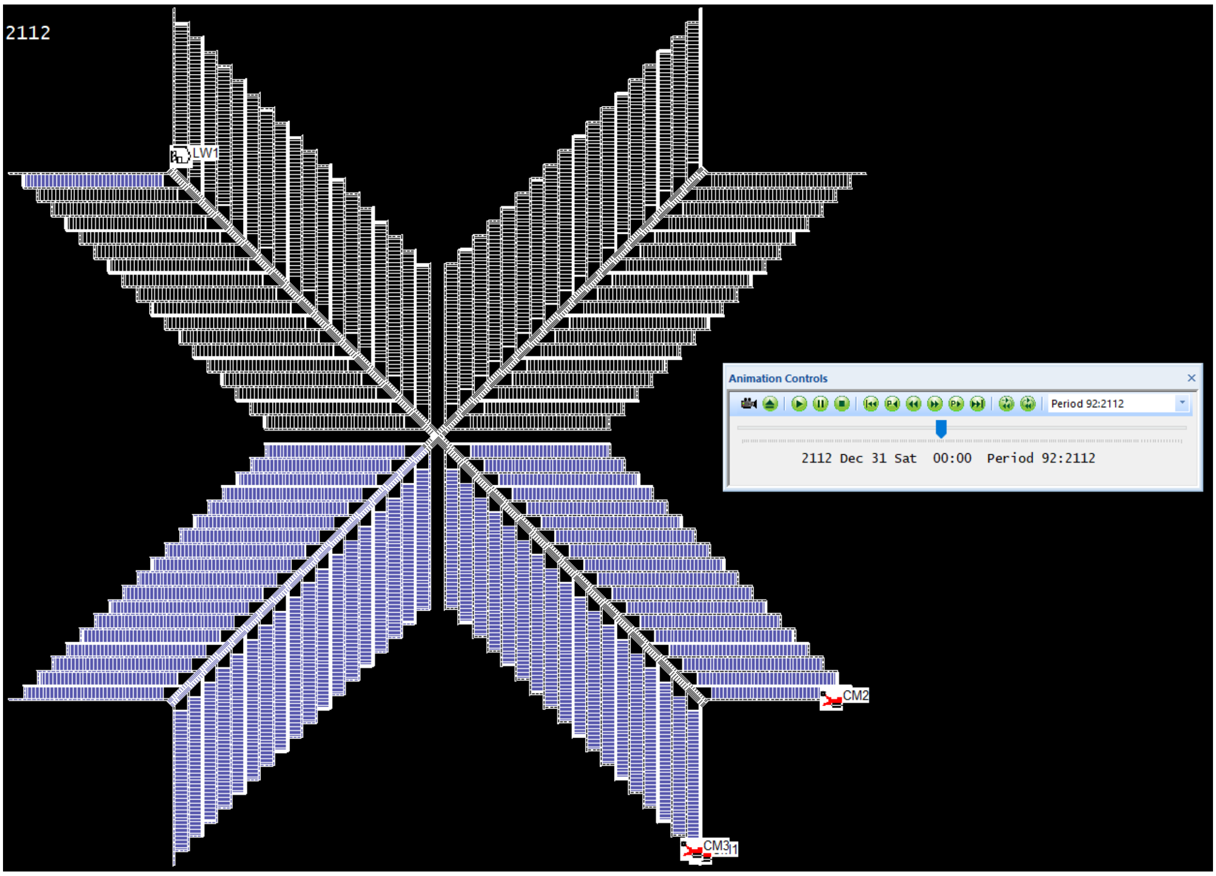


Figure 4-16: Schedule status for Milestone 6 in Quarter 4 2112 for Case 1.

4.2.1.1 Milestone 7 – Quarter 2 2114

MILESTONE 7 MINIMA. Milestone 7 (QTR2 2114), shown in Figure 4-17, shows the impact of three developments units very close to the portal and even with the longwall at its most inbye panel in the Northwest area / domain, it is at the take-off / finish line meaning its distance impact is 3.7 km less than at the start line.

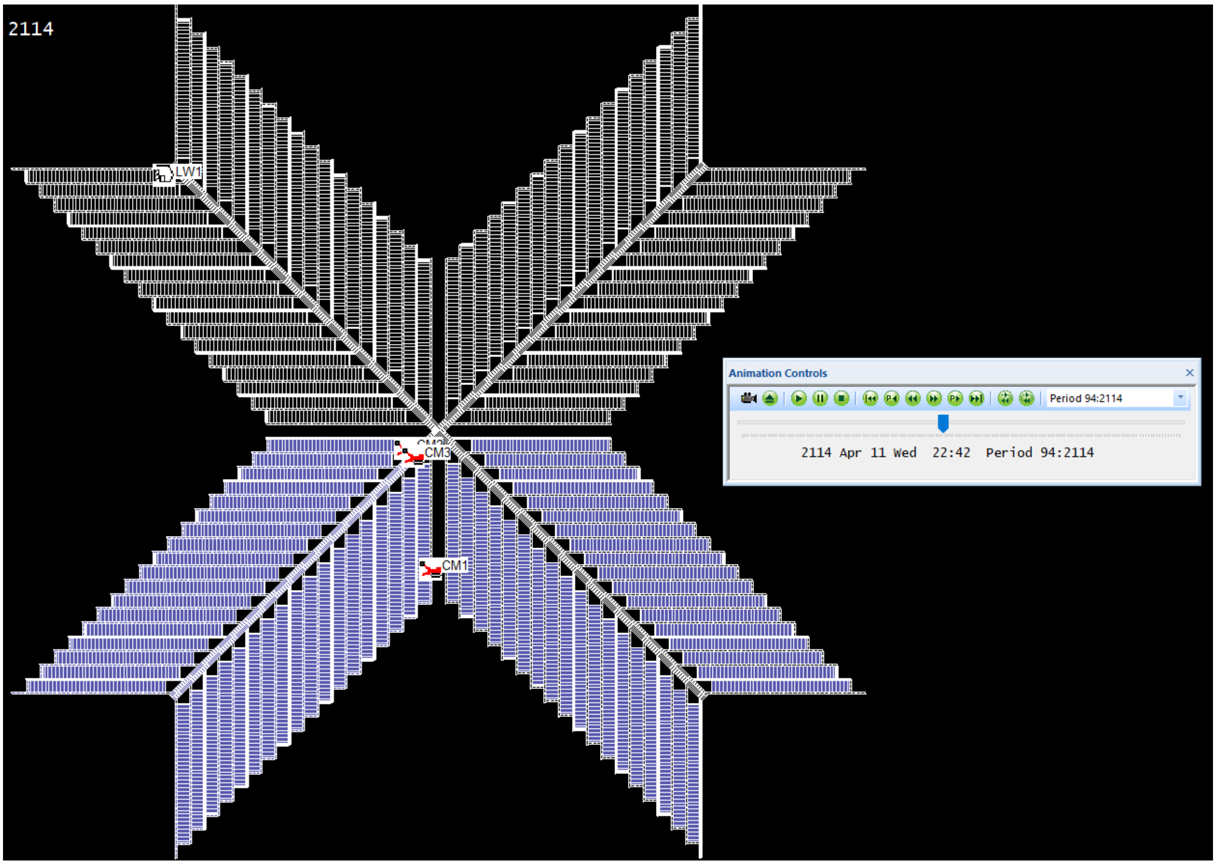


Figure 4-17: Schedule status for Milestone 7 in Quarter 2 2114 for Case 1.

MILESTONE 8 MAXIMA. (QTR 2 2138) is shown in Figure 4-18. All development units are at the extents of the Southwest area / domain in three separate productive places. This would be considered a “perfect storm for logistics strain” where every development unit is at its maximum distance away from the portal. The longwall is only at mid domain but has just commenced so is still quite far inbye and whilst it adds to the strain is not as critical as the development units.

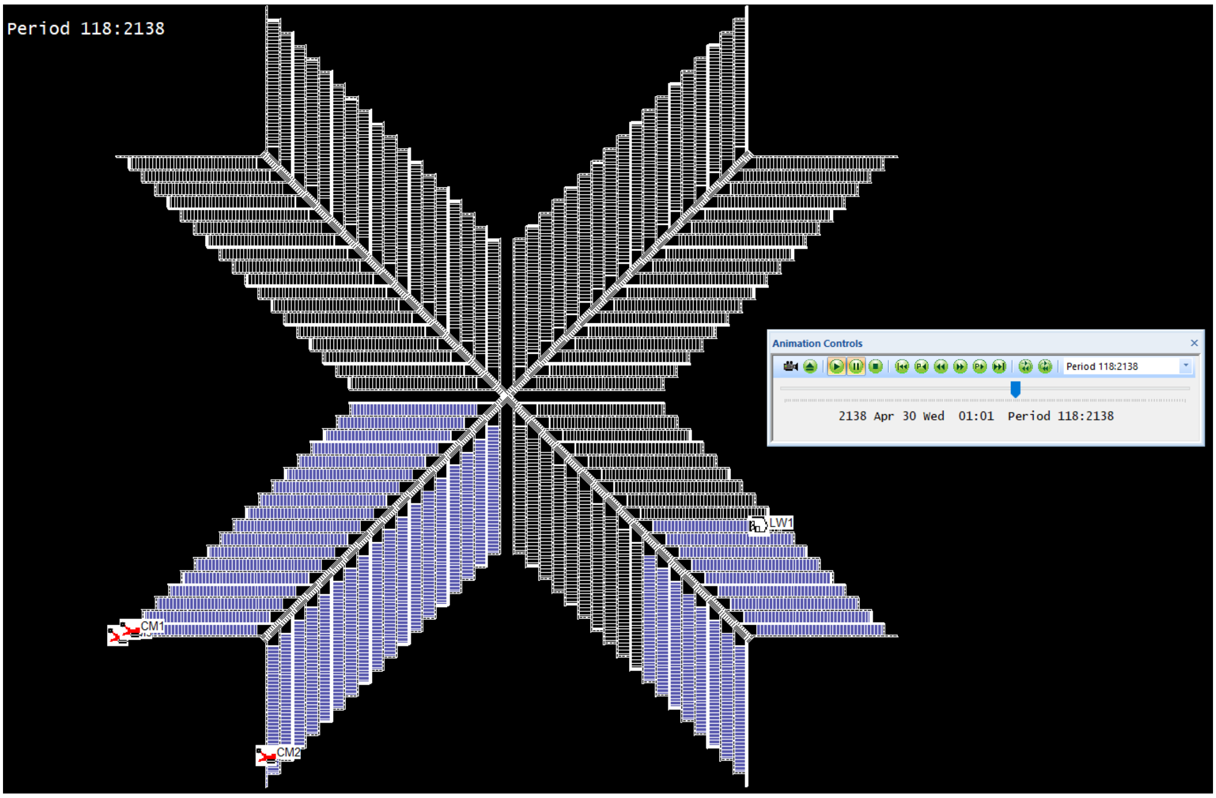


Figure 4-18: Schedule status for Milestone 8 in Quarter 2 2138 for Case 1.

Milestone 9, shown in Figure 4-19, and onwards are longwall operations only as all development operations have ceased. Milestone 9 in Quarter 3 2138 is the immediate result of demobilising three development units, reducing the combined distance to the portal from 53 km to 8 km in five months, thus, dramatically alleviating logistics strain for the remainder of the life of mine where only the longwall in the Southeast Area/Domain is operating.

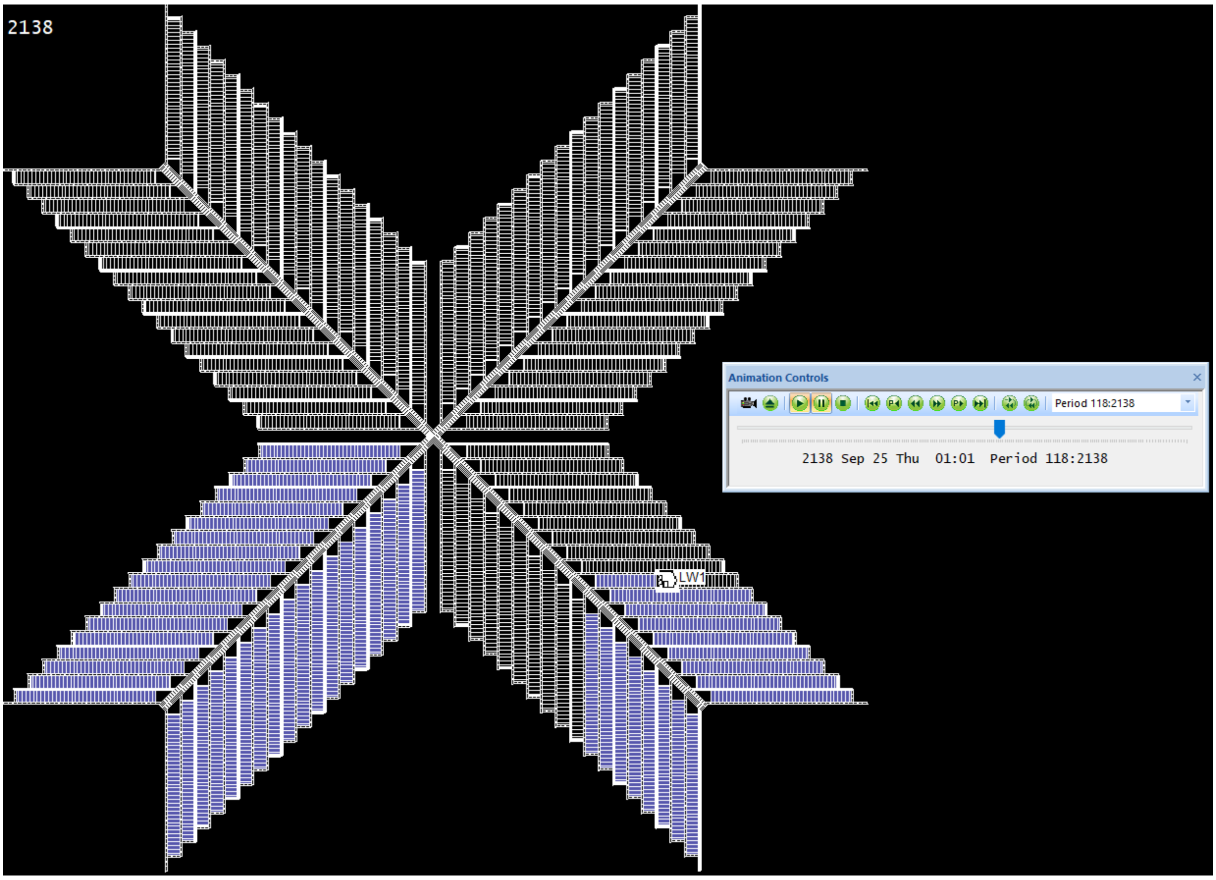


Figure 4-19: Schedule status for Milestone 9 in Quarter 3 2138 for Case 1.

Milestone 10 Quarter 1 2157 is a maximum but with only the longwall as it completes the Southeast area / domain. Milestone 11 (Quarter 3 2160) is the effect of the longwall returning close to the portal in the Southwest area / domain resulting in a drop in the combined distance and therefore logistics strain. Both Milestone 10 and 11 are shown in Figure 4-20.

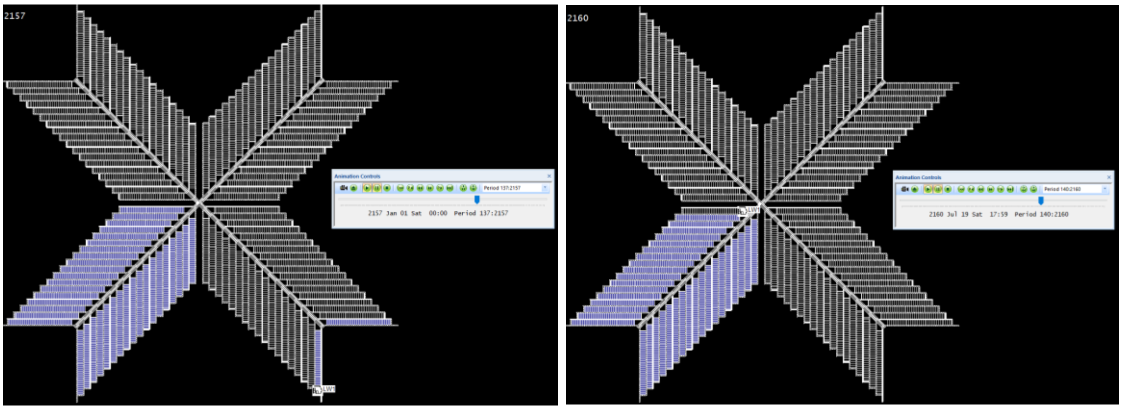


Figure 4-20: Schedule status for Milestone 10 and Milestone 11 for Case 1.

Milestone 12, shown in Figure 4-21, is a small maximum at the completion of the life of mine schedule when the longwall is at the most inbye location of the Southwest area / domain. Whilst the relative logistics strain is very low it does highlight again the impact of logistics strain as units radiate away from the portal and return as outlined in Chapter 1.

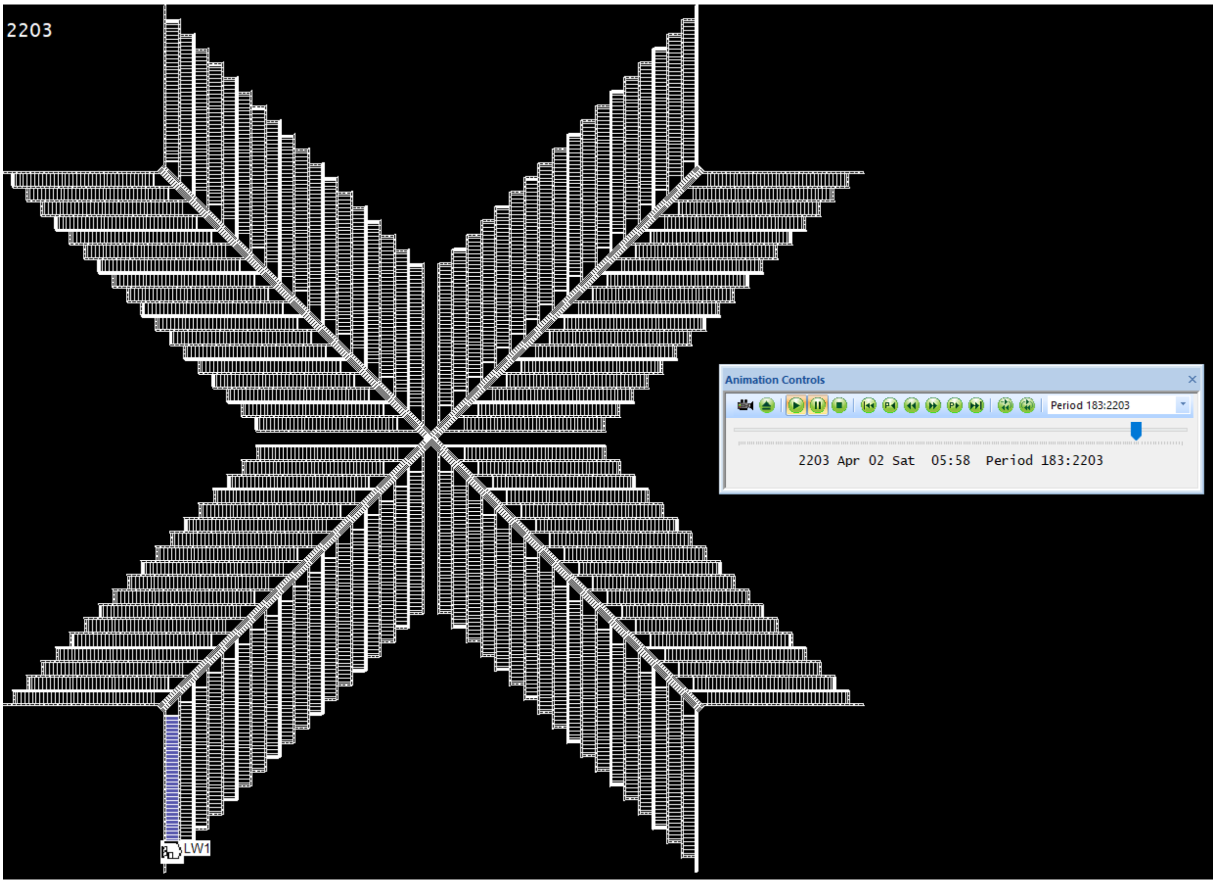


Figure 4-21: Schedule status for Milestone 12 Case 1.

4.2.2 Loads Per Day

Whilst combined distance from a supply portal is an indicator of logistics strain, it is not the only indicator, nor should it be viewed in isolation. Loads per day is an indicator of development productivity. Loads per day are dependent on productivity, and for development, primary support, but it is not impacted by distance from the portal. It is possible to have low logistics strain and have very high combined distance if the productive units are moving very slowly. In fact, if productive units are moving very slowly the cumulative distance from the portal will have sustained peak and trough duration which would be an indicator of high logistics strain but loads per day would be low which would counteract the distance effect.

Figure 4-22 presents the loads per day through time for Case 1. The physical locations of the production districts of these points are shown in Figure 4-23. As all support is green support, loads per day only varies by productivity in main headings and gateroads which is 100 metres and 150 mpw respectively. The reduction in deliveries per day between 2060 and 2100 is therefore directly attributable to the reduction in development units. This is due to sufficient inventory ahead of the longwall also reflective in combined distance from the portal, but where combined distance rises as migration away from portals occur, the loads per day is uniform with fluctuations being attributed to the proportion of mains (100 mpw) vs gateroad drivage (150 mpw). Point 1 and Point 2 in Figure

4-22 confirm this with point 1 (higher deliveries) being when all development units are in gateroads and point 2 when development units are in mains. Other day-to-day fluctuations are attributed to temporary non-production times due to in path delays such as flits / relocations to other panels. By 2138 development is completed leaving only the longwall operating. This reduces the required average deliveries to six per day.

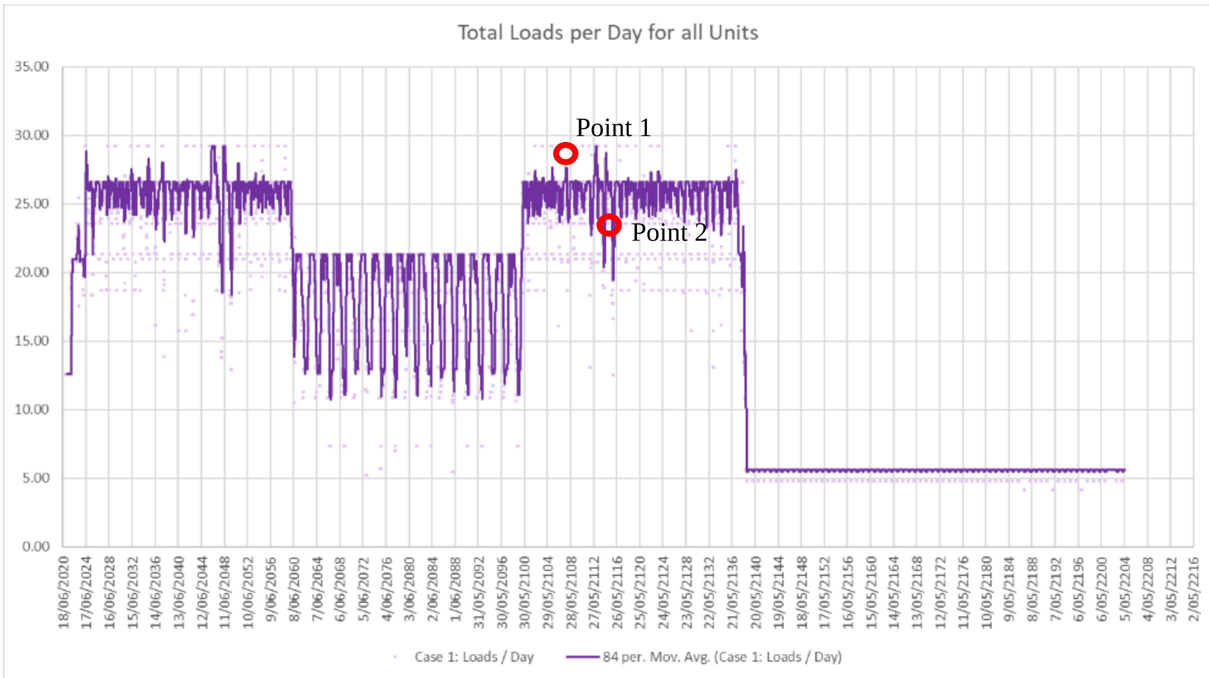


Figure 4-22: Case 1 loads per day for all units.

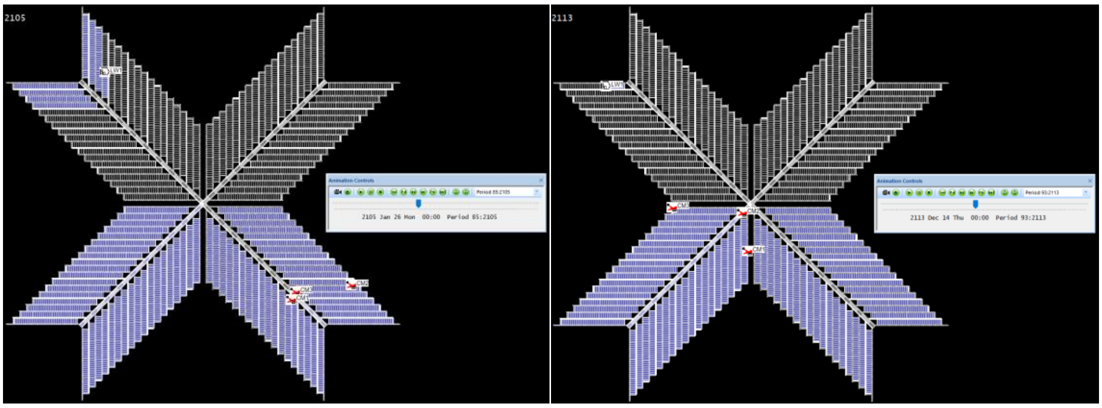


Figure 4-23: Production district locations for point 1 and point 2. Left (Point 1) high delivery day with all development units in gates vs right (Point 2) a lower delivery day with two development units in gateroads and one unit in mains.

Whilst combined distance from portal and loads per day are two indicators of logistics strain neither should be viewed in isolation and could be misleading if given to the wrong operational hands if not viewed together. Loads per day is a fast way for relevant departments (such as the mining logistics department) to understand their obligations required to maintain the schedule within the short to medium term. If for example, the best average loads per day for an operation is 20 loads per day and there is an upcoming week where it is anticipated that due to the combination of all panels productivity and primary support that require 30 loads per day, then the operation is at serious threat of logistics breaking strain. Now for the purposes of this example, if for the three weeks prior, loads per day required were only 15, there are 21 days to stockpile supplies by increasing loads per day to an average of between 18 and 19 deliveries. This will still be under the best average of 20 loads but would alleviate the risk of logistics breaking strain and therefore not cap development rates.

4.2.3 Loads on road

Loads on road is a key performance indicator developed in this thesis that combines the combined distance with total loads per day and will be for the purpose of research be interchanged with the term *logistics strain*. Designed to be a quick glance KPI either at a short-term tactical level or at a long-term strategic level, it highlights the practicality of how many machines are in the process of delivery at any given instant in the mine. The higher the combined distance, the higher the loads on road, similarly the higher loads per day, the higher the loads on road, if both were required together then even more higher loads on road would signify significant logistics breaking strain. However, when combined distance is low and loads per day are high then logistics strain is alleviated by distance and aggregated by required deliveries. The "loads on road" aims to cover this. Case 1 loads on road is shown in Figure 4-24: -

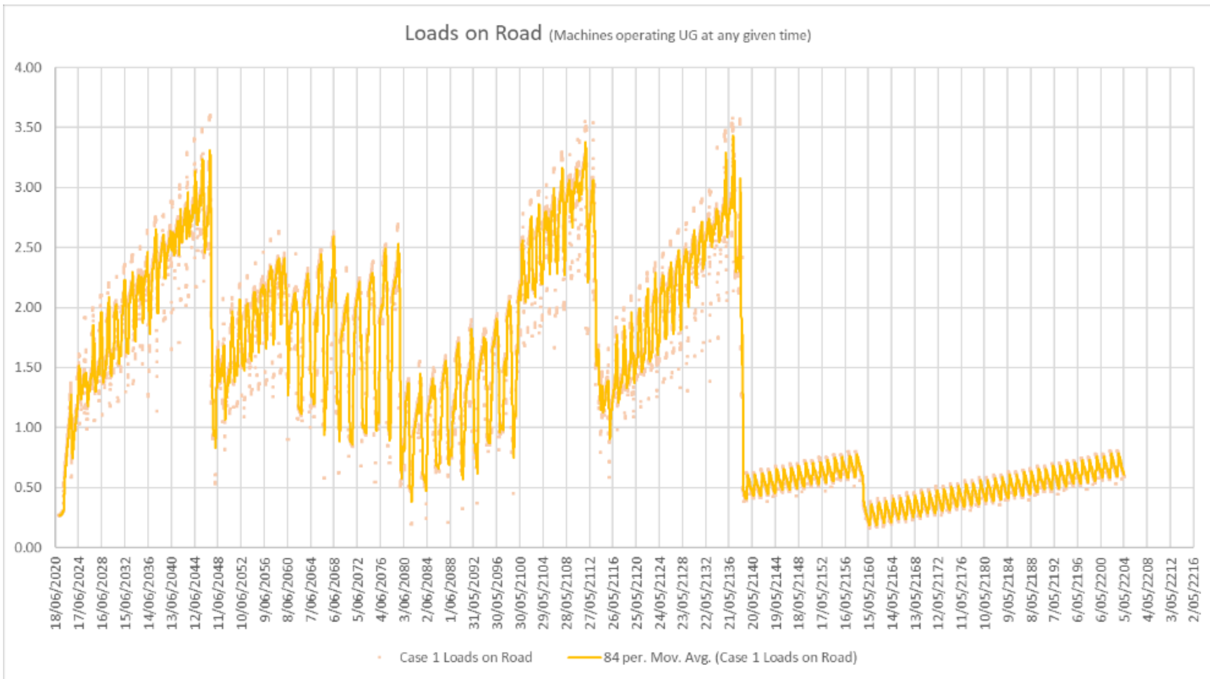


Figure 4-24: Loads on road, the number of delivery LHDs operating at any given instant in the life of mine. Also known as logistics strain.

As can be seen, the maximum number of machines is about 3.6. A fleet of delivery vehicles would need to be purchased for this which would also account for machine availability. For Case 1 loads per day, due to the homogeneous primary support, the loads on road are reflective of the combined distance kpi, remembering that case 1 is the base case for all other cases.

Loads on road can quickly be understood by operational key stakeholders and may immediately be able to determine if the requirements are not feasible (logistics breaking strain threshold). Planners may then be able to reconfigure the mine or the type of delivery to reduce loads on road or increase the operational capacity to meet the demand for deliveries. Figure 4-25 shows an example of thresholds that may be encountered by key stakeholders that will define logistics breaking strain. In this example logistics breaking strain is operational practicality, for example simply the inability to jam more than 2.4 machines on the road at any given time within the mine. This bottleneck may be removed by reducing light sections or having inbye and outbye transport roads to reduce shunting, which will lead to the uncovering of a personnel bottleneck, so more staff are dedicated to the logistics team. This in turn uncovers the next bottleneck of machine availability, so more machines are purchased (which may revert to a new bottleneck of operational practicality with more machines on road). In this case the last bottleneck would be ventilation capacity, where too many machines are required on the road for what the ventilation system can sustain to meet legislated requirements and therefore a mine design change to accommodate larger ventilation quantities or a fan upgrade is warranted. These cascading constraints are a representation of the Theory of Constraints (TOC) discussed in Section 2.5.6 In this example there is no circumstance where ventilation is a limiting factor. It should be noted that due to the dynamic nature of bottlenecks once it disappears it may re-arise at any time after the removal of a higher bottleneck.

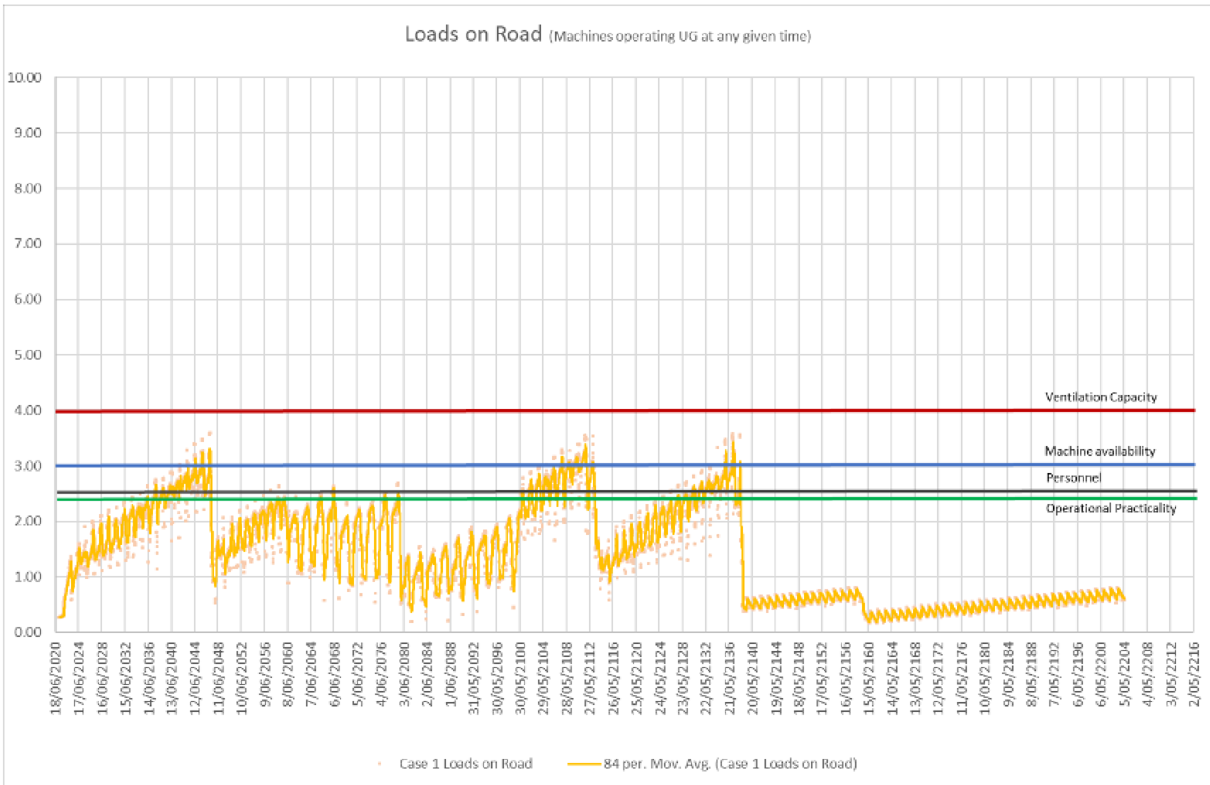


Figure 4-25: An example of bottlenecks that bring about logistics breaking strain.

Please note that this is only an example and would be determined on a mine-by-mine basis with a view that the earliest proactive intervention to address the issue compared with reactive intervention will typically be cheaper and less of an operational distraction.

4.3 Cases 1a (slowing productivity) and 1b (reducing development inventory)

Case 1 has two variants that were studies to understand their comparative impact to logistics strain throughout the life of mine. Case 1a studies the impact of slowing down all productive units whereas Case1b studies the impact of reducing development rate, so it matches Case 1 longwall rate and therefore does not build as much development inventory in advance.

4.3.1 Case 1a: The Impact of Slowing Down Productive Activities

Case 1a studied the impact of completely slowing all the productive units by 50% productivity. Therefore, all paths are the same and the combined distance from the portal also remains the same. Figure 4-26 demonstrates the comparative cumulative distance from the portal with Case 1 in grey and Case 1a in red. Note that the peaks and troughs of the 12-week rolling average combined distance are at the same level, but the period between peaks has approximately doubled.

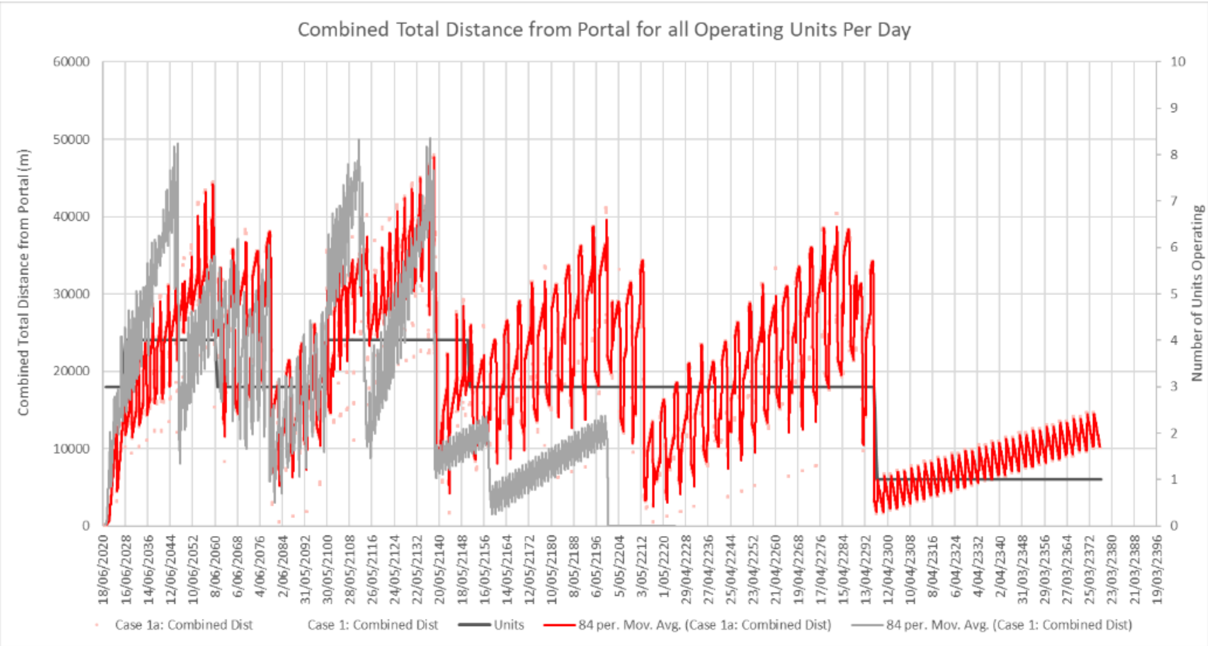


Figure 4-26: Comparison between Case 1a(red) and Case 1(grey) for cumulative distance from the portal.

Figure 4-27 outlines the total loads per day for all units.

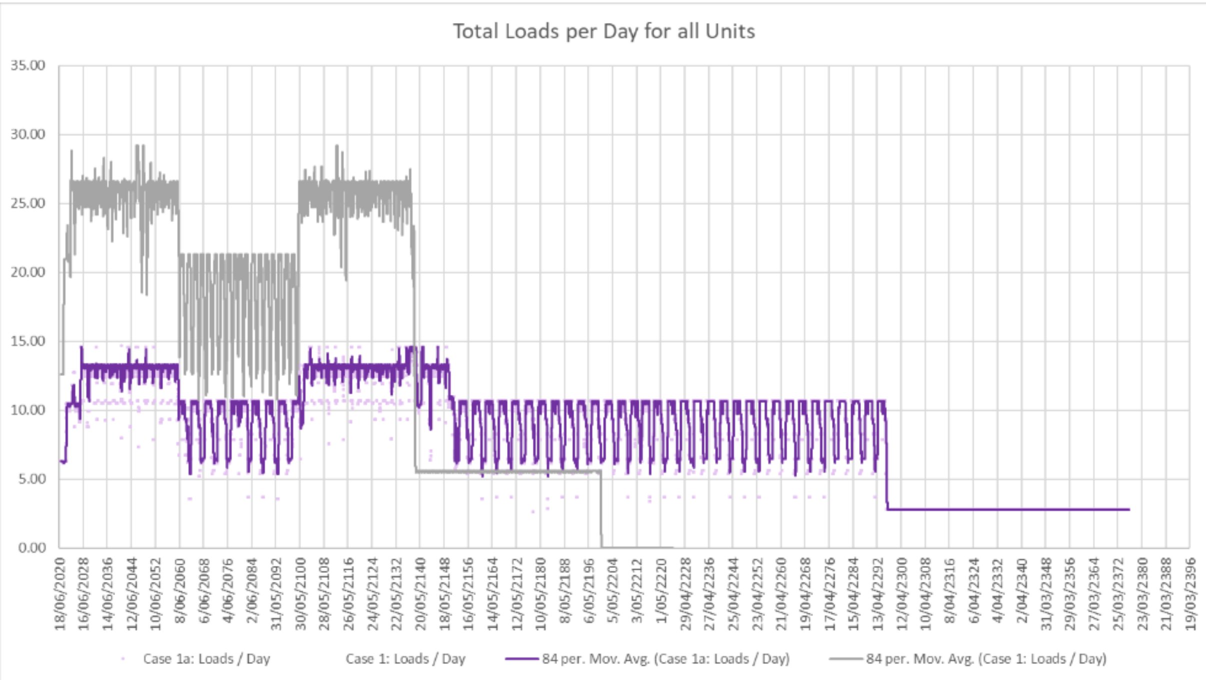


Figure 4-27: Comparison between Case 1a (purple) and Case 1(grey) for total loads per day for all units.

Loads per day have understandably halved for the first 120 years of the schedule. Loads on road are higher after 2140 meaning development has now extended from 2138 in Case 1 out to 2295 in Case 1b and longwall completion for Case 1a in 2376 from Case 1 in 2200. The loads on road for Case 1a has halved compared to Case 1 because even though the combined distance peaks are at the same levels as Case 1, the loads per day has halved which means logistics strain has halved but must continue for almost double the time. Figure 4-28 compares loads on road between Case 1a and Case 1.

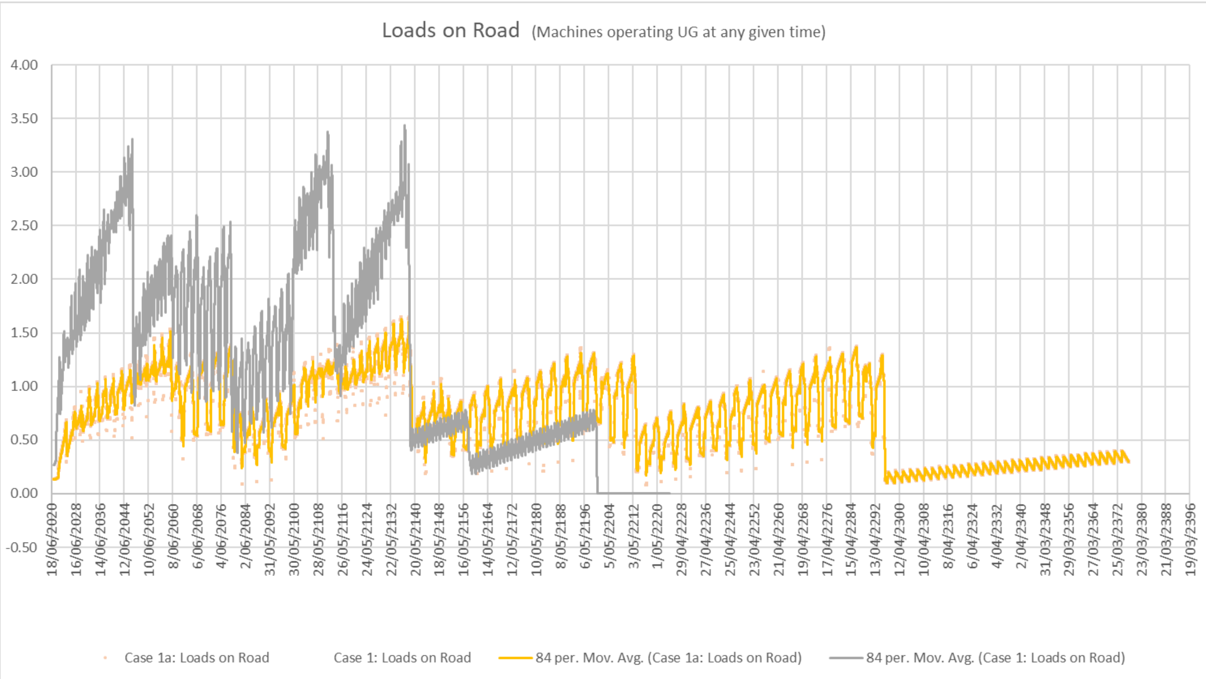


Figure 4-28: Comparison between Case 1a (orange) and Case 1(grey) for loads on road (Logistics Strain).

Case 1a's schedule is expected to be double the duration of Case 1, as 1a is half the productivity but Case 1a's duration is slightly faster than double as both cases have a constant longwall changeout duration. Therefore, the period of the migrating away and return to portals has only approximately doubled, which in turn has a reduction in logistics strain even at peak combined distance from the portal. In other words, if you slow down production proportionally to counteract increasing combined distance, logistics breaking strain will never arise.

4.3.2 Case 1b: The Impact of Reducing Development Inventory in Advance

It should be noted that whilst some management in Case 1 of development inventory has occurred, it is not in the forefront of the planner's mind when timescales are this large. However, knowing the impact of development inventory with respect to logistics strain can now be studied. Case 1b has the same scheduling paths as Case 1 but slows the development rate so that it does not "run-away" ahead of the longwall. Figure 4-29 shows the comparison between Case 1 and Case 1b for schedule status as at mid-2136.

In Case 1 development is 1.5 area/domains (approximately 51 longwall panels) ahead of the longwall unit. In Case 1b the total number of development units are the same but their hours per week, via a roster adjustment, has been reduced meaning that development is only 0.25 area/domains (nine longwall panels) ahead of the longwall unit. The comparative impact on the combined distance from the portal is shown in Figure 4-30. The point data and the 12-week moving average for Case 1b (low inventory) are in light red and red respectively, and the Case

1 (high inventory) 12-week moving average is in grey. It is important to note that the development units finish their drivage in the schedule in 2190 compared to Case 1 in Figure 4-10 previously where development is completed much earlier in 2138.

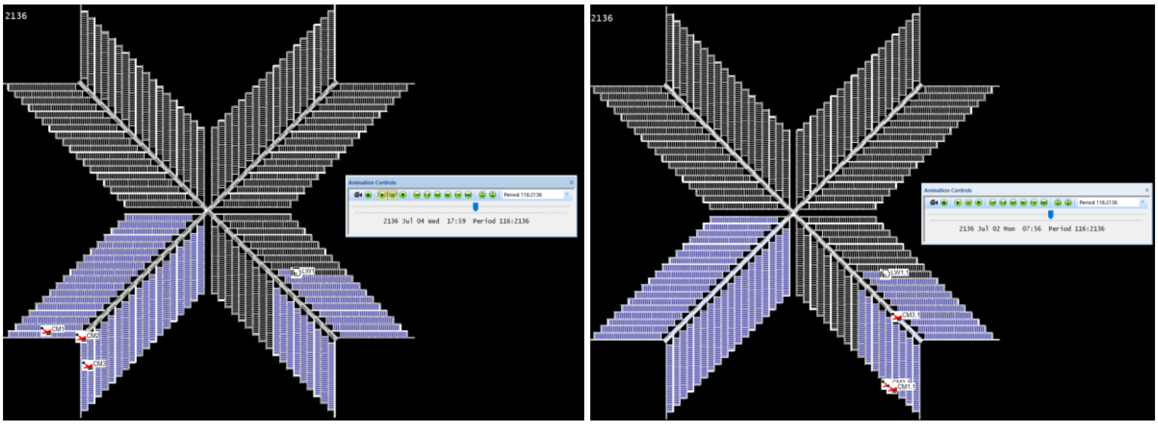


Figure 4-29: Development inventory between Case 1 (Left) and Case 1b (right)

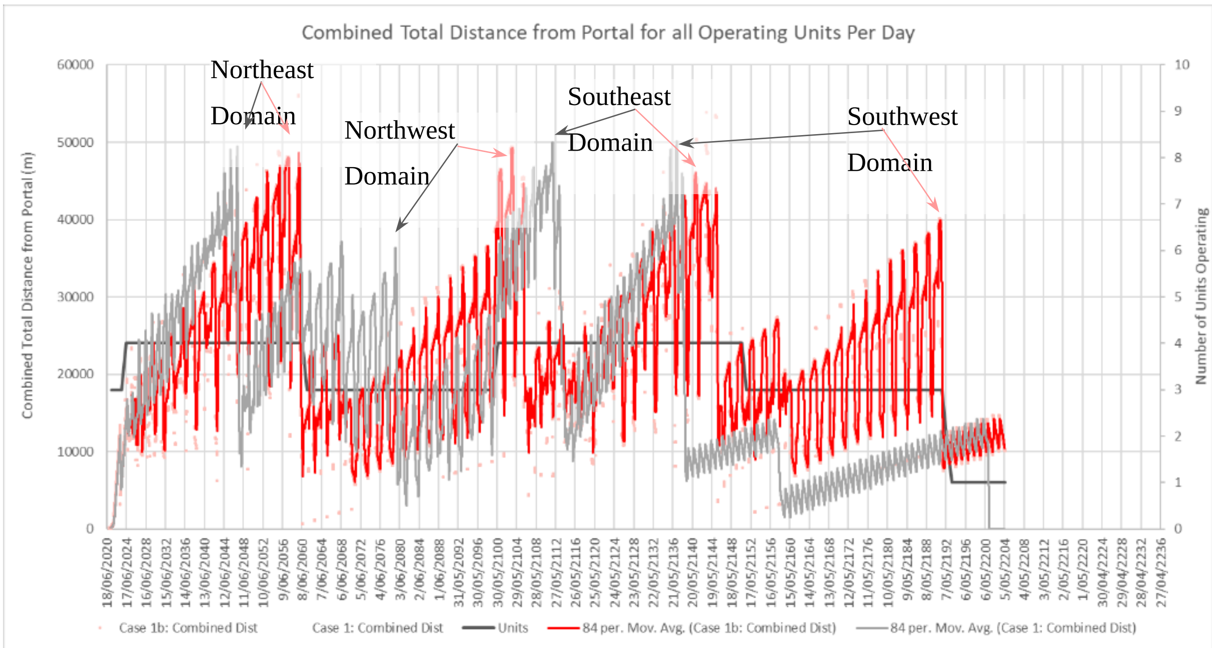


Figure 4-30: Case 1b lower development inventory combined distance from portal vs Case 1.

Examining Figure 4-30, Case 1 (grey) certainly has a more aggressive gradient as development moves out to the area/domain extremities faster when compared to Case 1b (red) where development is slowed down for area/domain Northeast (present to 2047). This would mean a faster ramp up of logistics capability. Frequency of combined distance oscillations is higher for Case 1, but Case 1b peaks at or above 40,000 m four times, whereas Case 1 peaks only three times missing peak number two because only two development units are employed in the schedule between 2060 and 2100 to extract the inbye panels Northwest Area/domain. In contrast Case 1b the third unit restarts prior to development of the most inbye panels between years 2100 and 2105 and therefore Peak 2, for the Northwest Area/domain is much higher than Case 1.

Whilst Case 1 has higher ramp up to maximum logistics strain, Case 1b has higher logistics strain for longer periods of time. This is because in Case 1b, development inventory in advance is low meaning that it is likely that all development units and the longwall are inbye within the same domain. Case 1 with development units being further ahead means that for the same longwall location for Case 1b, the development units have likely returned to develop the next domain nearest to the portal and therefore combined distance from the portal has subsequently dropped. Therefore, when looking at both cases there is no better case when looking at logistics strain through combined distance only.

Loads per day are less due to total reduced development for Case 1b. Figure 4-31 shows the comparison between Case 1 in grey and Case 1b in purple. For peak loads per day when all four productive units are operating there is just below a 20% reduction in loads per day required from 2025 onwards which is to ensure that the longwall commences on time. Between 2060 and 2100 the loads per day difference between Case 1 and 1b reduces to 11%. From 2025 development inventory in advance is managed through the reduction in development unit rostered hours. Development units CMs 1 and 2 are both rostered to work 144 hours per week, but the 3rd development has the highest reduction in rostered hours reduced to only 48 hours per week, rather than seven days per week in Case 1. Therefore, when development unit 3 is demobilised between 2060 and 2100 the impact is less than would be if development unit CMs 1 or 2 were stood down for the same period.

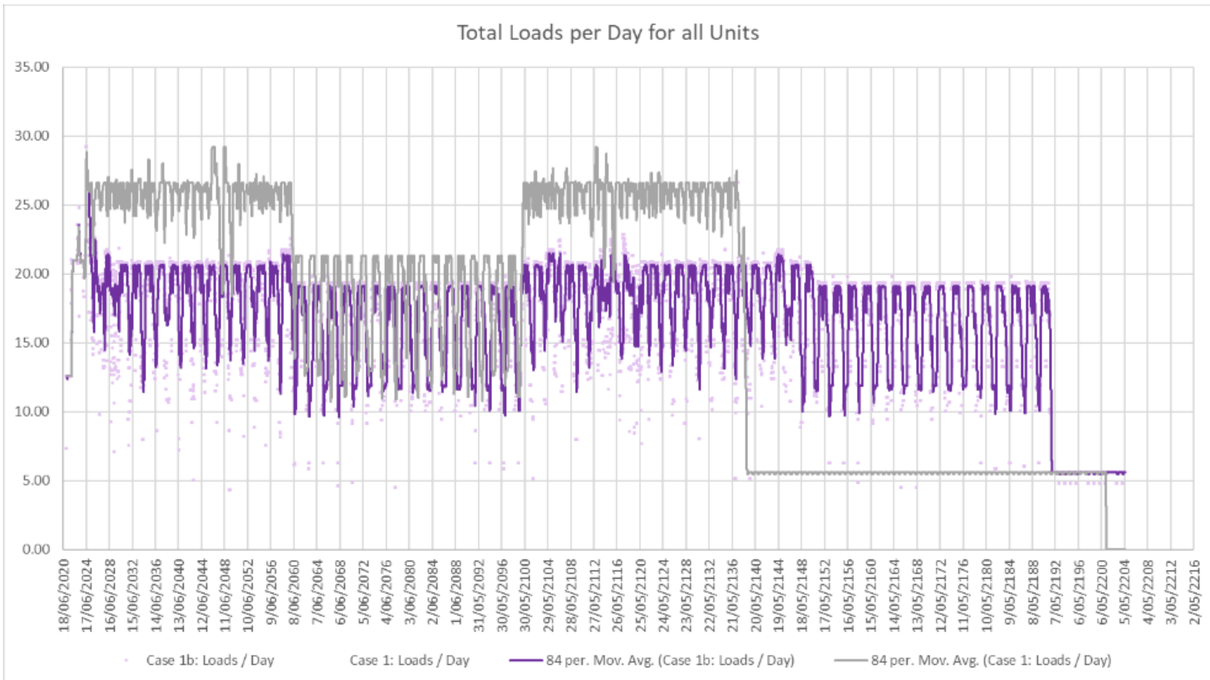


Figure 4-31: Case 1b vs Case 1 for total loads per day for all units.

Loads on road (logistics strain) shown Figure 4-32 is reduced except for the last few panels of longwall only where both options 1 and 1a are realigned. Compared to option 1a where all productivities were downgraded, case 1b is a much more efficient schedule which does not compromise longwall production. The combination of the combined distance which still peaks (albeit slower) at the same levels with a reduction in loads per day leads to a lower logistics strain and slower arrival and logistics strain peak.

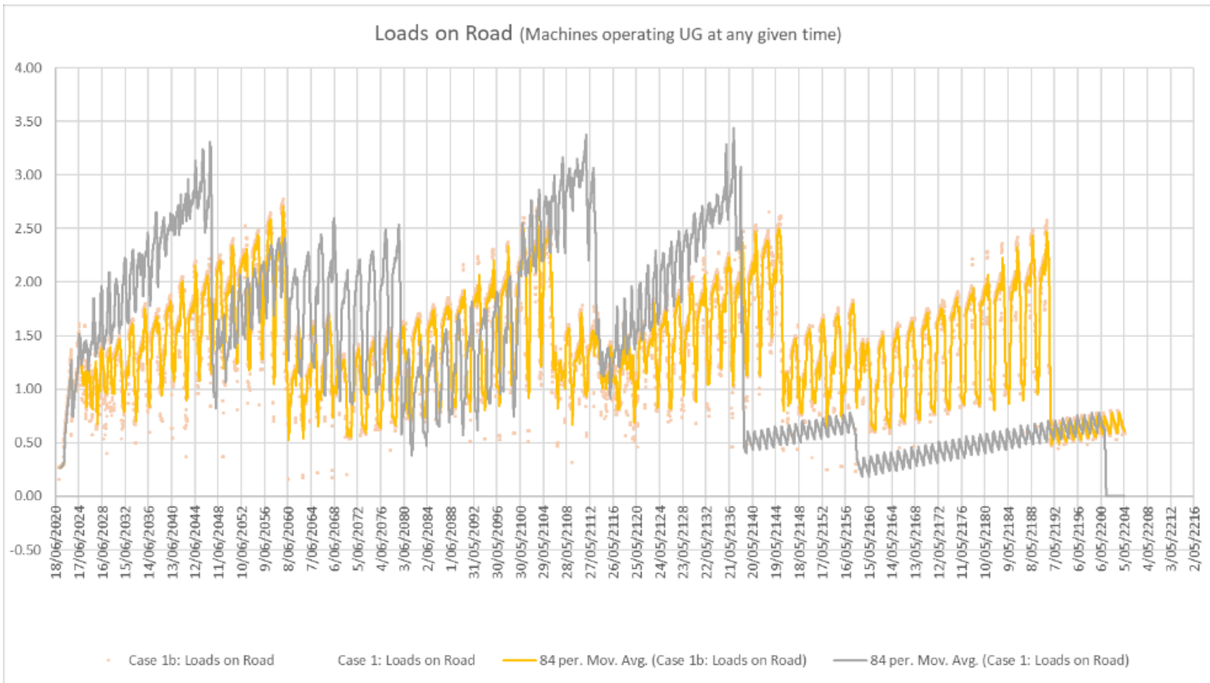


Figure 4-32: Case 1b vs Case 1 for loads on road (logistics strain).

4.4 Case 2: Extension out to Northeast Extension Area/Domain

Case 2 simply adds the Northeast extension Area/Domain after the completion of the Southwest domain which is completed at the same time as Case 1. The Northeast extension has a considerable linear distance of mains headings that must be driven to get to the new Area/Domain and is still supported by the central portal. The period plot for Case 2 is shown in Figure 4-33.

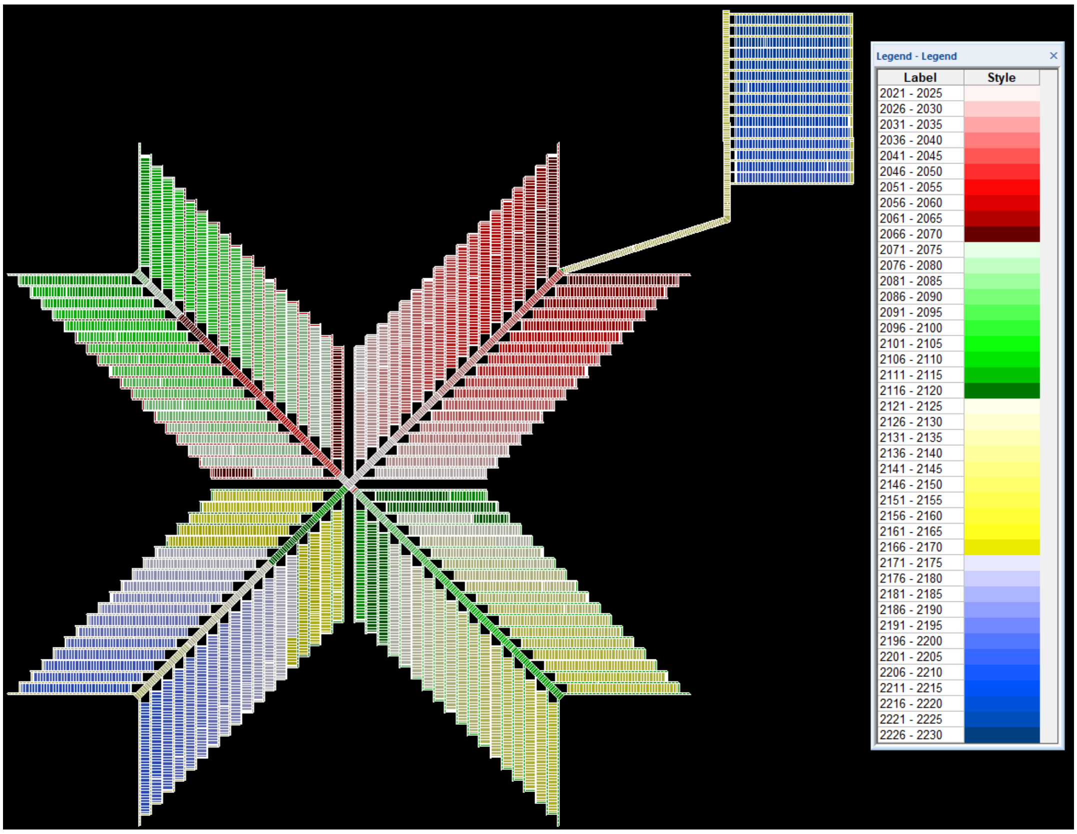


Figure 4-33: Period plot of Case 2.

The Northeast domain adds an additional 20 years to the mine life. The third development unit continues to be curtailed between 2060 and 2100 and is then demobilised for a smaller period whilst mains drivage is being driven out to the Northeast extension Area/Domain and there is not enough pit room for three units.

4.4.1 Combined Distance

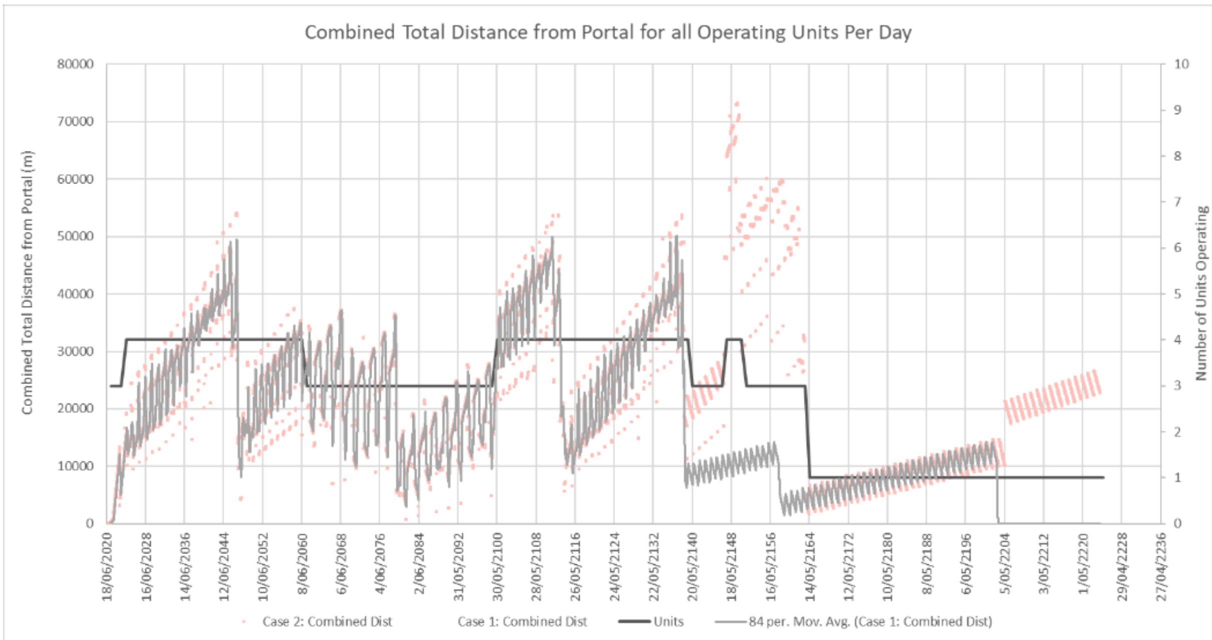


Figure 4-34: Case 2 vs Case 1 daily combined total distance from the portal for all productive units.

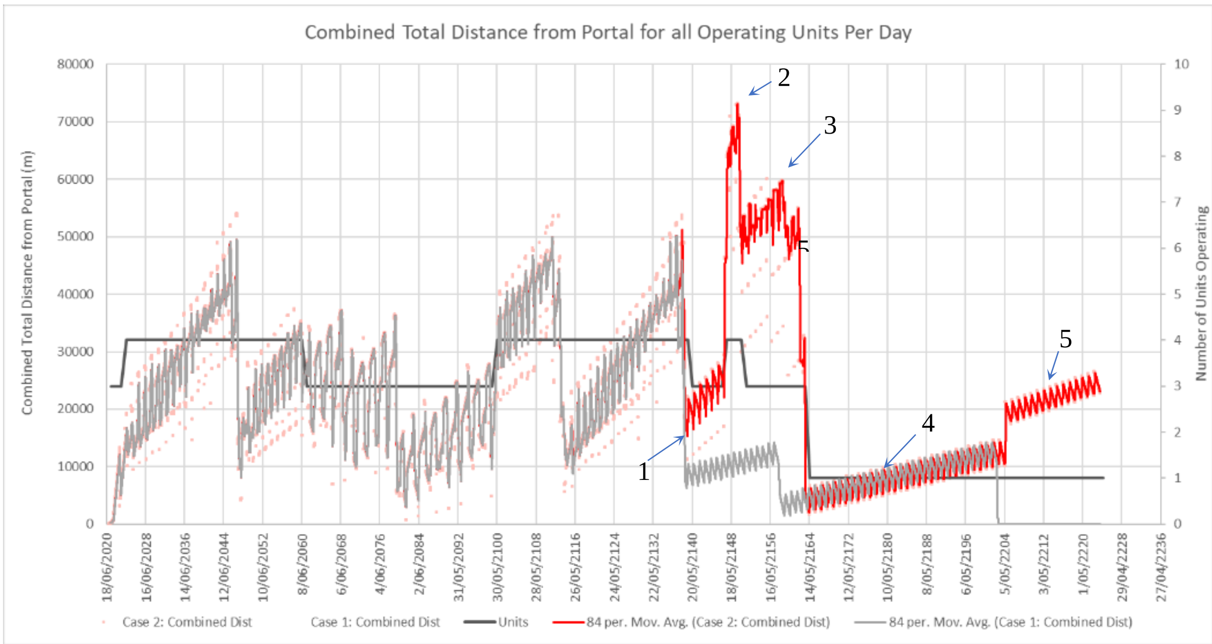


Figure 4-35: Case 2 vs Case 1 Daily combined total distance from portal for all productive units with a 12-week rolling average trendline.

Figure 4-34 monitors the combined distance from each productive face to the portal daily in light red (point data) and the number of units operating each day (black line). Figure 4-35 includes the 12-week rolling average of the daily combined distance. The light grey line is the Case 1 base case 12-week rolling average for both graphs. As can be seen from 2140 onwards the combined distance falls. The first 120 years of the schedule is exactly as for Case 1.

At Milestone 1, shown in Figure 4-36, development is no longer curtailed and two development units are commissioned to drive the main headings out to the Northeast extension Area/domain. As there are only two development units operating the combined distance is reduced.

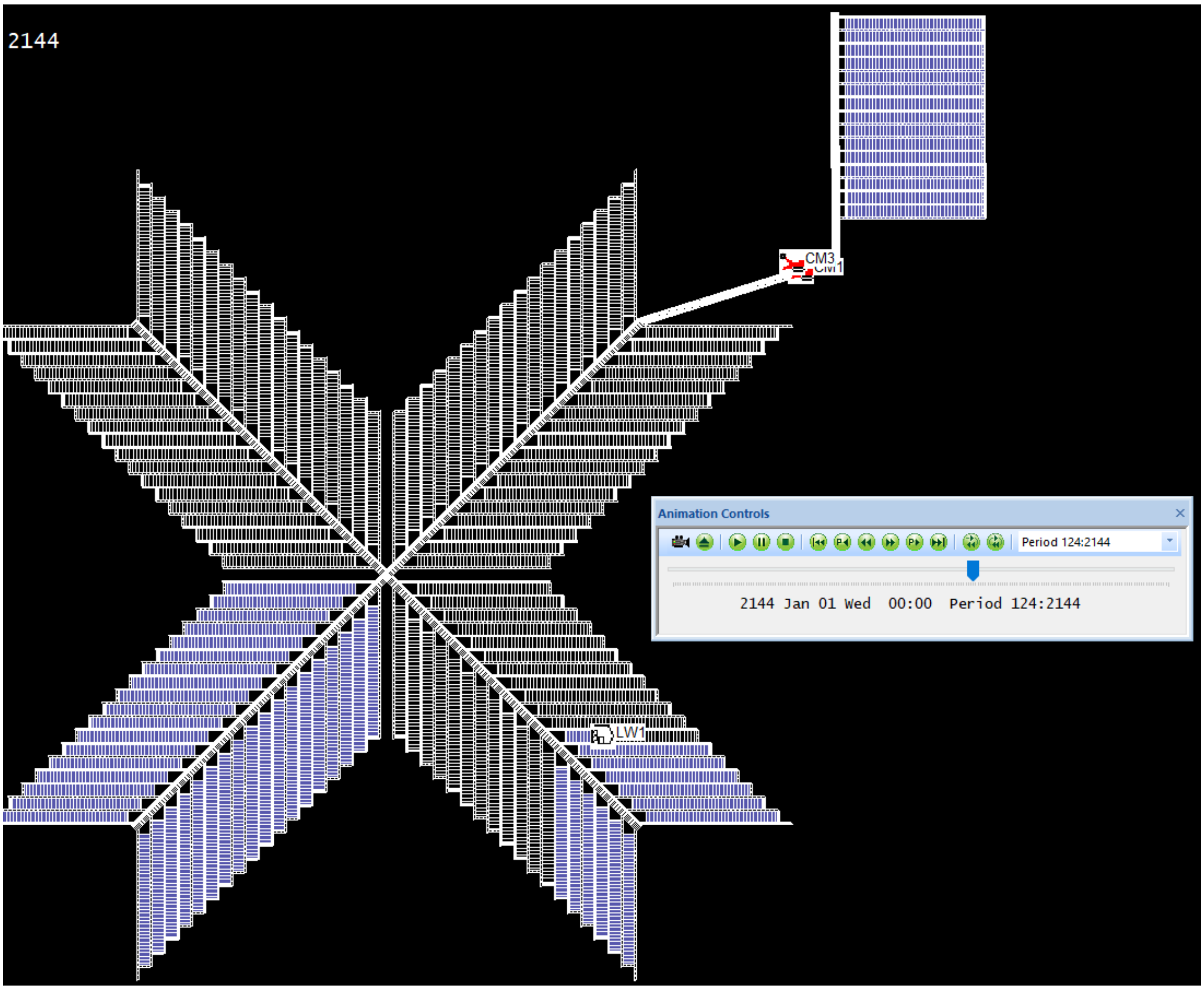


Figure 4-36: Milestone 1: Drivage out to Northeast extension.

Milestone 2, shown in Figure 4-37,possesses enough pit room in the Northeast extension area / domain for three development units for a short period of time in the outbye areas leading to the highest combined distance peak of the life of mine schedule.

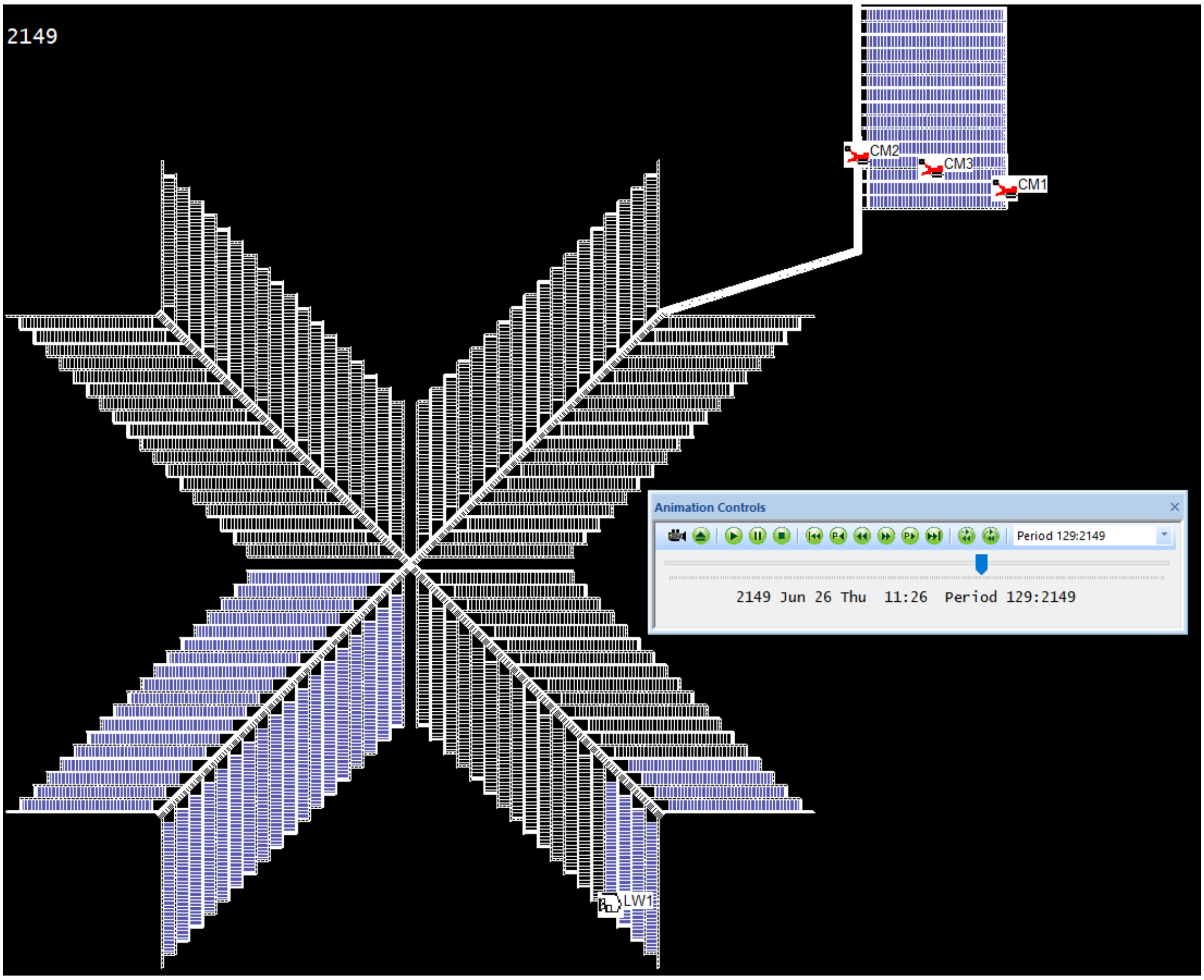


Figure 4-37: Milestone 2: Peak combined distance for LoM plan.

Milestone 3, shown in Figure 4-38, is operating at the inbye extents of the Northeast extension but with two development units which drops the combined distance from the portal below the previous peak of Milestone 1. Development is curtailed with only the longwall operating in the Southwest domain for Milestone 4 resulting in a sharp decrease in the combined distance.

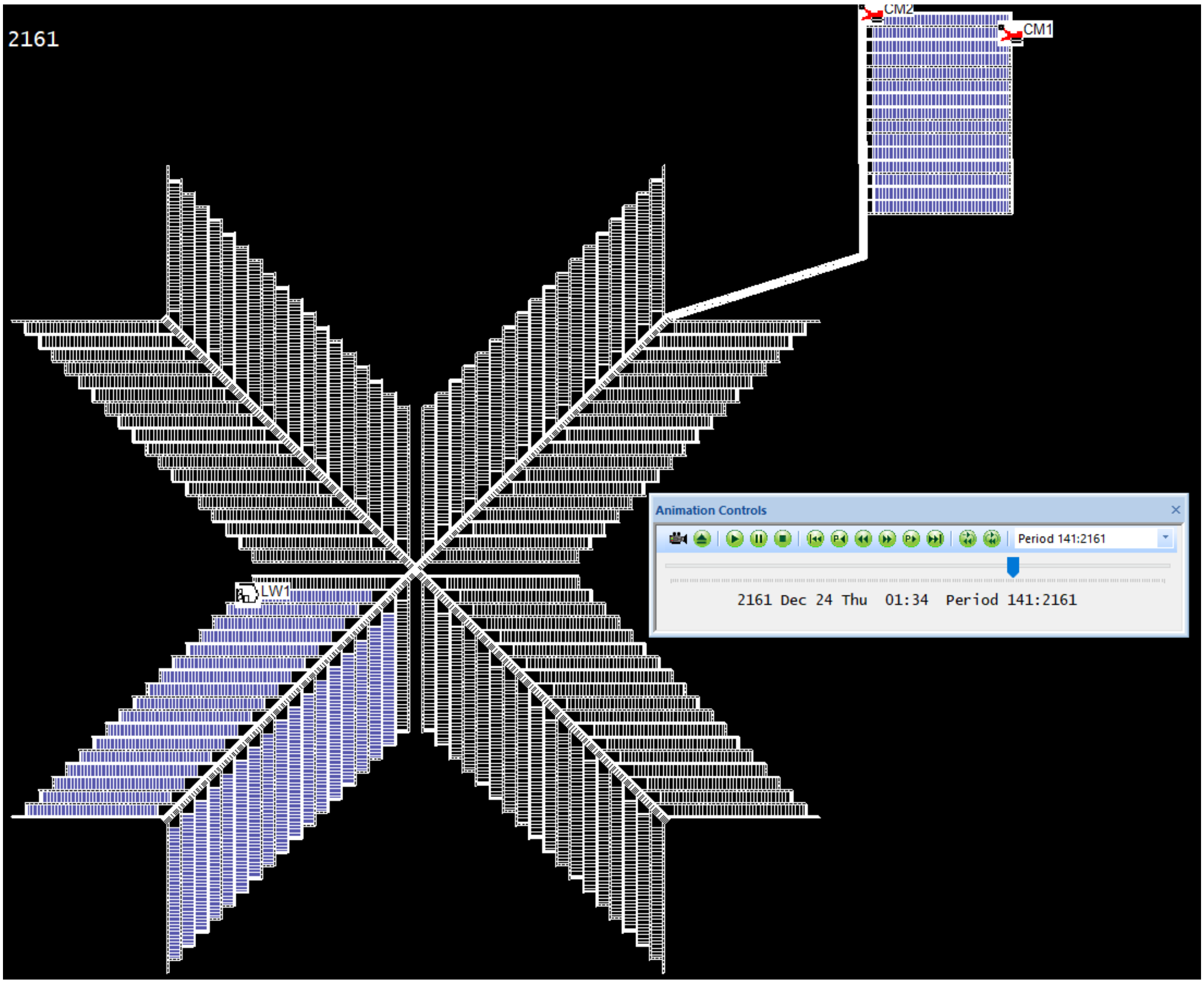


Figure 4-38: Milestone 3: Development near completion.

In Milestone 4, shown in Figure 4-39, only the longwall is operating as all development units have been demobilised. There is only one path between pit bottom and the longwall production district. In absolute terms this demonstrates a large relief on logistics strain, but it also slows a steady increase in strain as the longwall progresses inbye to the south-western extents without the influence of other production districts on logistics strain.

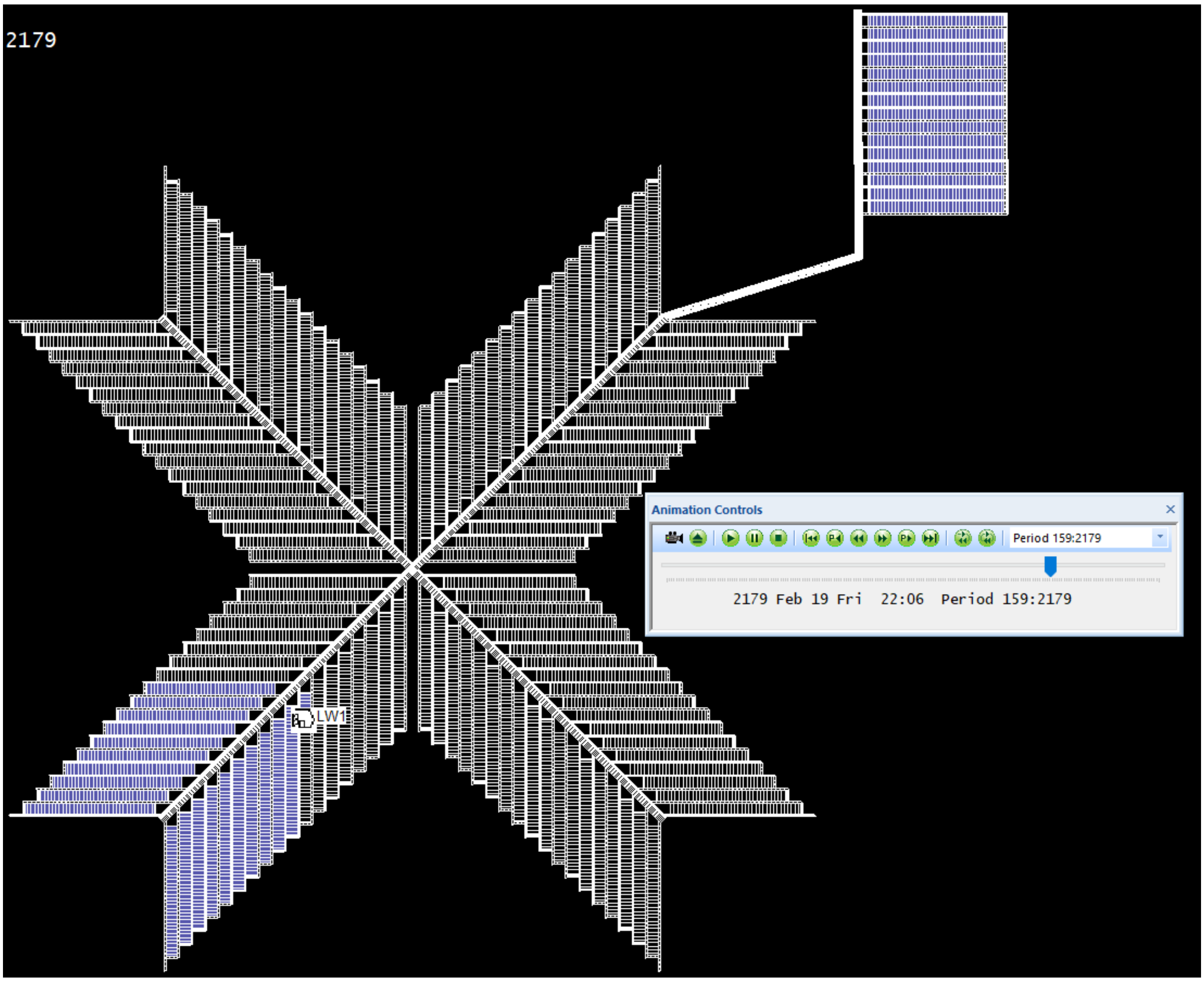


Figure 4-39: Milestone 4: Longwall only operation with rehand each side of southwest mains resulting in a slow increase in combined distance from the portal.

The combined distance for the longwall only then rises again in Milestone 5, shown in Figure 4-40, as a step change in distance occurs since deliveries must travel an additional 7,000 metres along the access mains from the end of the Northeast Area/Domain to the Northeast Extension. The small oscillation around this milestone is due to each longwall panel as it retreats to mains and then changes out to the next longwall inbye at the end of next gateroad to then retreat again back towards the mains headings. The gradient of the longwall combined distance per day in Milestone 5 is higher than can be seen around Milestone 4 because in the first four Area/domains including the Southwest area/domain of Milestone 4 rehanding of the longwalls occurs each side of the mains slowing progression away from the portal. The Northeast extension Area/domain only has longwalls on one side of the mains and therefore the relative speed of the longwall is double in this Area/domain.

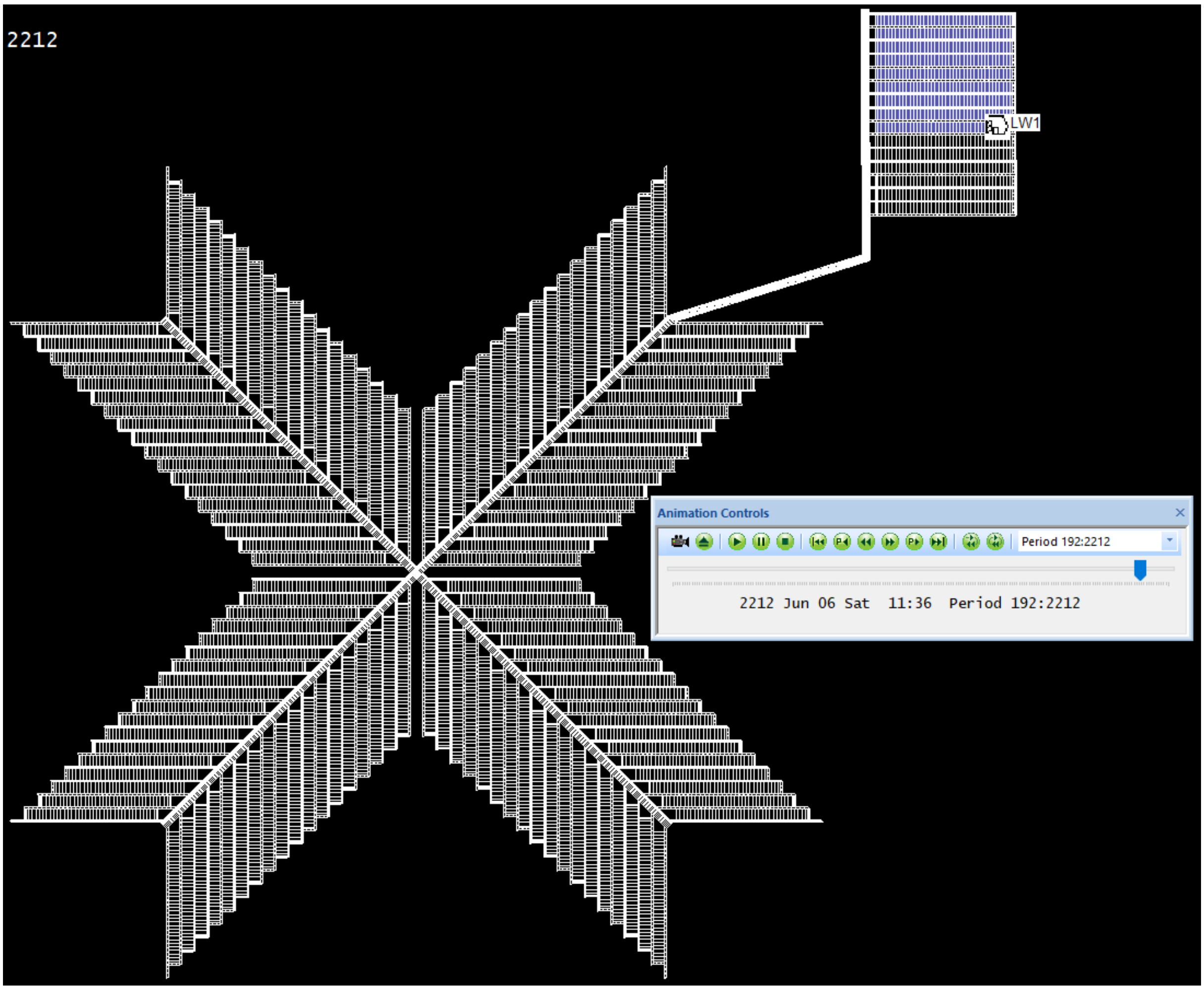


Figure 4-40: Milestone 5 Longwall extraction Northeast Extension Area/Domain with no rehand resulting in a fast increase in combined distance from the portal.

4.4.2 Loads per day

The loads per day, shown in Figure 4-41, peaks at the same requirement as that of Case 1. Both Cases 1 and 2 have a peak daily delivery rate of 29.2 loads averaging typically over 12 weeks to peak at 26.5 loads per day. It continues to be a direct reflection of the number of productive units employed at that time within the life of mine schedule. Case 1 and Case 2 diverge only when development of the Northeast domain is undertaken in case 2, where in Case 1 development was curtailed.

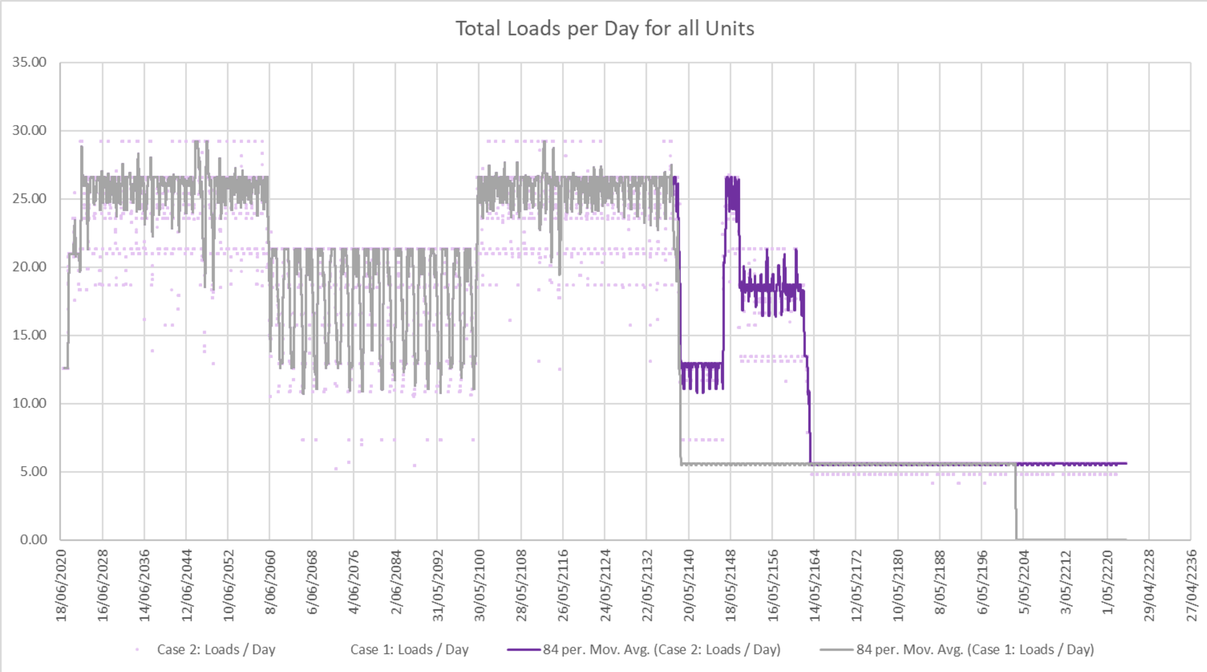


Figure 4-41: Case 2 vs Case 1 loads per day for all units.

4.4.3 Loads on road

Loads on road, shown in Figure 4-43, takes a sharp increase with the introduction of the Northeast Area/Domain. Case 1 was 3.6 compared to 4.7 in Case 2 loads in road and is a sharp increase from operating in the previous Area/Domain even with the reduction of development units. This highlights the impact on logistics strain that requires a large step around or mains corridor to enter a new Area/Domain demonstrated in reality in Figure 4-42.

Figure 4-42: An actual mine with domain step arounds/mains corridors. Note the Area3A to 3B step around is a full longwall length.

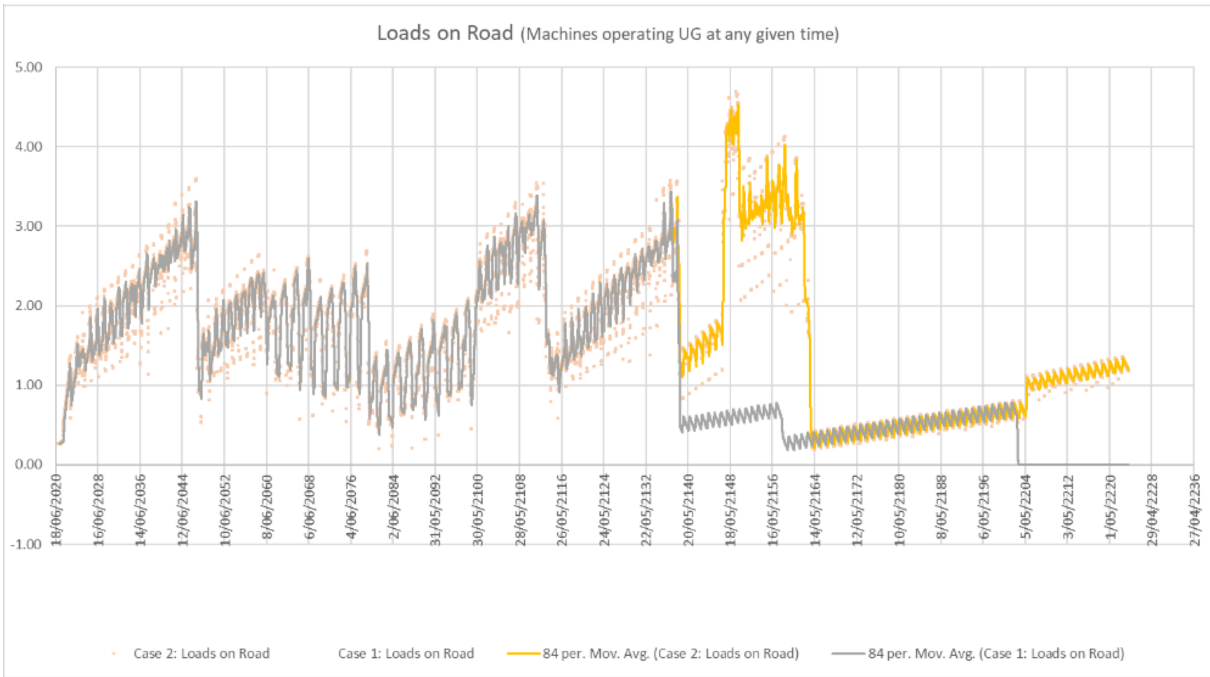


Figure 4-43: Case 2 vs Case 1 loads on road / logistics strain for Case 3 (orange).

4.5 Case 3: The introduction of varying Primary Support

Case 3 introduces variable primary support and with it a slowing of overall development productvity. This is turn reduces the development inventory in advance (much like Case 1b) in this case to a more realistic schedule. It should be remembered that both Case 1 and Case 2 have homogenous primary support so that variables such as path, development inventory in advance, unit mobilisation and demobilisation, productivities, and large step around mains corridor impacts could be isolated avoiding interference from changes to primary support and hence variable delivery. The period plot for Case 2 is shown in Figure 4-44.

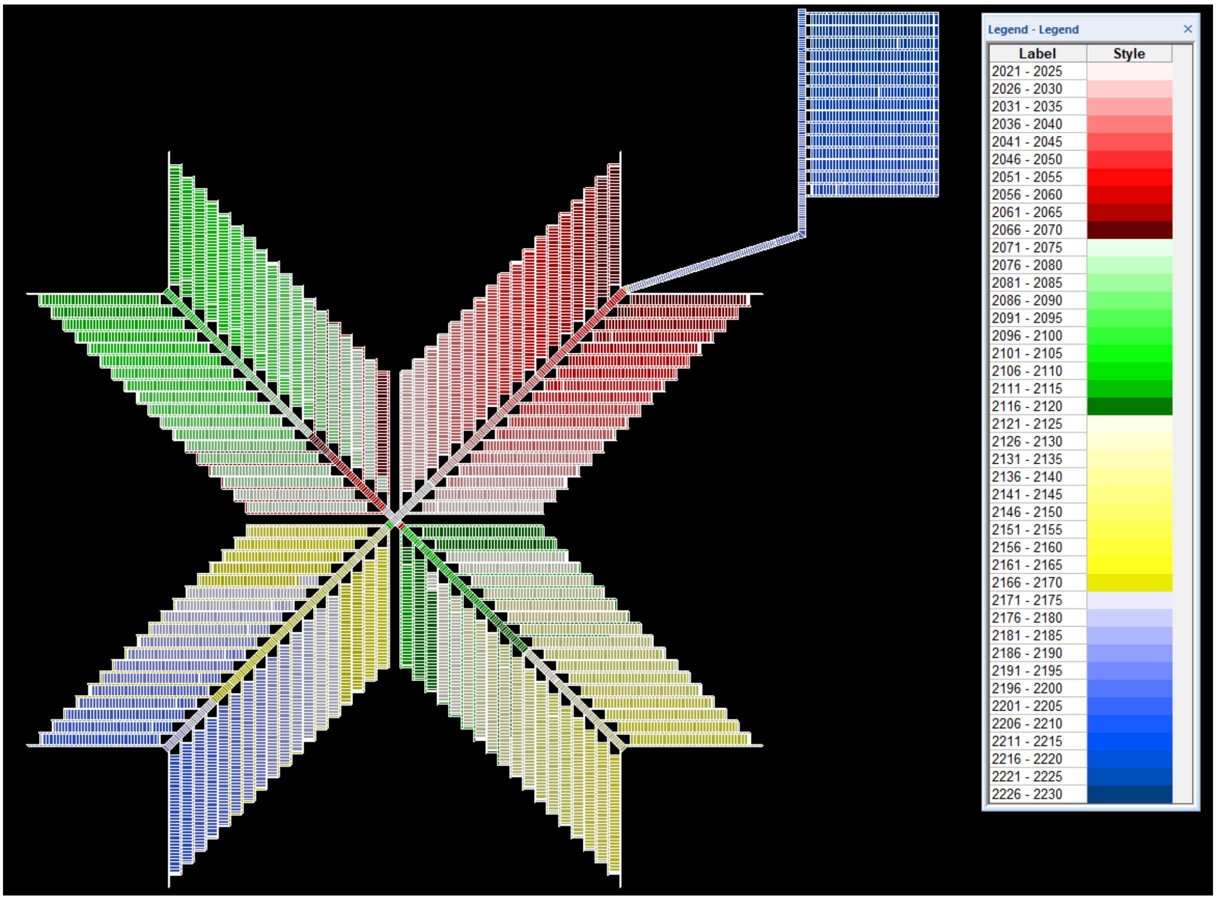


Figure 4-44: Period plot of Case 3.

It is important to note that there are slight changes to development unit paths at a granular level as productivies per unit have been impacted by the new primary support regime. Development inventory in advanced, how far development is ahead of a longwall, is reigned in due to a reduction in productivity based on the the more complex primary support regime to only maintain a reasonable longwall float. The schedule is setup at a tactical level to make its own small discrete decisions by individual development units based upon pit room, machine availability and priority panels at the time which is standard practice in mine planning. That being said at a macroscopic level the underlying strategic theme of the development path is maintained across Case 2 to Case 3. Longwall path does not change and continues to rehand across the mains with the exception of the Northeast extension domain.

As can be seen in Figure 4-46 the combined distance peaks for the first four areas/domains are approximately the same albeit with the gradients to these peaks being shallower because development inventory in advance is less due to the lower development rates. The combined distance per unit of time gradients continues to be low as each of the first 4 domains (NE, NW, SE, and SW) are rehanding the longwall across the mains as per Case 1 and 2. In the Northeast extension area/domain two development units and the longwall with a reduction in development inventory in advance means that the combined distance of all productive units is high compared to Case 2 where development has ceased. The combined distance per unit of time gradient increases because the longwall panels continue to operate on the one side of mains for the area/ domain like Cases 1 and 2.

4.5.1 Combined Distance

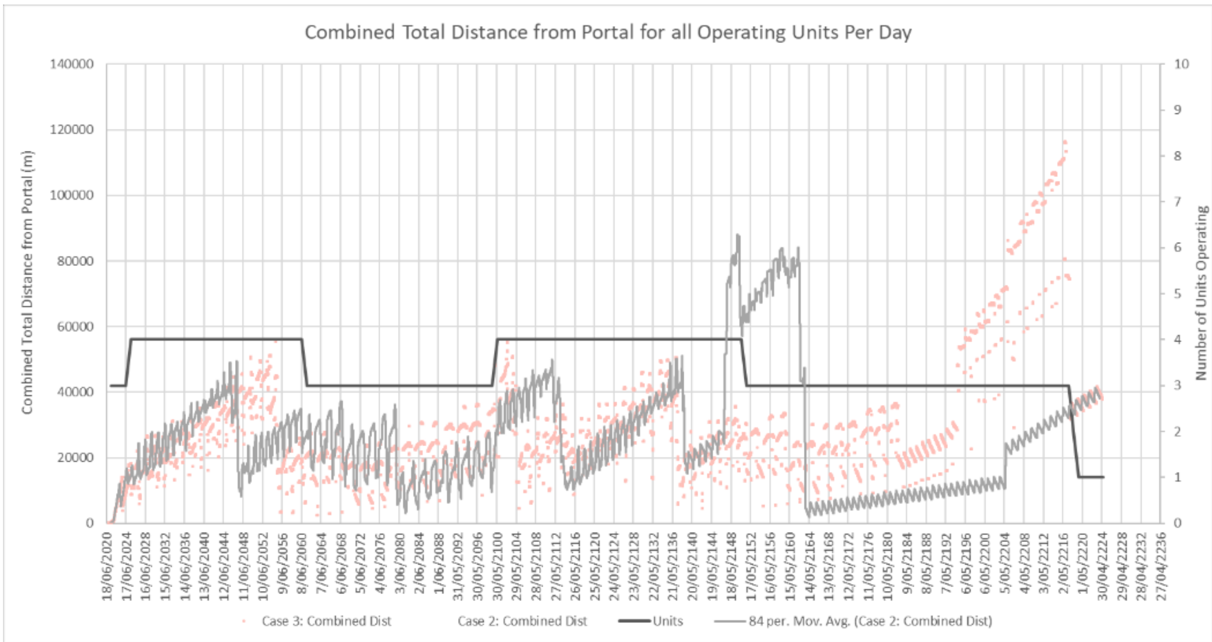


Figure 4-45: Case 3 vs Case 2 daily combined total distance from the portal for all productive units.

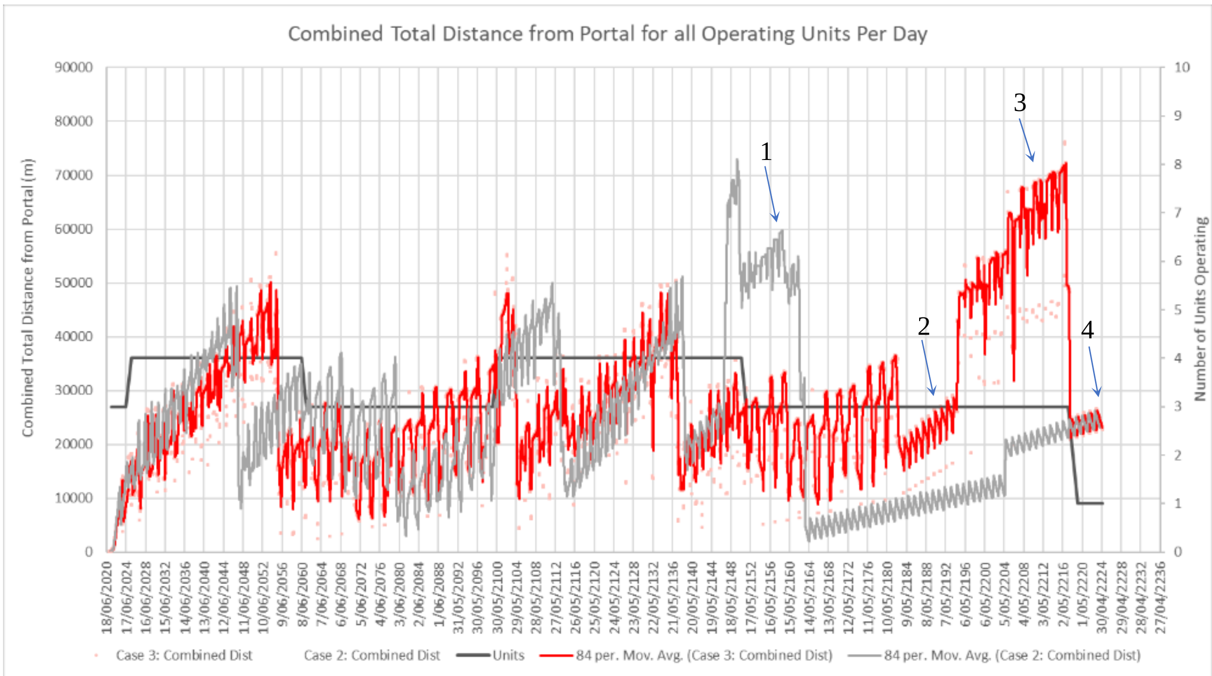


Figure 4-46: Case 3 vs Case 2 daily combined total distance from portal (red) for all productive units with a 12-week rolling average trendline.

Milestone 1 shows the significance of Case 2 development inventory in advance due to higher development rates of "all green" primary support. Figure 4-47 highlights the difference between the two cases for Milestone 1. In Case 2 development is very far inbye in the Northeast Extension Area/domain leading to significant combined travel distances whereas for Case 3 all the development units are within the Southwest Area/Domain with development midway through the area / domain and the longwall being very close to the portal.

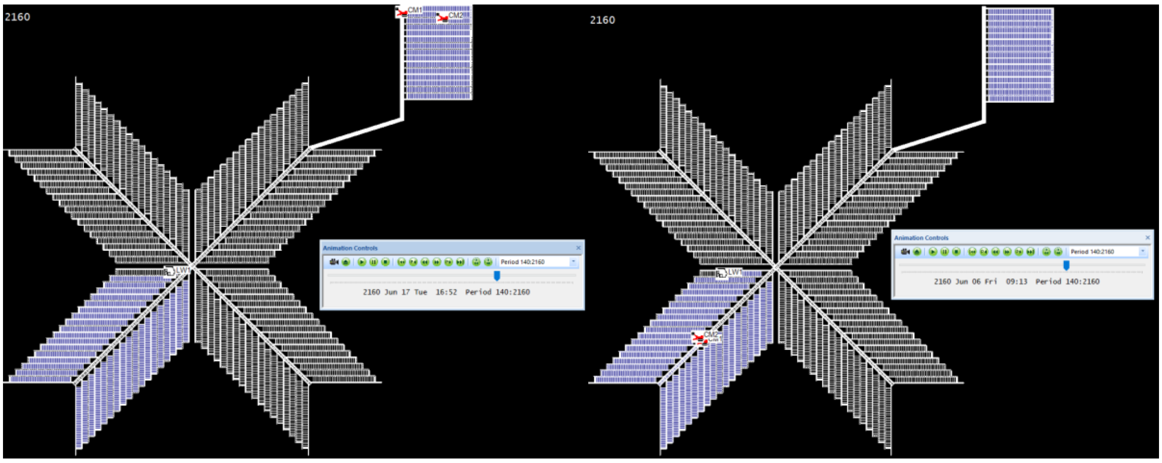


Figure 4-47: Milestone 1 Left Case 2 and Right Case 3.

Milestone 2, shown in Figure 4-48, is a combination of slow mains headings super units driving out to the Northeast extension area/domain with the longwall midway through the Southwest area/domain. There is a steady growth in combined distance from this point with longwalls progressing southwest and development inventory in advance required to maintain longwall continuity between the Southwest Area/Domain and the Northeast Extension Area/Domain.

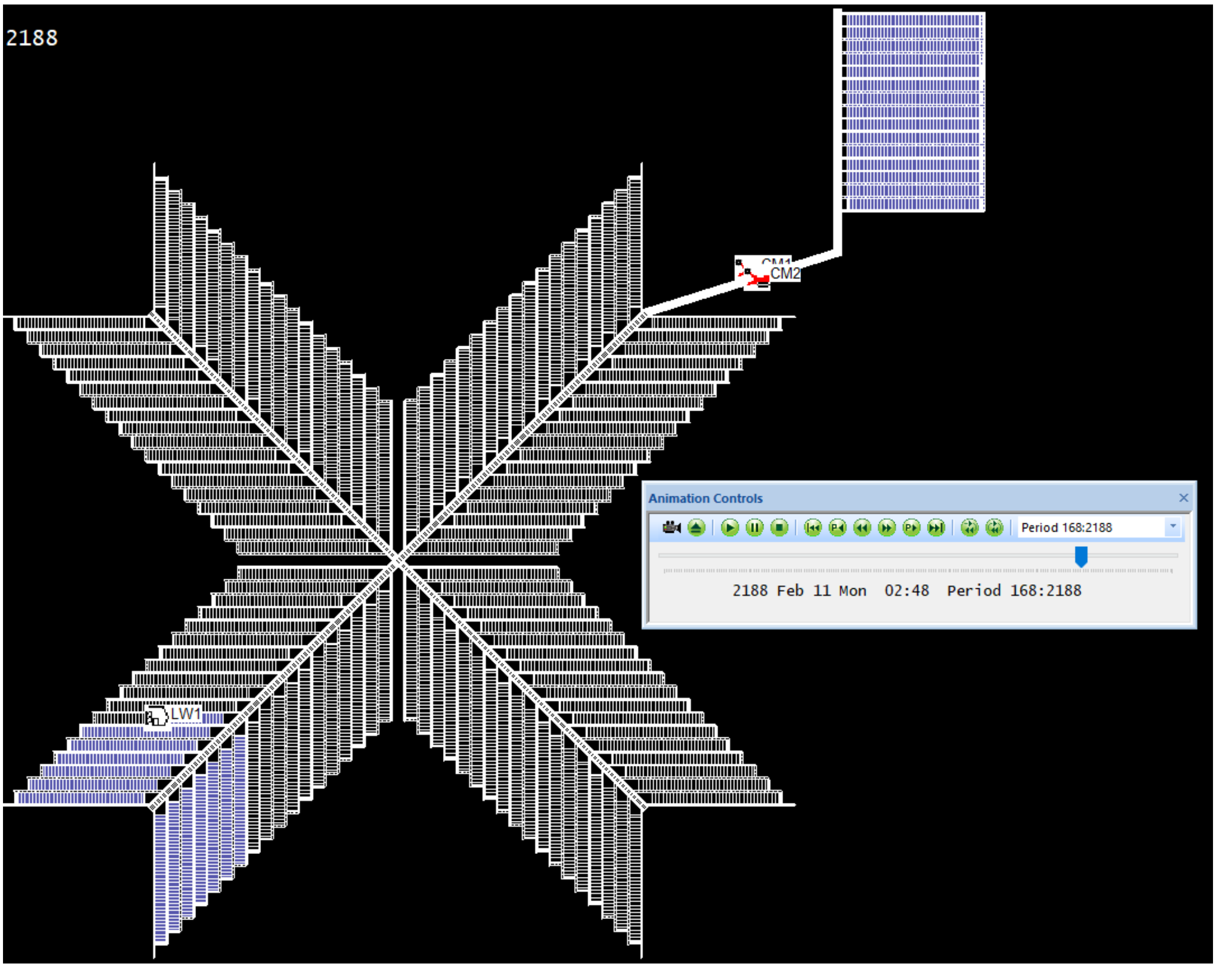


Figure 4-48: Case 3 Milestone 2.

Milestone 3, shown in Figure 4-49, highlights the impact of all productive units being in proximity of one another in the Northeast Extension Area/Domain. Here the development inventory in advance has been reduced which in turn means that combined distance from the portals is at a very high peak.

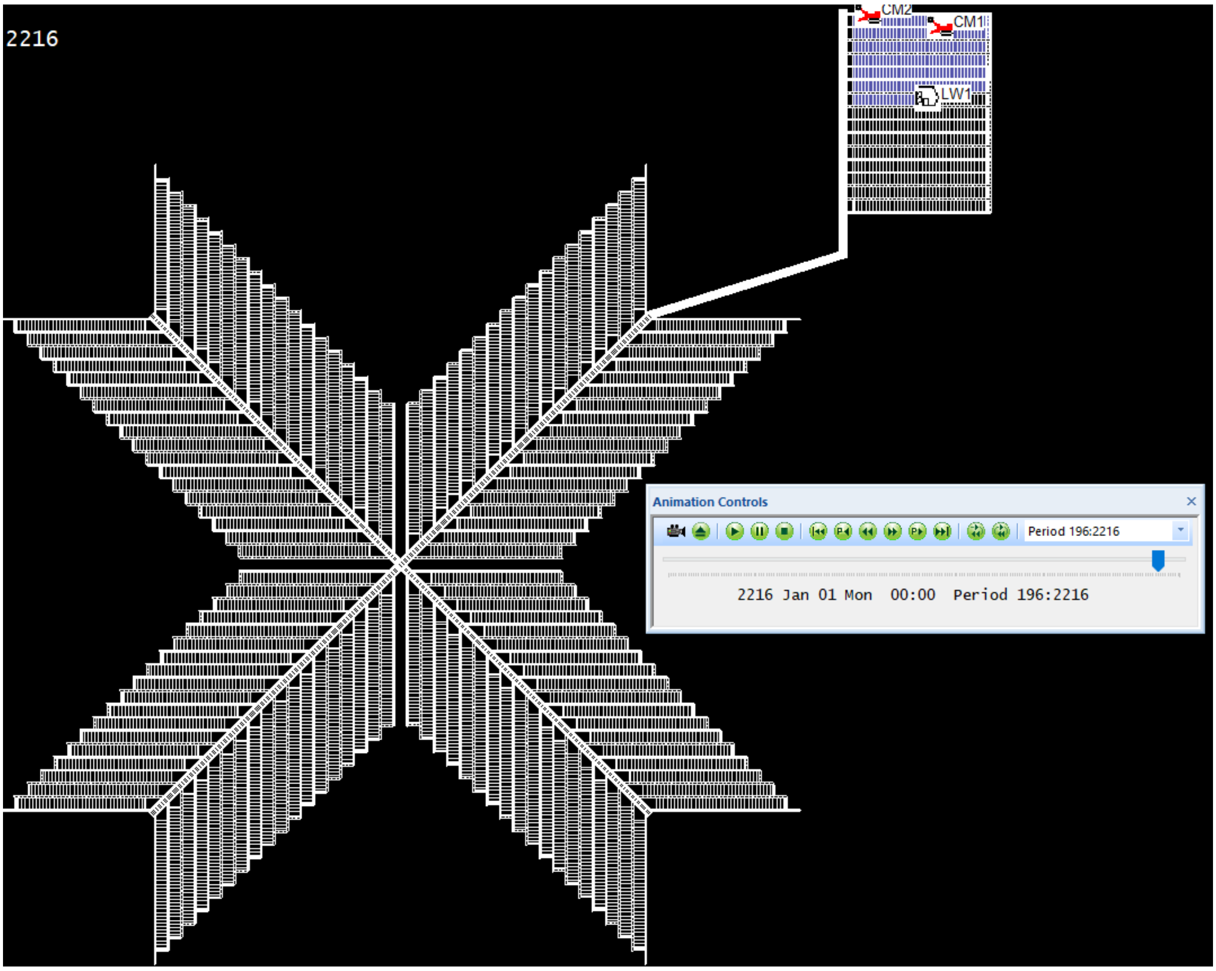


Figure 4-49: Case 3 Milestone 3.

Milestone 3 shows the impact of development completion in the Northeast Area/Domain and the combined distance from this point is then nearly the same when considering a slightly delayed longwall start date for Case 3 with slower development rates due to the introduction of varied primary support.

4.5.2 Loads per day

The loads per day, shown in Figure 4-50, are significantly higher compared to Case 2, which is a direct reflection of the impact of additional deliveries required for the varying primary support. The amplitude of delivery requirements for day-to-day use is also significantly higher. Figure 4-50 shows the loads per day and circles in red one of the outlying peaks of loads per day which occurs on the 11/4/2102 peaking at 49 loads. This is because all the development units are in yellow support which as proposed in Chapter 3 Table 3-10 is now confirmed as the "perfect storm" for deliveries per day.

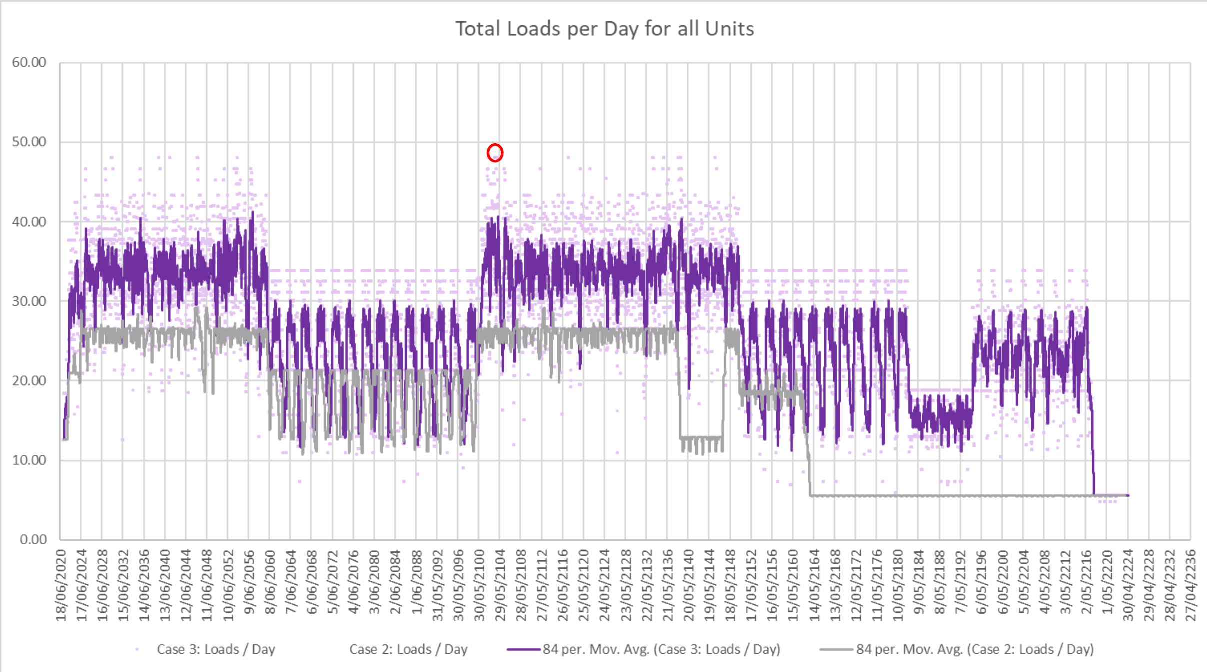


Figure 4-50: Case 3 vs Case 2 loads per day (purple) circling a "perfect storm" of all yellow support for all development panels on 11/4/2102.

This confirms the mine planner now has a tool, through this thesis, that can alert the mining logistics department to the peaks with early warning to build materials inventory within each panel if the logistics strain (loads on road) demands it.

4.5.3 Loads on road

With the combination of increased deliveries per day from the varying primary support combined with distance, loads on road / logistics strain in Case 3 overshadows Case 2 especially in the Northeast Area/domain. Loads on road takes a sharp increase with the introduction of the Northeast Area/Domain. The logistics strain peak is 62% higher at 7.6 than the peak of Case 2 at 4.7 machines underground at any given time. Whilst the gradient of combined distance was generally lower in Figure 4-46 previously, when it is combined with the significantly higher delivery requirements per day, the loads on road / logistics strain gradient is now higher for Case 3 meaning an overall logistics strain that is higher in Case 3 than for Case 2 even with the exaggerated development inventory in advance in Case 2. Figure 4-51 projects the life of mine daily loads on road for Case 3. The logistics strain peaks will be reduced to what is shown in the 12-week rolling average which equates to approximately 0.75 loads on road at any given time if week-to-week deliveries prior to a peak event build supply inventory ready for the peak.

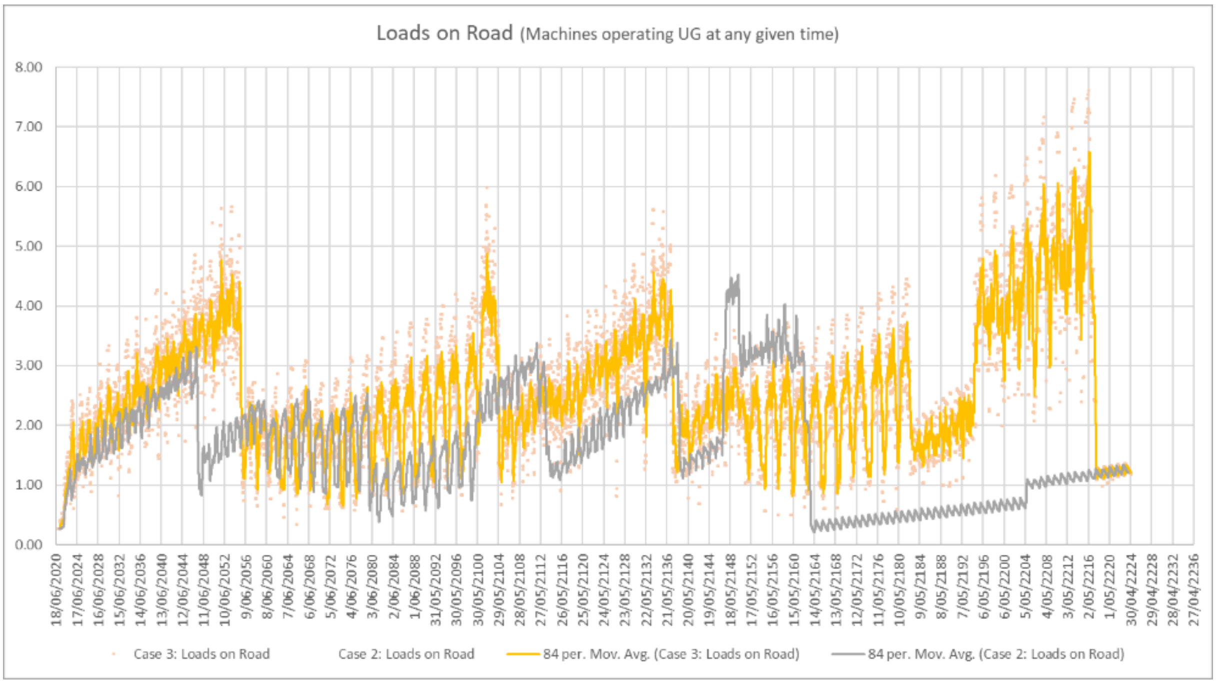


Figure 4-51: Case 3 vs Case 2 loads on road / logistics strain for Case 3 (orange).

4.6 Case 4: A change in scheduling path philosophy

Case 4 changes its path in the first four domains from rehanding longwalls across the mains, to going down one side of the mains and then returning to complete the area/domain. There is no change to the Northeast extension Area/domain as it is single sided. Figure 4-52 is the period plot for Case 4, and shows the progression from Northeast area/domain right side of the mains, then left side of the mains looking inbye. Progression thereafter is the Northwest area/domain right of mains then left of mains, the Southeast domain right of mains then left of mains, then southwest right of mains then left of mains looking inbye along each mains heading..

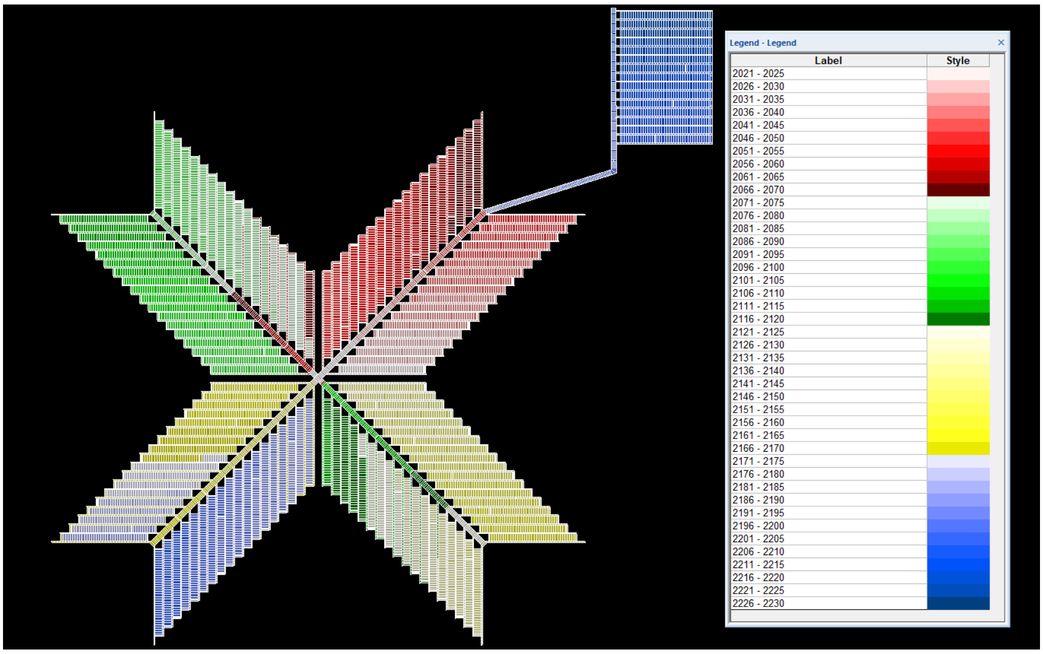


Figure 4-52: Period plot of Case 4.

4.6.1 Combined Distance

Although the life of mine cumulative tonnes per development metre is the same at mine completion, drivage of the entire mains for only one side of longwall extraction means that there is higher pressure on development for the first half of the domain (the right side) and less pressure on development as the mains are already driven for the left side. Figure 4-53 and Figure 4-54 confirm this as the gradient of the combined distance is higher for Case 4 as compared to Case 3 for the first four Area/domains as inbye extents are reached sooner.

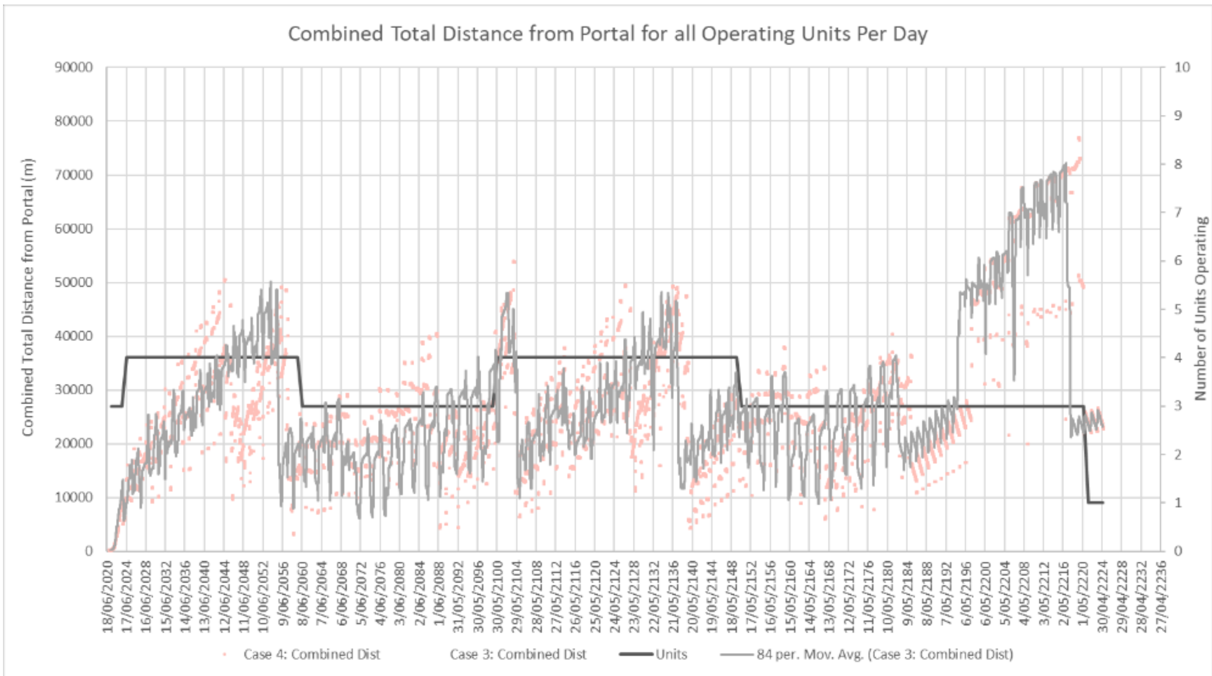


Figure 4-53: Case 4 vs Case 3 daily combined total distance from the portal for all productive units.

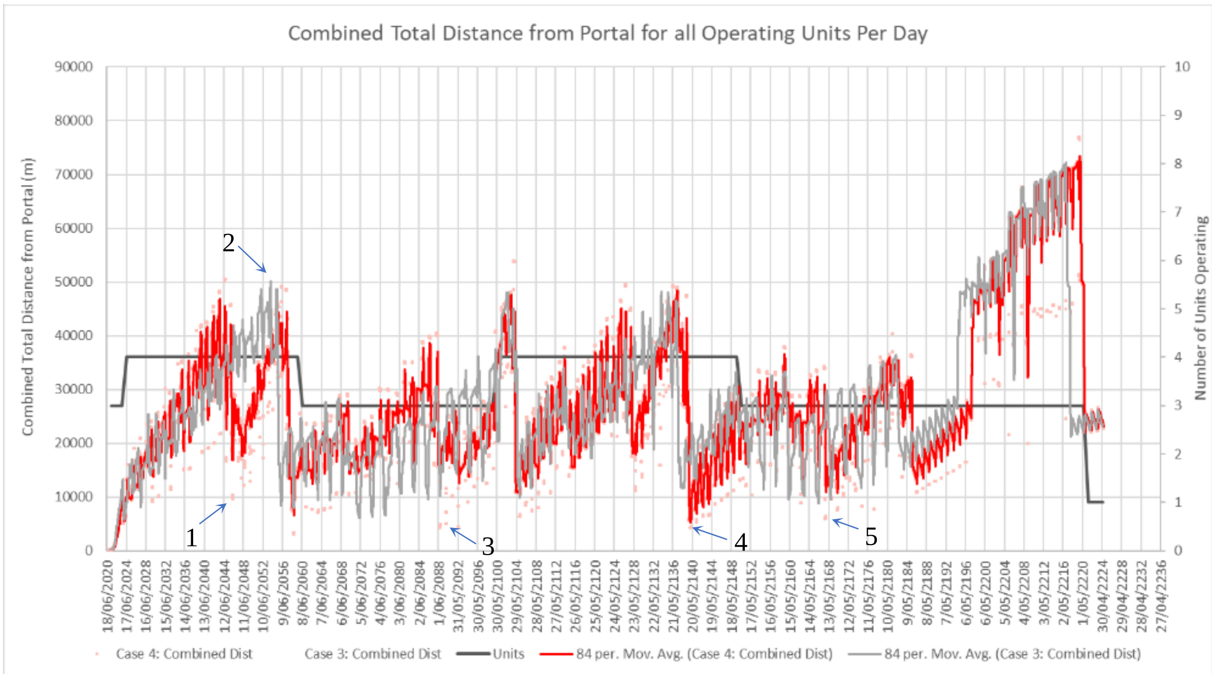


Figure 4-54: Case 4 vs Case 3 daily combined total distance from portal (red) for all productive units with a 12-week rolling average trendline.

With respect to the first four area/domains, Case 4 reaches the extents of the area/domain for one side before returning to the proximity of the portal to extend away again. Therefore, extents for each area/domain are reached in approximately half the time and the frequency of achieving peak combined distance per domain is doubled. Milestone 1, shown in Figure 4-55, shows how Case 4 has returned to being relatively close to the portal for all development units whilst Case 3 continues to move away albeit at a slower rate.

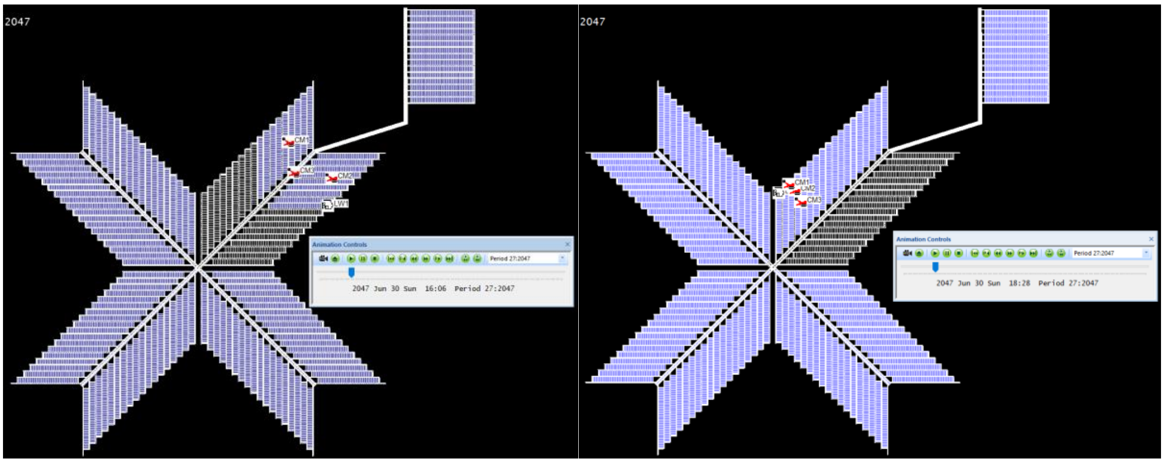


Figure 4-55: Milestone 1 left is Case 3 and right is Case 4, highlight the doubling of frequency of return to the portal.

A very important observation is that whilst Case 4 has double the frequency and a higher gradient of combined distance per day compared with Case 3, Case 3 has a 10% higher peak combined distance than Case 4. This is because Milestone 3 has more pit room at the inbye extents of the area/domain to have all machines operating compared with Case 4. This is shown in Figure 4-56 for Milestone 2: -

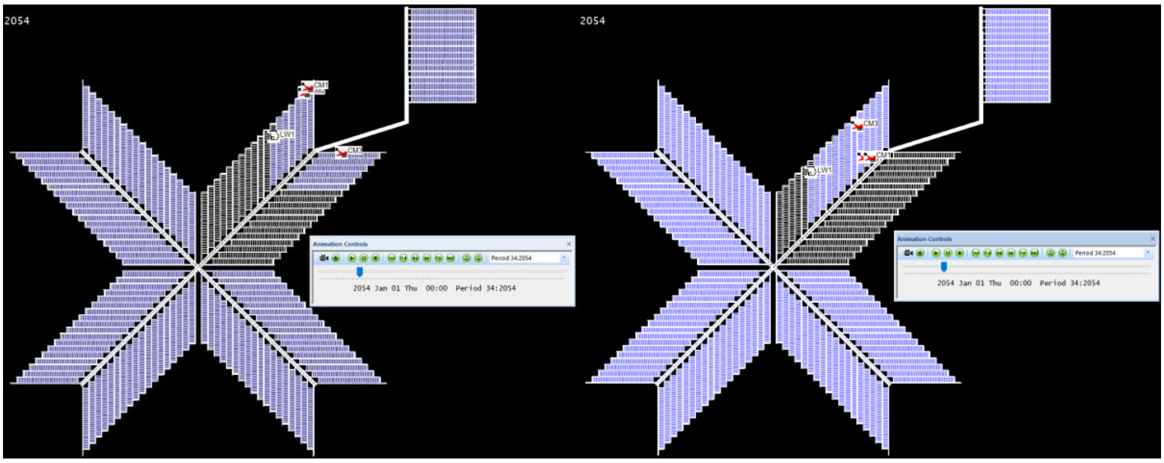


Figure 4-56: Milestone 2 left is Case 3 and right is Case 4 highlighting that Case 3 can sustain higher combined distances than case 4.

The peak combined distance for the Northeast Area/domain is 55.6 km for Case 3 and 50.6 km for case 4. In summary, Case 4 arrives at combined distance peaks sooner and has more of them, but Case 3 builds combined distance slower but can have higher combined distances.

Milestone 3, shown in Figure 4-57, is like Milestone 1 with Case 4 returning to proximity to the portals as Case 3 continues to extend out. The change in combined distance is less because the number of productive units has reduced to two development units and the longwall.

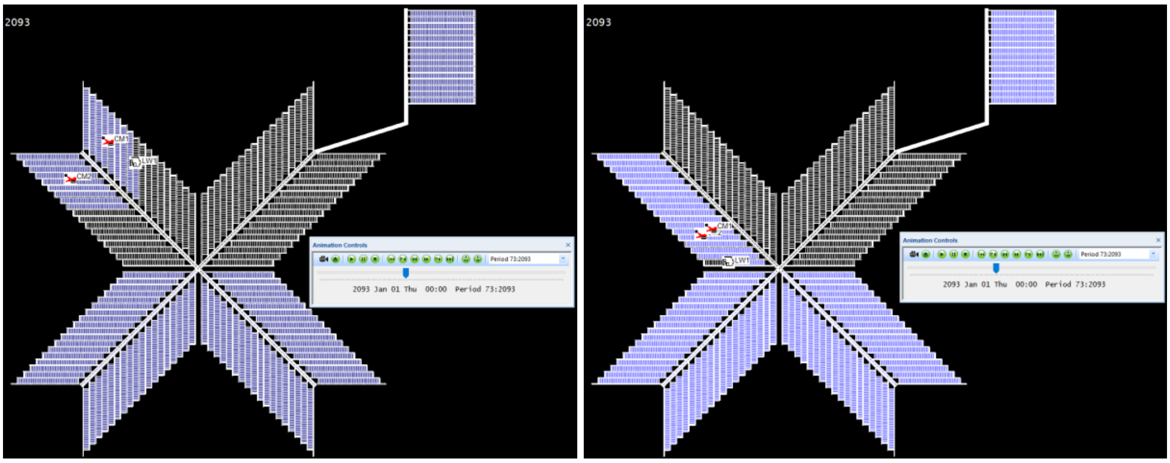


Figure 4-57: Milestone 3 left is Case 3 and right is Case 4.

Milestone 4, in Figure 4-58, shows that every second trough is the return to proximity to the portals for both cases. This confirms that Case 4 is around double the frequency of combined distance peak – trough cycles as for Case 3.

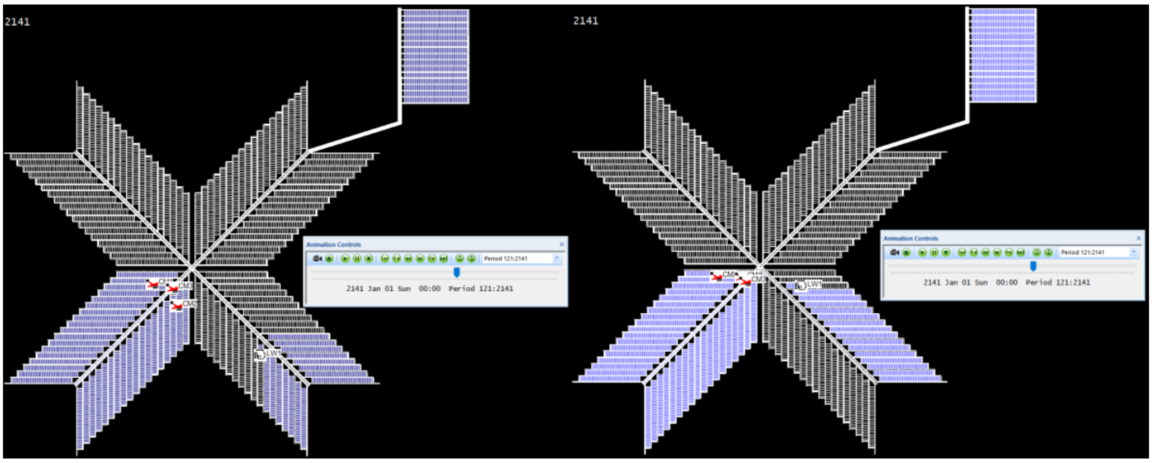


Figure 4-58: Milestone 4 left is Case 3 and right is Case 4.

Milestone 5, shown in Figure 4-59, is similar to Milestone 3 with Case 4 returning to proximity of the portal for the two development units and the longwall after completing the left side of the area/domain to complete the right side. Case 3 continues to build combined distance albeit slower in the same domain with development 75% though the domain heavily offsetting the distance contribution made by the longwall which is much closer to the portal.

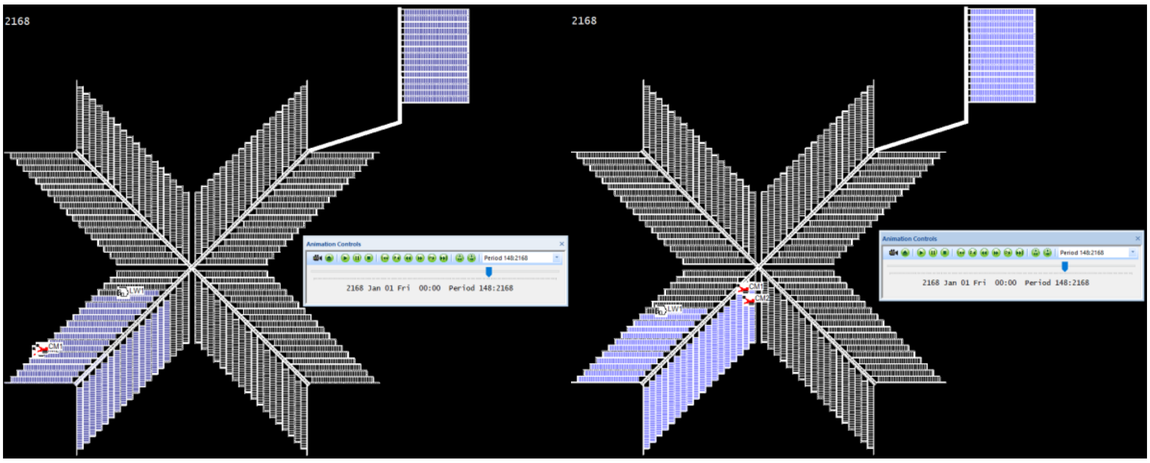


Figure 4-59: Milestone 5 left is Case 3 and right is Case 4.

4.6.2 Loads per day

Case 3, shown in Figure 4-60, has steady loads per day requirements directly reflective of the number of productive machines operating. Case 4 on the other hand alternates steadily either above or below the Case 3 requirements. Case 4 loads per day for the first half of the first four Area/Domains are lower than Case 3. For example, from LoM start to just prior to Milestone 1. This is because Case 4 has a higher proportion of mains drivage which is slower as it is entirely driven in the first half of the Area/domain extraction timeframe, thus, requiring less deliveries. Case 4 loads per day increases above Case 3 for the second half of the domain because Case 4 in this timeframe no longer has any mains at all to drive and therefore the overall development rate and hence the loads per day requirement is higher.

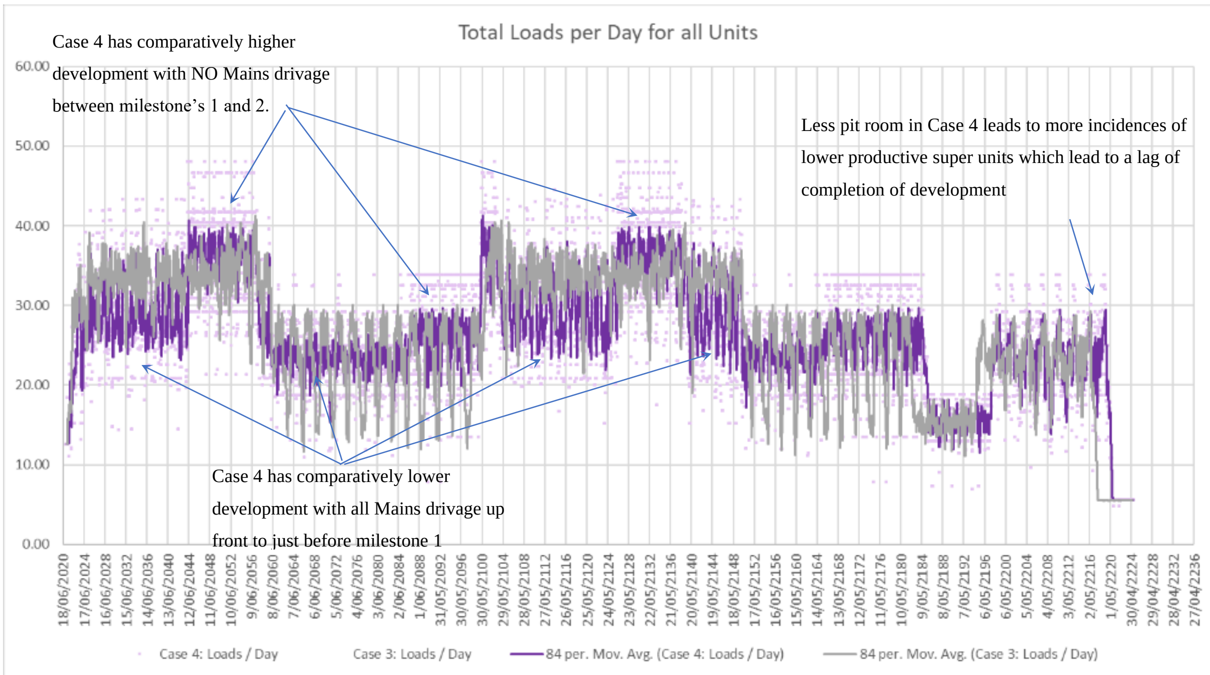


Figure 4-60: Case 3 vs Case 2 loads per day (purple) circling a "perfect storm" of all yellow support for all development panels on 11/4/2102.

The loads per day for the Northeast extension area/domain is almost identical because development is the same through this domain with no rehanding opportunity for the longwall. Case 4 continues to have development loads per day beyond Case 3 because Case 4 has less pit-room without alternating drivage of gateroads each side of the mains as the area/domain progresses which in turn leads to more incidences of super units throughout the life of mine which are less productive than if the units were in their own respective panel.

4.6.3 Loads on road

Referring to Figure 4-61, in the first four areas/domains, which is the migration away and return to portals, the logistics systems, associated infrastructure, and machinery would have to be setup and ready to handle peak loads in half the time for Case 4 compared to Case 3. On the other hand, Case 4 does not have to sustain high logistics strain durations compared to Case 3. Case 3 continues to build, albeit slower, logistics strain and has the pit room that allows more units to be a maximum combined distance away from the portals. Case 3 peak logistics strain is 4.8% higher than Case 4 but depending on the schedule of an individual mine should be monitored to ensure that it is not much more.

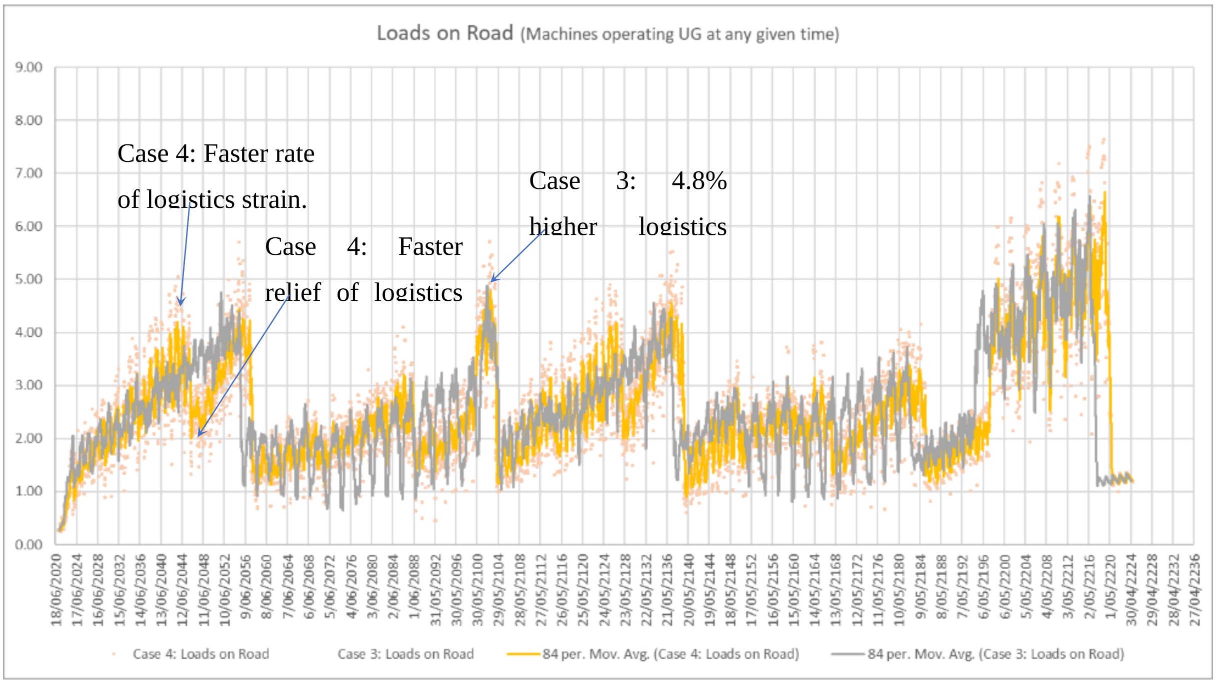


Figure 4-61: Case 4 vs Case 3 loads on road / logistics strain.

Logistics strain in the Northeast extension is comparable between Cases 3 and 4 and in all practicality beyond logistics breaking strain. Either case would likely need additional infrastructure due to the instantaneous and sizable step change that this area/domain demands to reduce this logistics strain which is explored in Case 5.

4.7 Case 5: Additional Portals installed inbye

Case 5 is the same schedule as Case 4 but has introduced a new portal down in each domain which is anticipated will alleviate logistics strain. The positions of the portals are shown in Figure 4-62:-

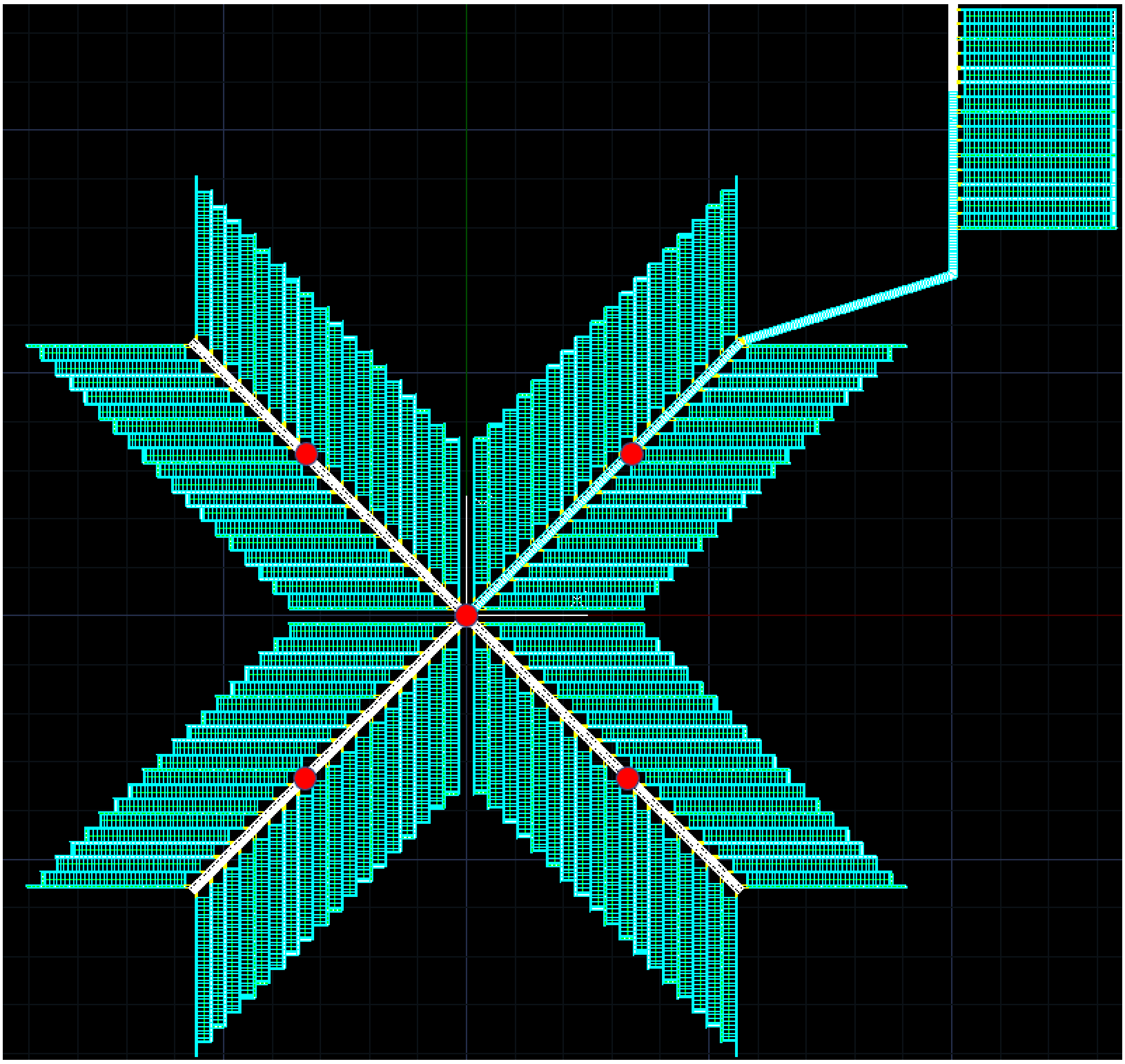


Figure 4-62: Portal positions for Case 5.

Figure 4-63 shows combined total distance for Case 5. At first glance it would be expected that the cumulative distance between Case 4 (red) and Case 5 (grey) should be the same for the first half of each of the area/domains that migrate away and then return to the central portal as this part of the schedule should be supported by the central portal rather than the inbye portal, but this is not correct. There are only certain windows where all machines are serviced by the original central shaft where the 12-week rolling average of Case 4 (grey), shown in Figure 4-64, directly overlies Case 5 (red) which are highlighted by Milestones 1, 4, 5, 6 and 7.

4.7.1 Combined Distance

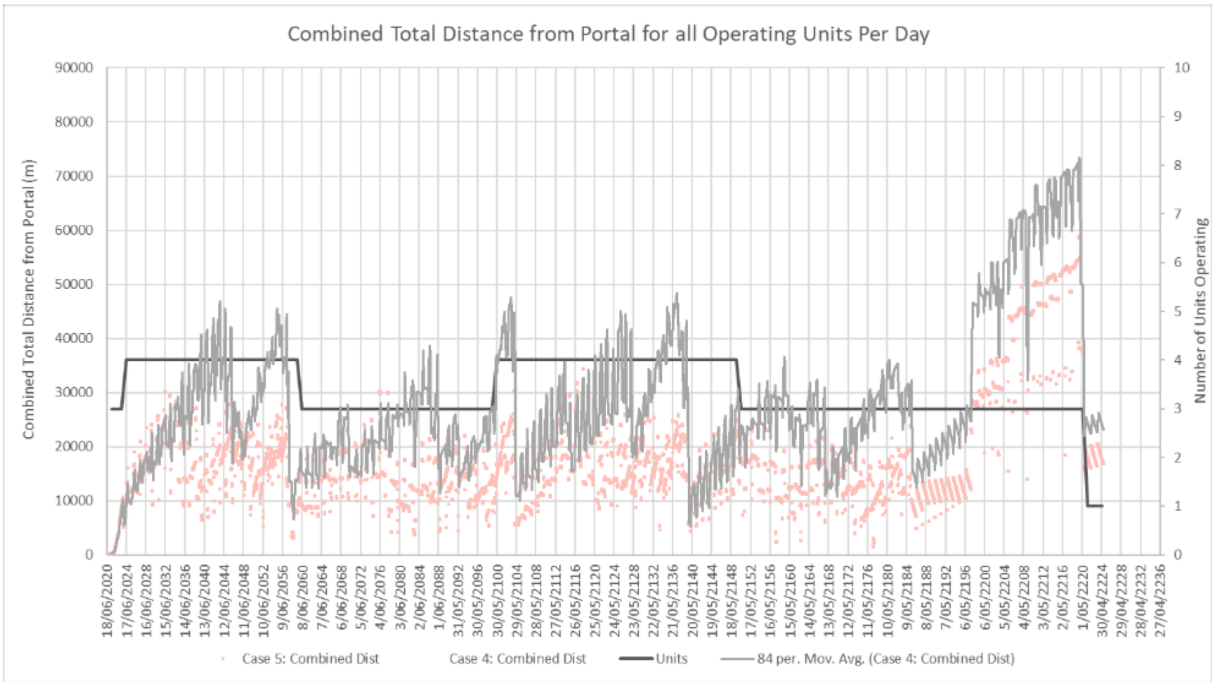


Figure 4-63 : Case 5 vs Case 4 daily combined total distance from the portal for all productive units.

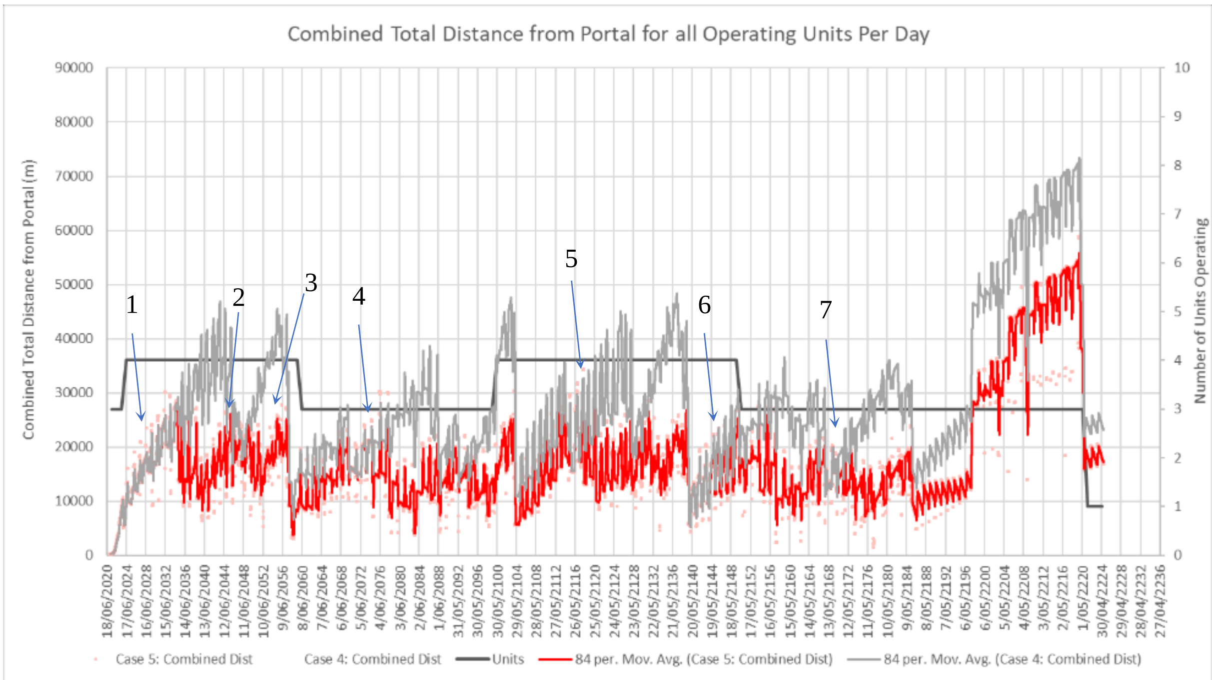


Figure 4-64: Case 5 vs Case 4 daily combined total distance from portal (red) for all productive units with a 12-week rolling average trendline.

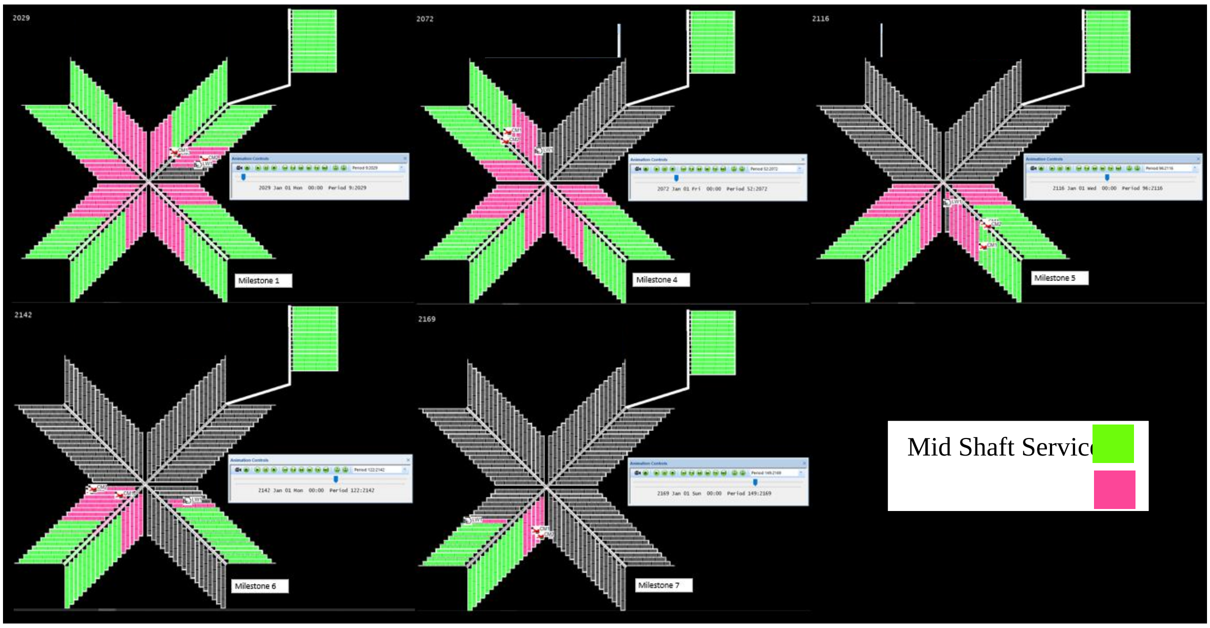


Figure 4-65: Case 5 and Case 4 Convergence of combined distance because all units are using the central shaft.

In Figure 4-65 to Figure 4-67 the green scheduling blocks are serviced by the inbye shaft, and the light red are serviced by the central shaft.

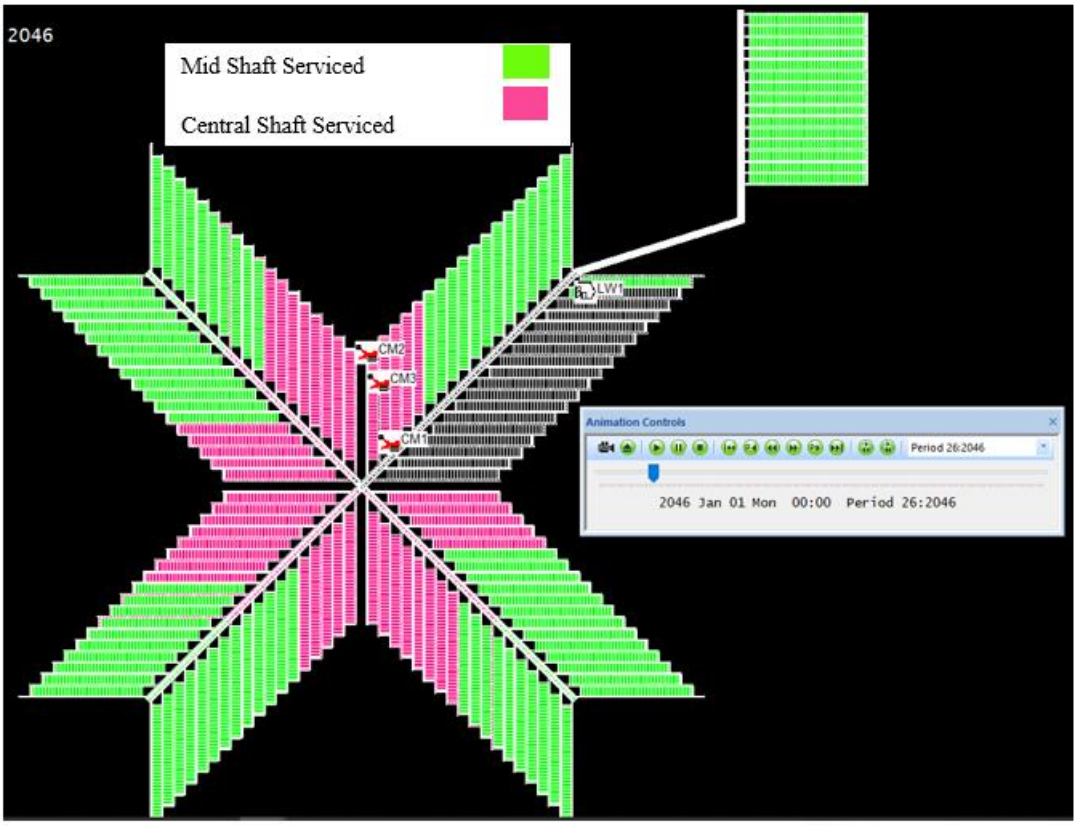


Figure 4-66: Milestone 2 using a combination of Portals used.

Milestone 2 is an example of both an inbye and the central portal being utilised. The longwall is being supplied using the inbye shaft, and the development units are supplied using the outbye shaft leading to a divergence between the combined distance in Case 4 and Case 5. Milestone 3 is serviced entirely by the inbye shaft again creating a divergence from Case 4 for the combined distance.

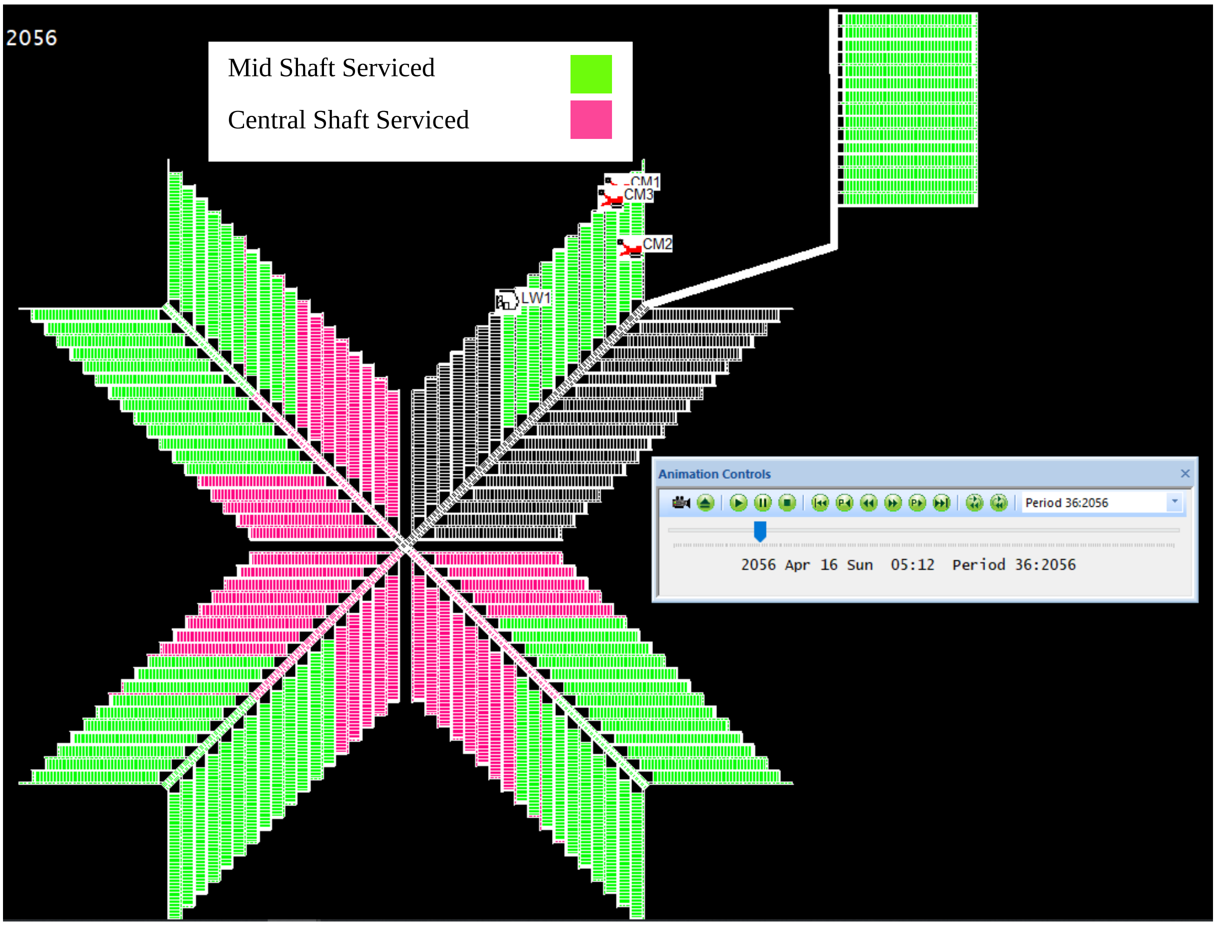


Figure 4-67: Milestone 3 using the inbye shaft serviced workings.

The Northeast extension has a combined distance which is lower in Case 5 than for Case 4 as the entire area/domain is serviced by the inbye portal. This creates a direct shift downwards for the combined distance because each machine is now serviced by a portal which is 6,000 m inbye from the central portal. Therefore, two development units and a longwall in this domain that would equate to a reduction of three x 6,000 m or 18,000 combined metres.

4.7.2 Loads per Day

As previously discussed, loads per day, shown in Figure 4-68, is unaffected by portal location. Cases 4 and 5 have identical schedules which means there is no difference in loads per day for the two cases. The combined loads per day for both Case 5 remains at a peak of 48 and a 12-week rolling average peak of 42 for three development units and a longwall (four productive units) and a peak of 34 and a 12-week rolling average peak of 30 for two development units and the longwall.

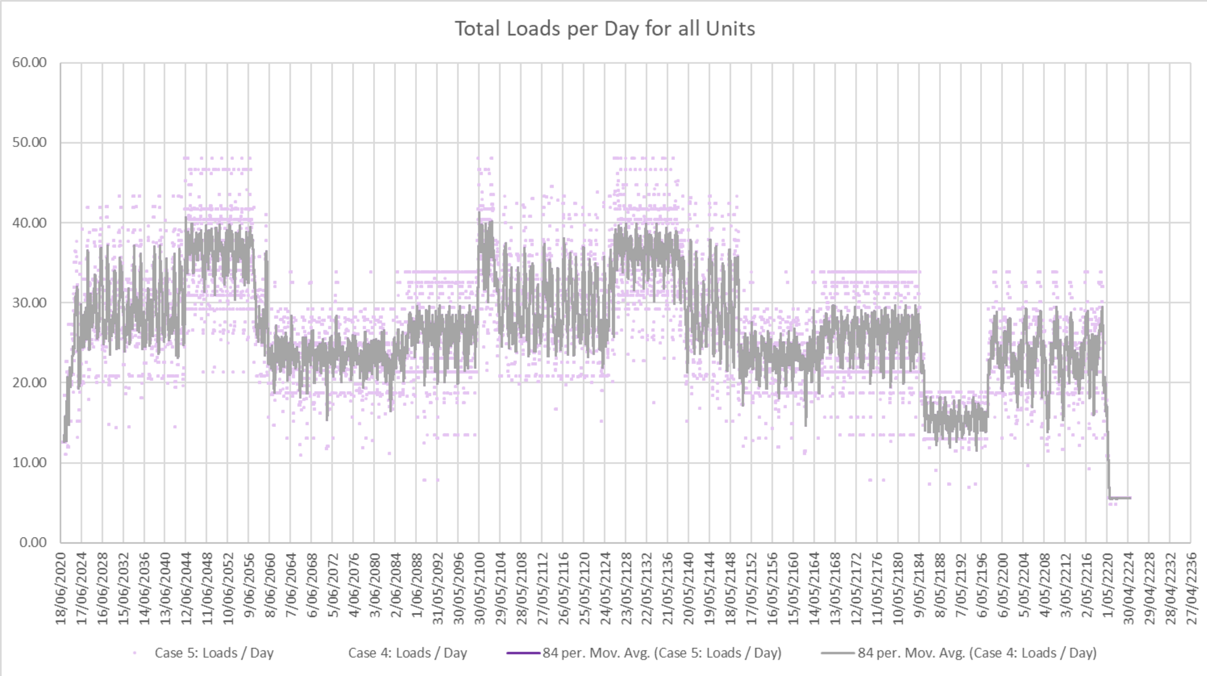


Figure 4-68: Loads per day between Case 4 and case 5 completely overly which confirms that their respective schedules are the same.

4.7.3 Loads on road

Figure 4-69 highlights the comparison of loads on road between Cases 4 and 5. The introduction of a new portal 6 km inbye of the central portal within each area/domain causes a steep reduction in logistics strain. As loads per day are the same between Cases 4 and 5, this reduction is due entirely to the combined distance from the portal(s).

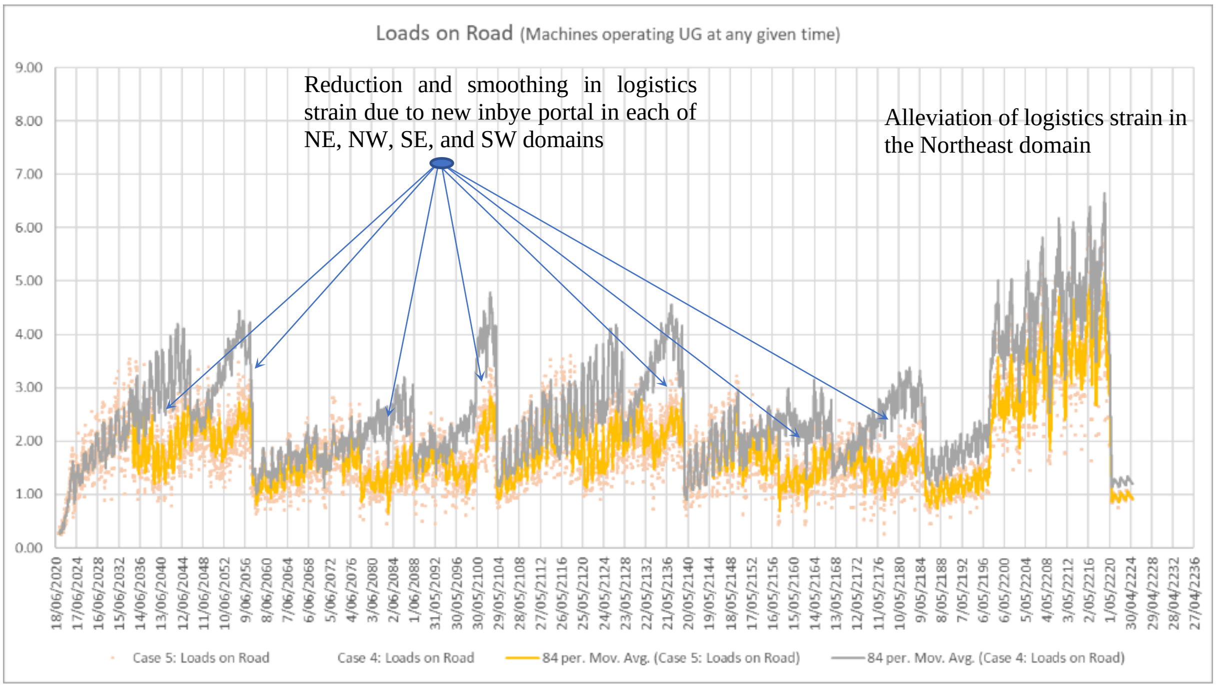


Figure 4-69: Loads on road / logistics strain.

The loads on road reduction can be seen by the smoothing effect of the loads on road/logistics strain in the outer extents of each of the first four area/domains after the new inbye portal is commissioned which has been reduced from a peak of 5.7 machines in Case 4 to a peak of 3.6 machines in Case 5 on road at any given time and in the Northeast Area/domain a reduction from 7.6 to 5.9 from Case 4 to Case 5, respectively.

It should be noted that the logistics strain even with the inbye portal in the Northeast panel may well be still too far for the Northeast extension panel and therefore logistics breaking strain is likely to still occur, albeit with some alleviation of logistics strain compared to Case 4 which would result in slightly higher actual productivity. For the reduction in logistics strain below the logistics breaking strain threshold to be comparable with the first four domains an additional portal should be planned slightly outbye the first longwall in the mains of this area/domain shown in yellow in Figure 4-70 and is further explored in Section 4.9.

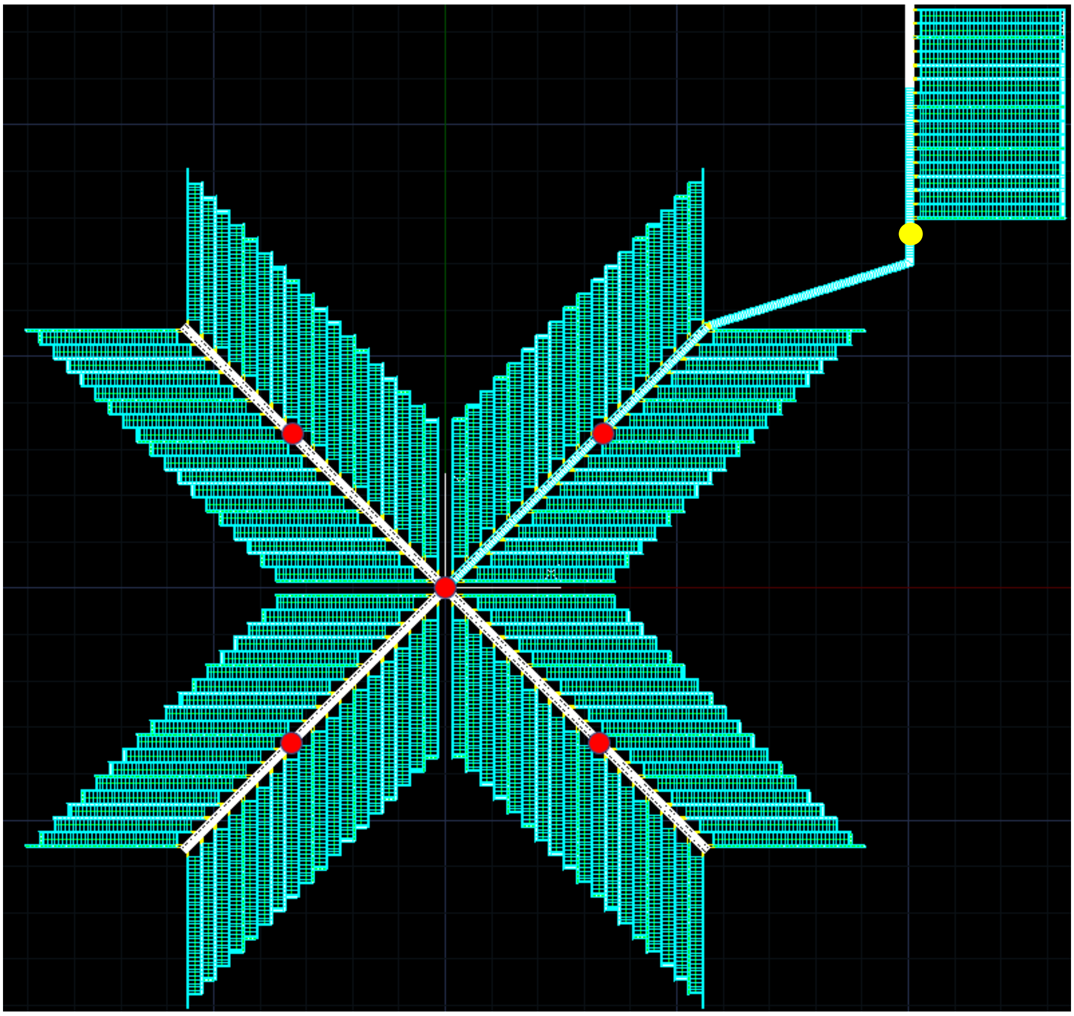


Figure 4-70: Elimination of logistics breaking strain with the introduction of an additional portal in yellow at Northeast extension area/domains "pit bottom".

Whilst this finding that the introduction of a closer portal to the current workings is visible and has always been known in the broader mining industry, this research and experimentation has isolated and quantified the actual reduction and proved that the changes to logistics strain (amplitude) is significantly reduced leading to a more standardised approach to logistics management within the mine in the long-term. In other words, if the planner knows the logistics breaking strain cap, they can, with the tools developed in this thesis, search for the most optimal position for an inbye portal for their mine for the lowest overall logistics strain through trial and error, which will allow capital project planning to be done well in advance, or at the very least, be accounted for in the operation's NPV.

4.8 Case 6: Migration away in a general direction from an Adit/Box Cut/ Cut and Cover Mine

Case 6 is the first of the migration away scenarios. The period plot for Case 6 is shown in Figure 4-71 and Case 6 contains only two longwall domains, the eastern longwalls of the Northeast domain and the Northeast extension domain which in turn means a significantly shorter mine life than all previous cases at 59 years. Figure 4-71 shows the Case 6 mine plan, highlighting the portal, in red, servicing all logistics for the life of mine.

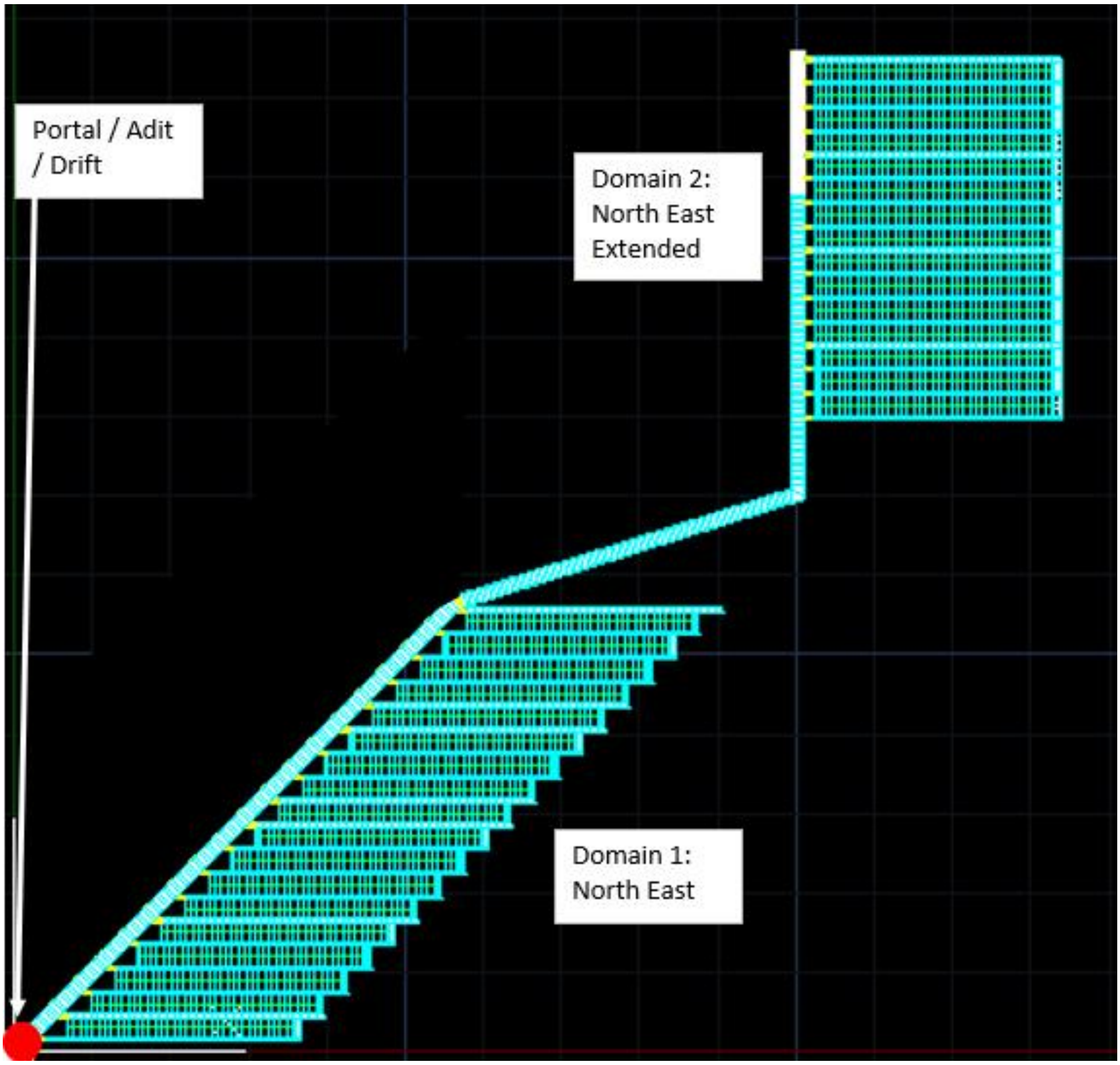


Figure 4-71: Case 6 Mine plan with only the Northeast (eastern side) and Northeast extension.

As there are only longwalls on one side of the Northeast domain there is also no rehand to the other side of the mains headings demonstrated in the period plot for Case 6 in Figure 4-72. This was to prove the hypothesis in Chapter 1 of ever-increasing logistics strain as you move away from the portal which would be the typical scenario of an adit, box cut or cut and cover operation.

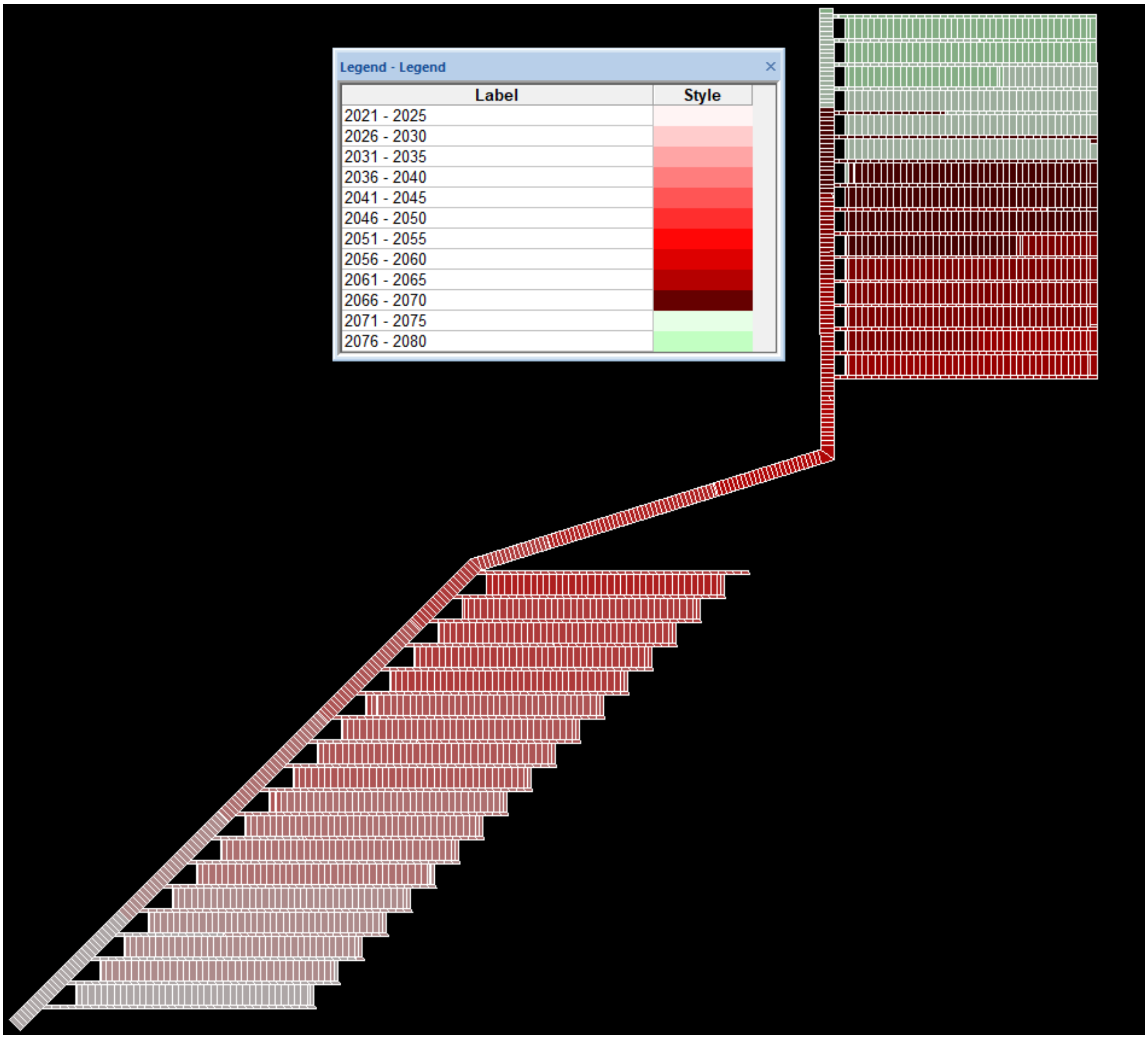


Figure 4-72: Period Plot of Case 6.

Figure 4-73 and Figure 4-74 show that the migration away from the portal into extension Northeast occurs much sooner. As expected, the combined distance gradients in the first half of the Northeast Mains and Northeast Extension are very similar. Case 6 is compared to Case 4 in Figure 4-75 and Figure 4-76 as it does not have the additional shaft inbye in the mains headings as per Case 5.

Milestone 1 is almost identical as development of the western domain is prioritised for the Northeast domain in both cases. It is not entirely identical because in Case 4 the first 100 m of the western gateroads are driven to avoid contravening any hazardous zone legislation in the future which would mean the interruption of electrical high tension power supplies inbye.

4.8.1 Combined Distance

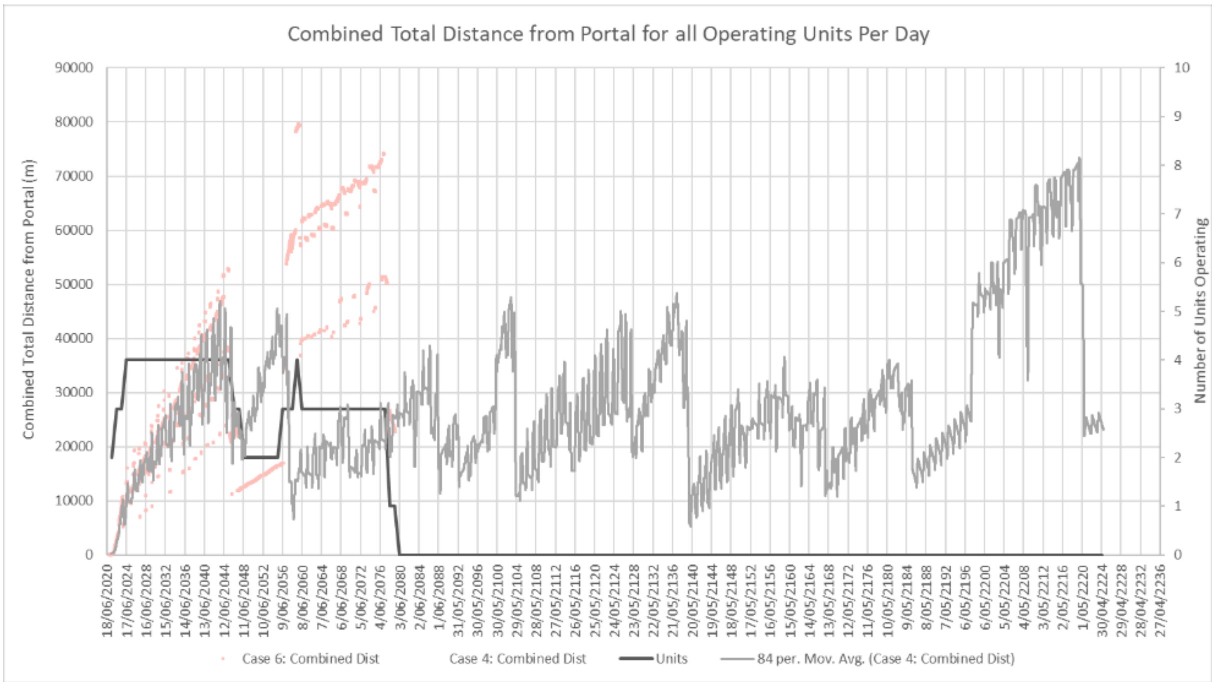


Figure 4-73 : Case 6 vs Case 4 daily combined total distance from the portal for all productive units.

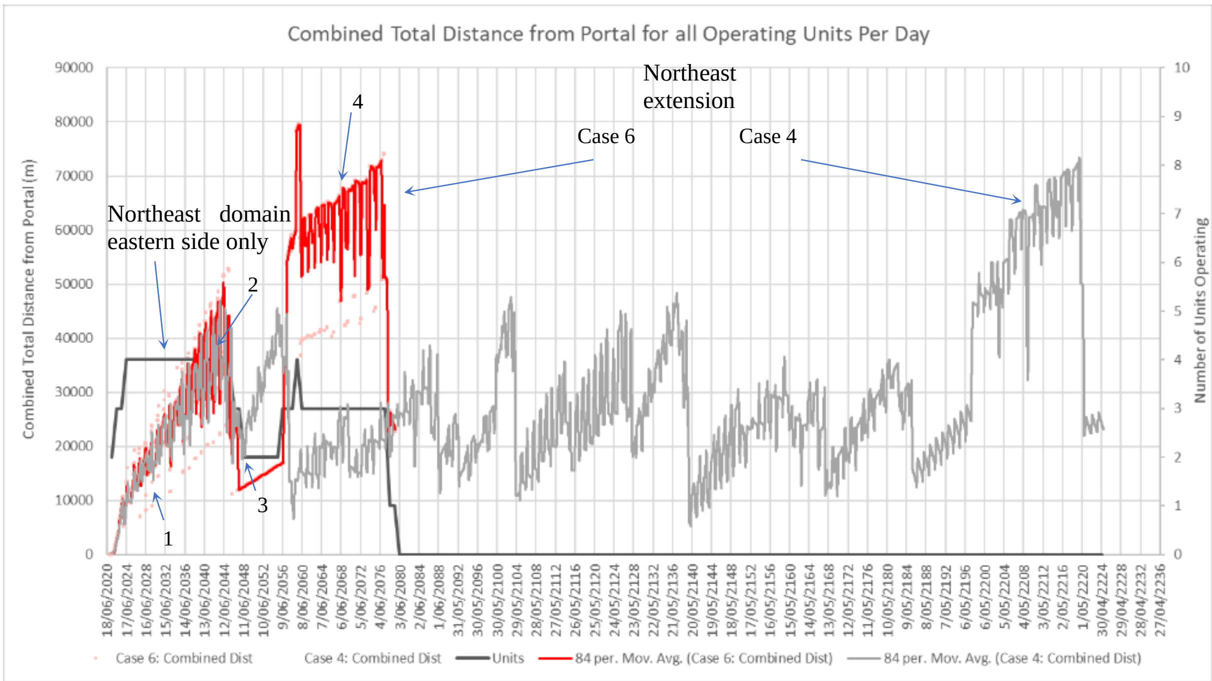


Figure 4-74: Case 6 vs Case 4 daily combined total distance from portal for all productive units with a 12-week rolling average trendline.

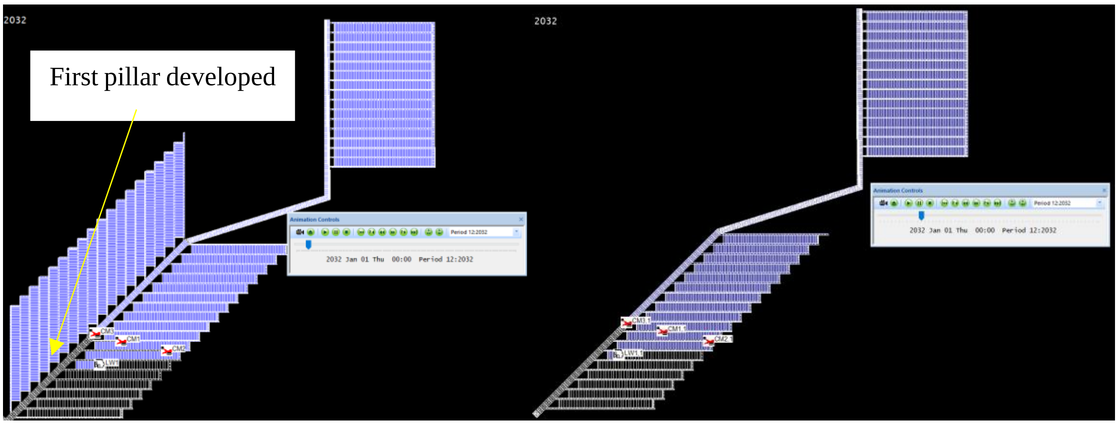


Figure 4-75: Milestone 1 left (Case 4) and right (Case 6). Case 6 development is slightly ahead with no hazardous zone implications that Case 4 must deal with up front.

Combined distance divergence at Milestone 2 is more noticeable due to the additional drivage in each western pillar 1 that Case 4 must complete. The difference in logistics strain between both cases here is negligible.

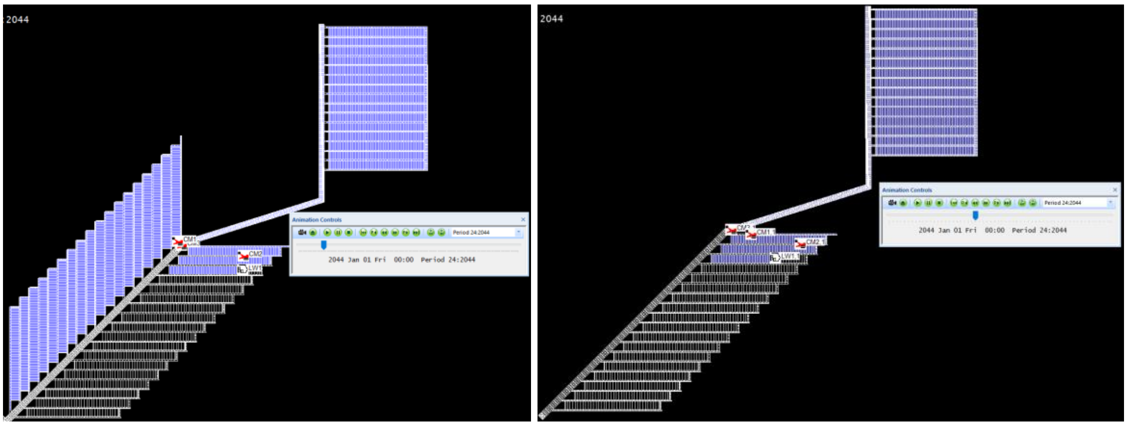


Figure 4-76: Milestone 2 Left Case 4 and Right Case 6. Case 6 development remains ahead due to reasons explained in case 1.

Milestone 3, shown in Figure 4-77combined distance is lower than for Case 4 because two continuous miners, in a lower productivity super unit configuration, are still driving the mains out to the Northeast extension which means one development unit is demobilised due to lack of pit room and the longwall is delayed due to lack of continuity. In Case 4, there is sufficient lead time to maintain longwall continuity into the Northeast area/domain by building development inventory in advance because of the four previous area/domains compared to half a single domain in Case 6. There simply is not enough time in Case 6 to have the Northeast extension ready.

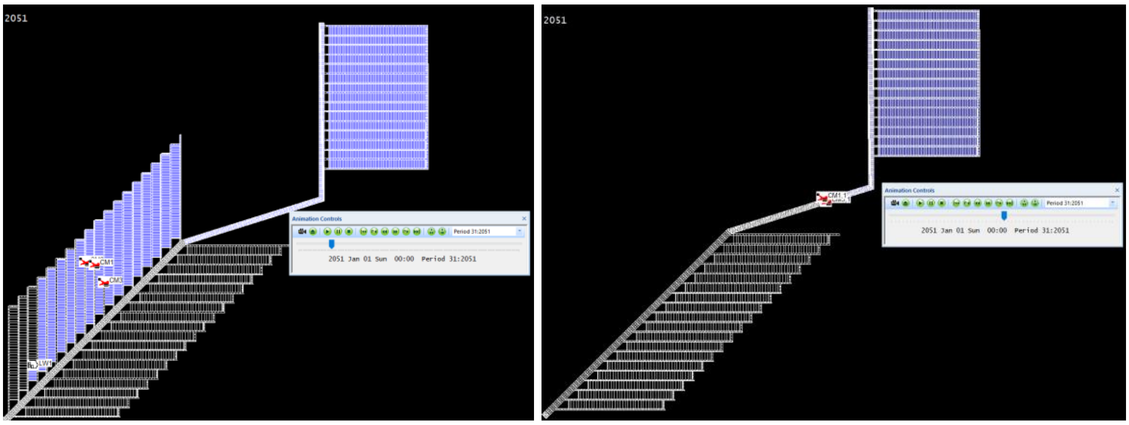


Figure 4-77: Milestone 3 left (Case 4) and right (Case 6).

Milestone 4, shown in Figure 4-78 is a progression through the Northeast extension area/ domain. It is similar but much earlier to the paths of all productive units for all previous cases. This in turn accelerates the much higher combined distances and hence this component is much earlier in the schedule.

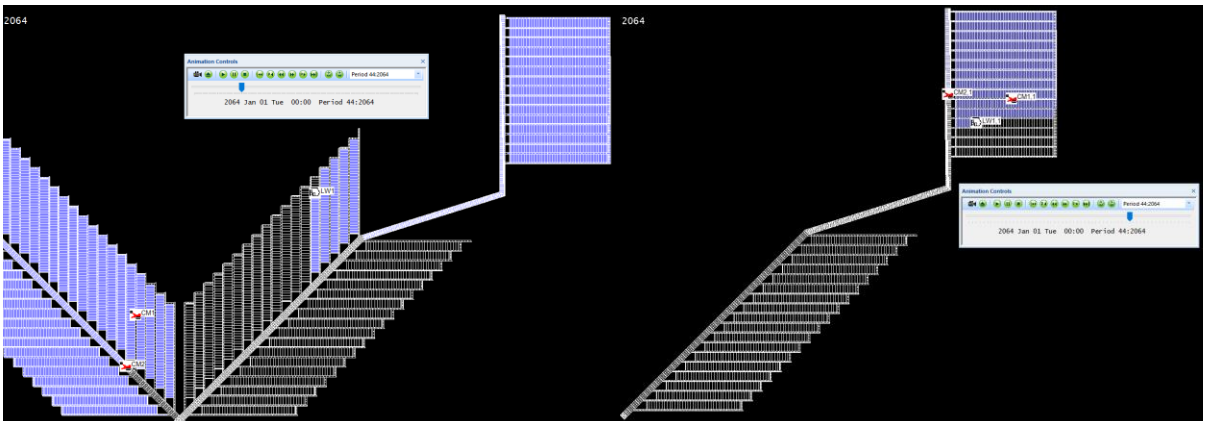


Figure 4-78: Milestone 4 Left Case 4 and Right Case 6. Case 6 is accelerated into the Northeast extension area/domain.

Loads per day for Case 6, shown in Figure 4-79, peak at 45 for the Northeast area/domain when all development units and the longwall are employed. When driving the main headings to the Northeast extension (Milestone 3) the loads per day drop based upon less units operating and lower productivity due to the super unit configuration compared to Case 4 where all productive units remain fully employed in the western side of the Northeast domain. The Northeast extension domain in Case 6 has a very similar profile to Case 4. Therefore, apart from the time that the development out to the Northeast extension where units are forcibly demobilised, the schedule on a domain-to-domain basis, loads per day, is very similar between both cases.

Case 6 loads on road, shown in Figure 4-80, for the Northeast Area/domain peaks at 5.0 and 7.7 for the Northeast Extension Area/domain. Therefore, the logistics strain for Case 6 and Case 4 is very similar when comparing Northeast and the Northeast extension Area/domains peaks. Strain is alleviated during drivage in Case 6 in Milestone 3 due to the lack of pit room and continuity as discussed previously. What Case 6 does show is the acceleration of logistics strain when migrating away from the portals and not returning, thus, partially confirming the hypothesis in Chapter 1 of the anticipated logistics strain where migration away from the portal without return occurs until a shaft is installed. The remainder of the hypothesis which includes the introduction of a shaft is confirmed in Case 6a.

4.8.2 Loads per Day

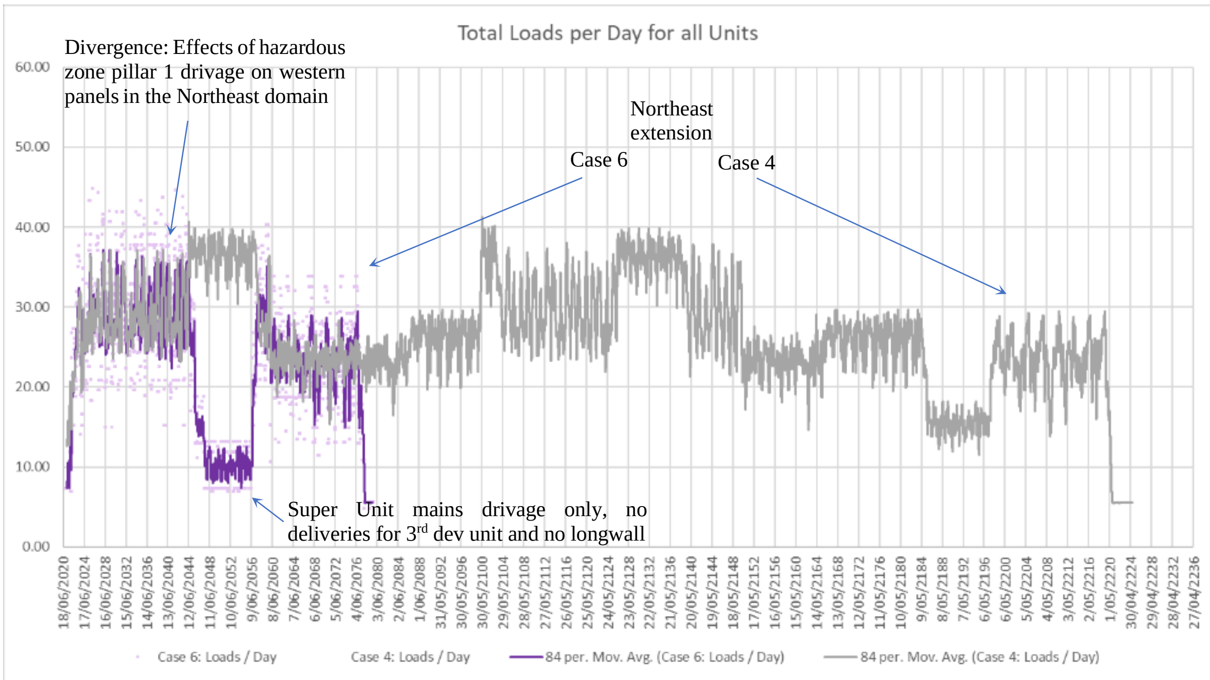


Figure 4-79: Loads per day between Case 4 and Case 6.

4.8.3 Loads on road

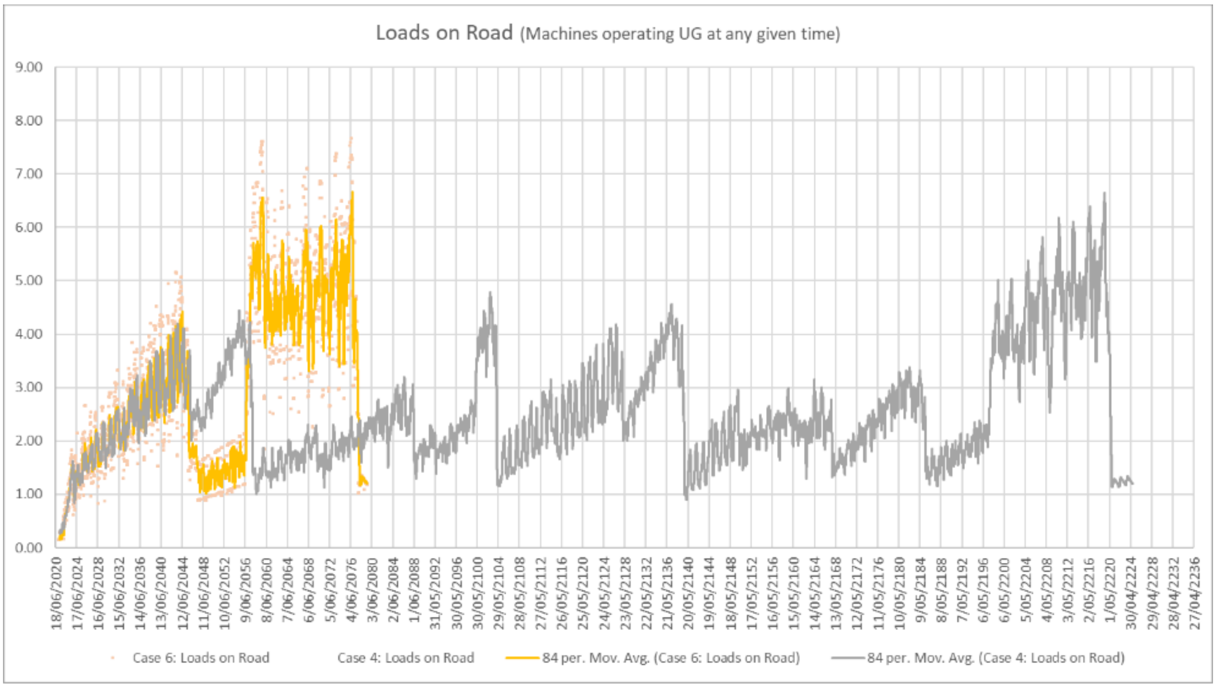


Figure 4-80: Case 6 vs Case 4 loads on road / logistics strain.

4.9 Case 6a: Case 6 plus a new portal inbye.

Case 6a is identical to Case 6 except that a portal is installed at the start of the Northeast extension domain. All panels inbye of the portal are serviced by that portal. Case 6a shaft positioning is shown in Figure 4-81.

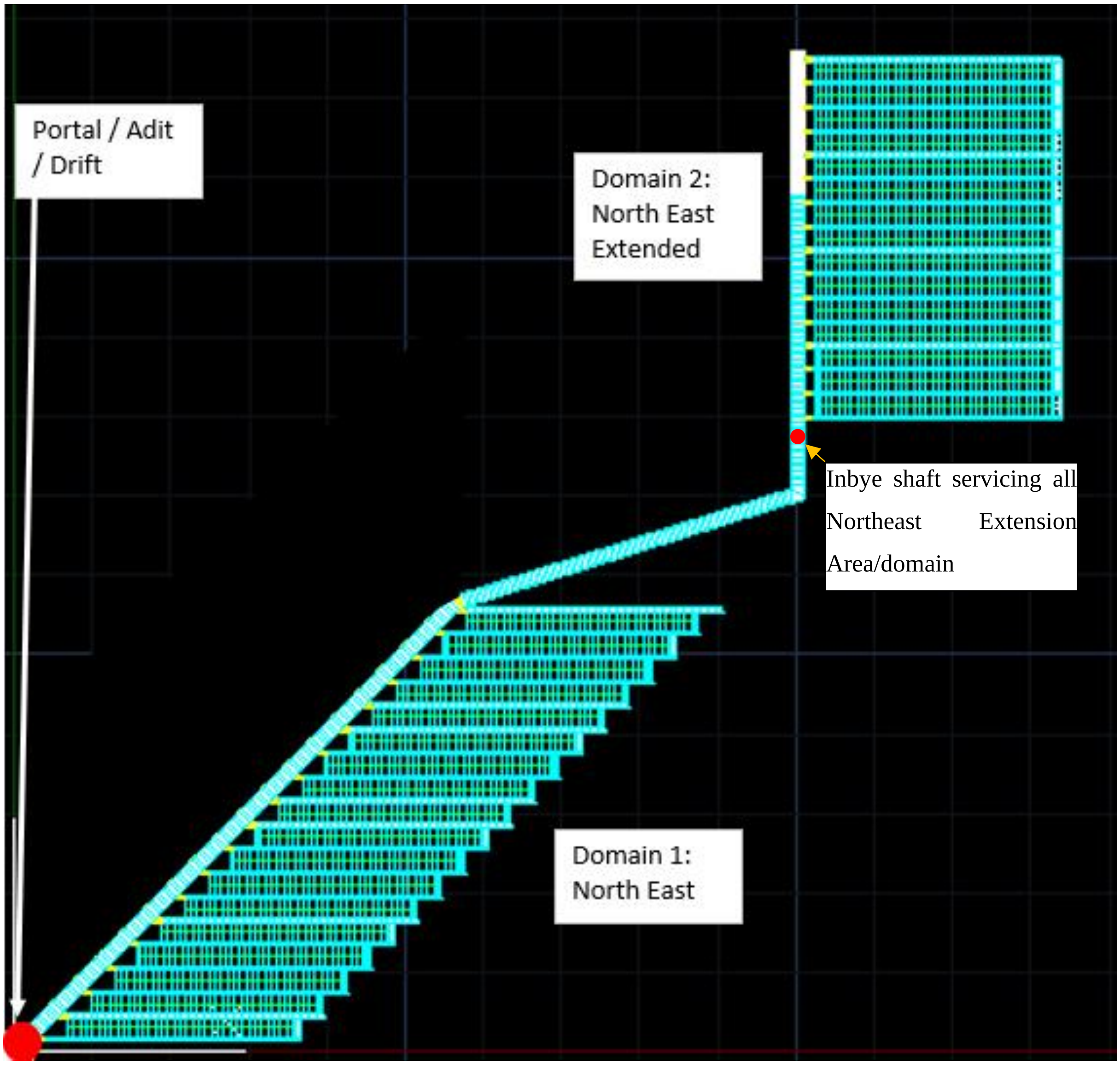


Figure 4-81: Case 6a showing the position of the inbye shaft to service the Northeast extension Area/domain.

4.9.1 Combined Distance

Referring to Figure 4-82 for Cases 6 versus 6a combined distance, the first half of the schedule which is in the Northeast Area/domain shows that the combined distance is the same. The benefit of the inbye shaft is realised as soon as it is reached in 2056 where combined metres fall with a peak combined distance in Case 6 being 118.5 km reducing to 61.5 m for two continuous miners and one longwall.

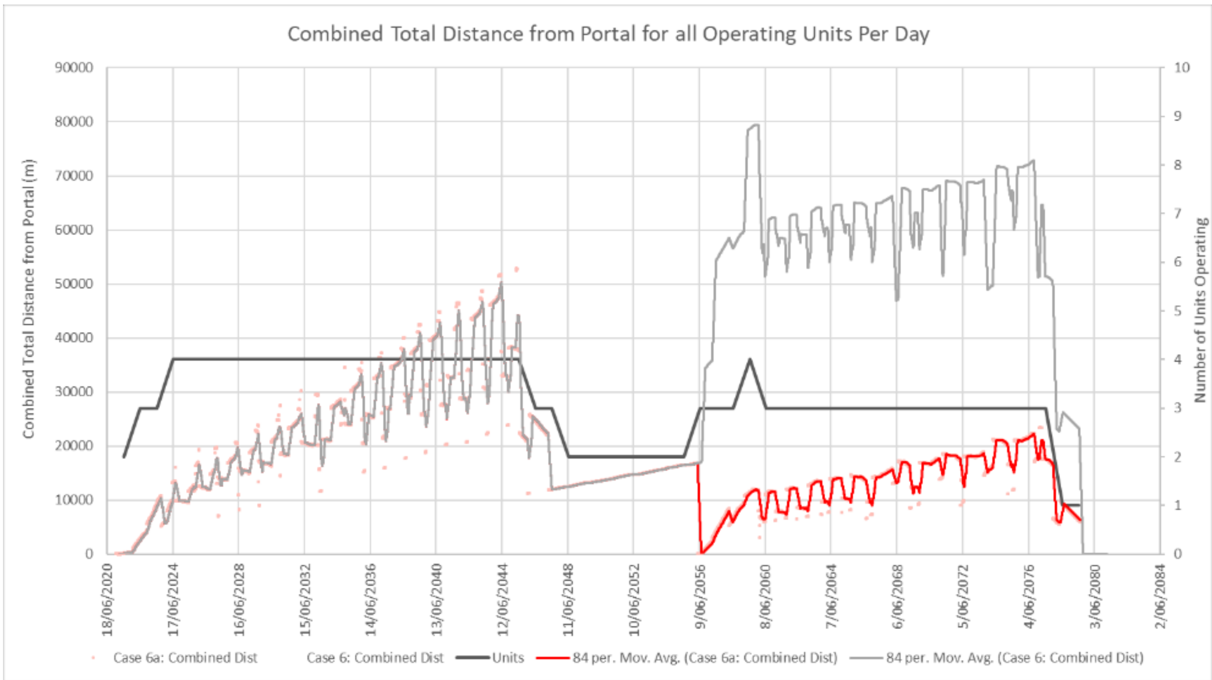


Figure 4-82: Case 6a vs Case 6 daily combined total distance from portal for all productive units with a 12-week rolling average trendline.

4.9.2 Loads per Day

Loads per day, shown in Figure 4-83, remain the same for Case 6 and Case 6a which is confirmation that the schedule of productive units is the same and therefore only the combined distance to the portal has any impact on logistics strain.

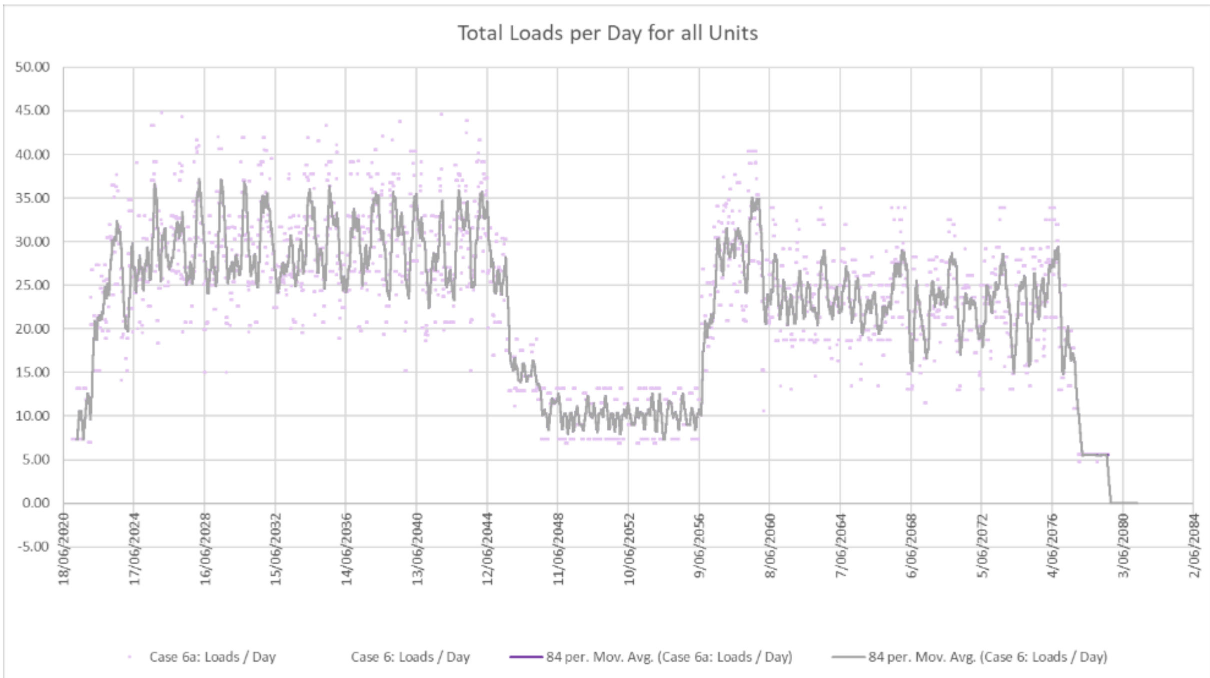


Figure 4-83: Loads per day between Case 6a and Case 6 (no difference).

4.9.3 Loads on road

Consistent with Case 5, the introduction of a new portal 17 km inbye of the central portal to service the Northeast extension Area/domain causes a steep reduction in logistics strain that can be seen in Figure 4-84. Again, this reduction is due entirely to combined distance from the portal(s). The peak loads on road/logistics strain have reduced from a peak of 12 to 6.5.

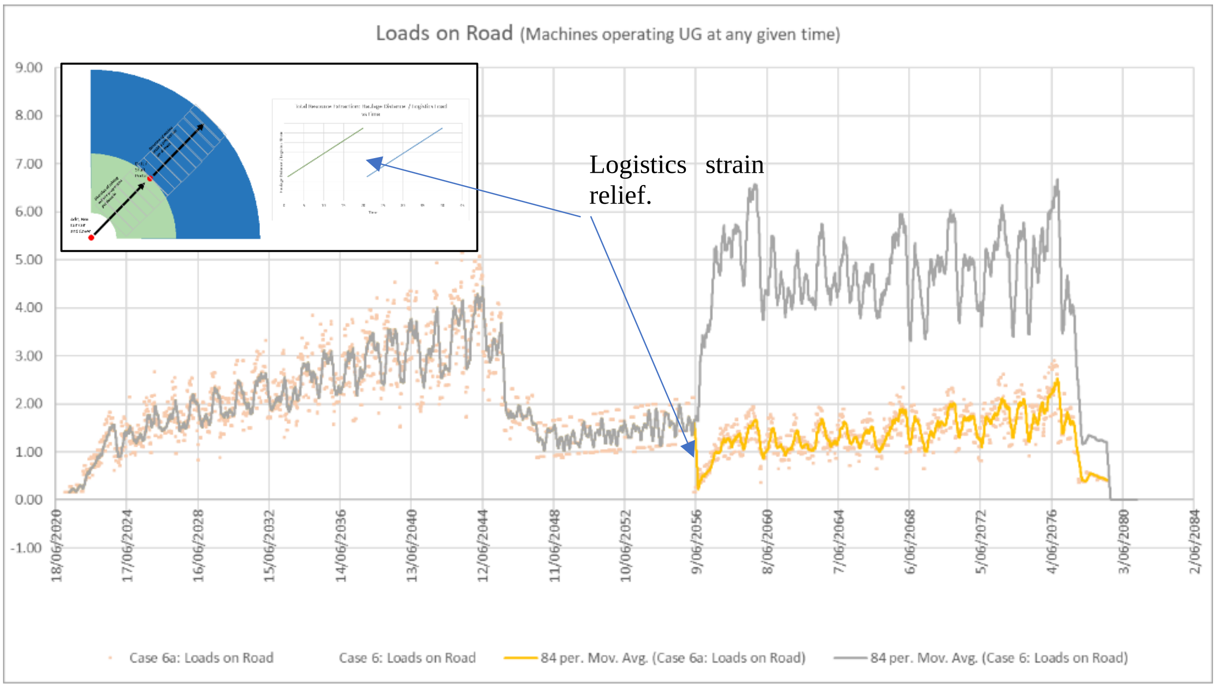


Figure 4-84: Case 6a vs Case 6 loads on road (Inset Chapter 1 Figure 1-5).

This proves the Chapter 1 hypothesis in Figure 1-5, and shown as an inset, that whilst mines continue to migrate away from their original portal that logistics strain for an operation increases as you migrate away but is alleviated with the introduction of an inbye shaft.

4.10 Case 7: Faster delivery speeds

As mentioned in Chapter 2, several underground mines of varying complexity were visited and interviewed. The mines that would be considered best practice were operations that had a higher speed of delivery because of concreted and well-lit roadways. Case 7 explores the impact of logistics strain by increasing the speed of the delivery vehicles by 50% which is entirely possible if travel road conditions are excellent. Therefore, the cycle time for delivery is reduced. Apart from the change in speed in delivery there is no other change between Case 7 and Case 6 which is why the combined distance in Figure 4-85 and productive units employed over time and Figure 4-86 loads per day are identical.

4.10.1 Combined Distance

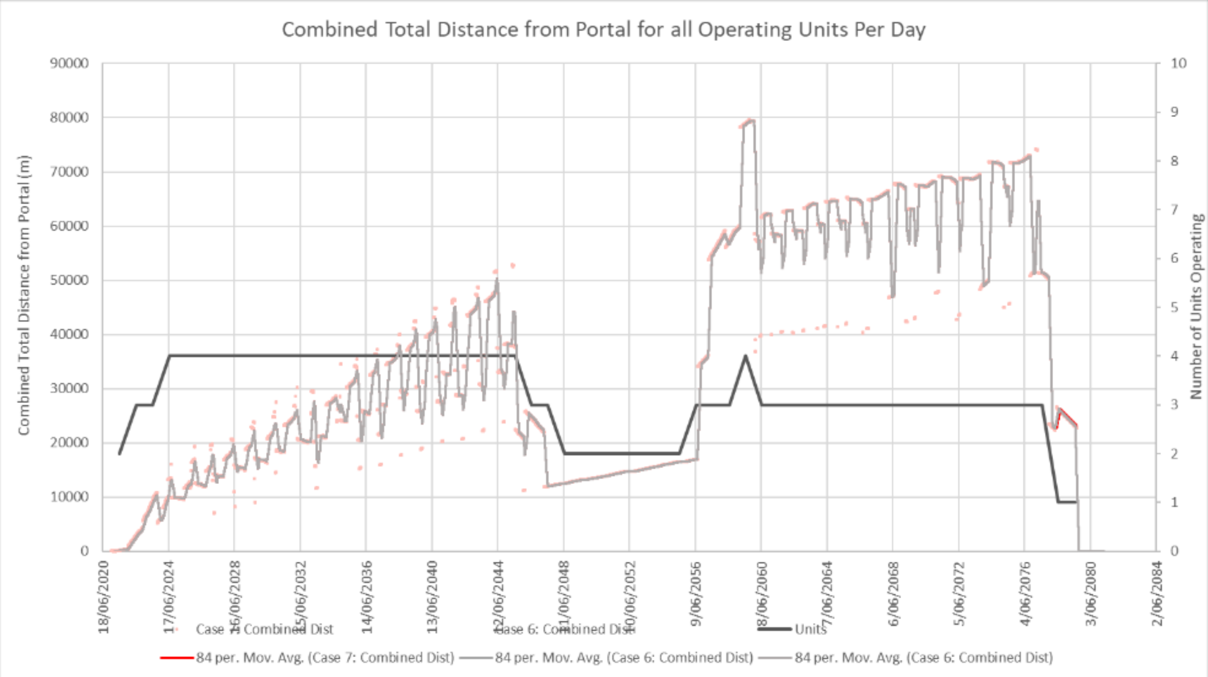


Figure 4-85: Case 7 vs Case 6 identical daily combined total distance from portal for all productive units with a 12-week rolling average trendline.

4.10.2 Loads per Day

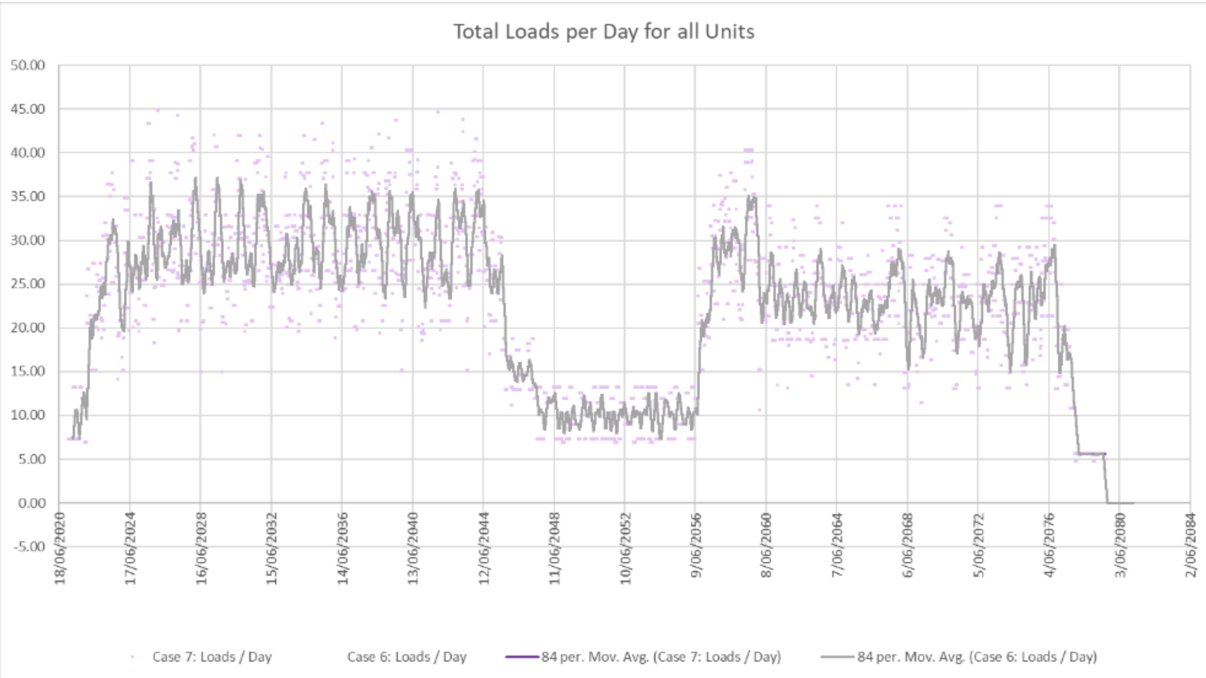


Figure 4-86: Loads per day between Case 7 and Case 6 (no difference).

4.10.3 Loads on road

Case 7 loads on road is shown in Figure 4-87. With a reduction in cycle time due to increased speed of delivery, the loads on road/ logistics strain have reduced compared to Case 6. The peak loads on road reduced from 5.2 to 3.7 and 7.7 to 5.4 in the Northeast and Northeast Extension Area Area/domains, respectively. It is important to note that the cycle time also includes the fixed time for loading/unloading and delays. This explains the divergence as the travel distance increases from the portal. Closer to the portal, the proportion of travelling time is lower and therefore the impact between Cases 6 and 7 is lower, but as the operation migrates further away from the portal, travelling time impact increases, meaning Case 7's faster speeds have a larger reduction in logistics strain.

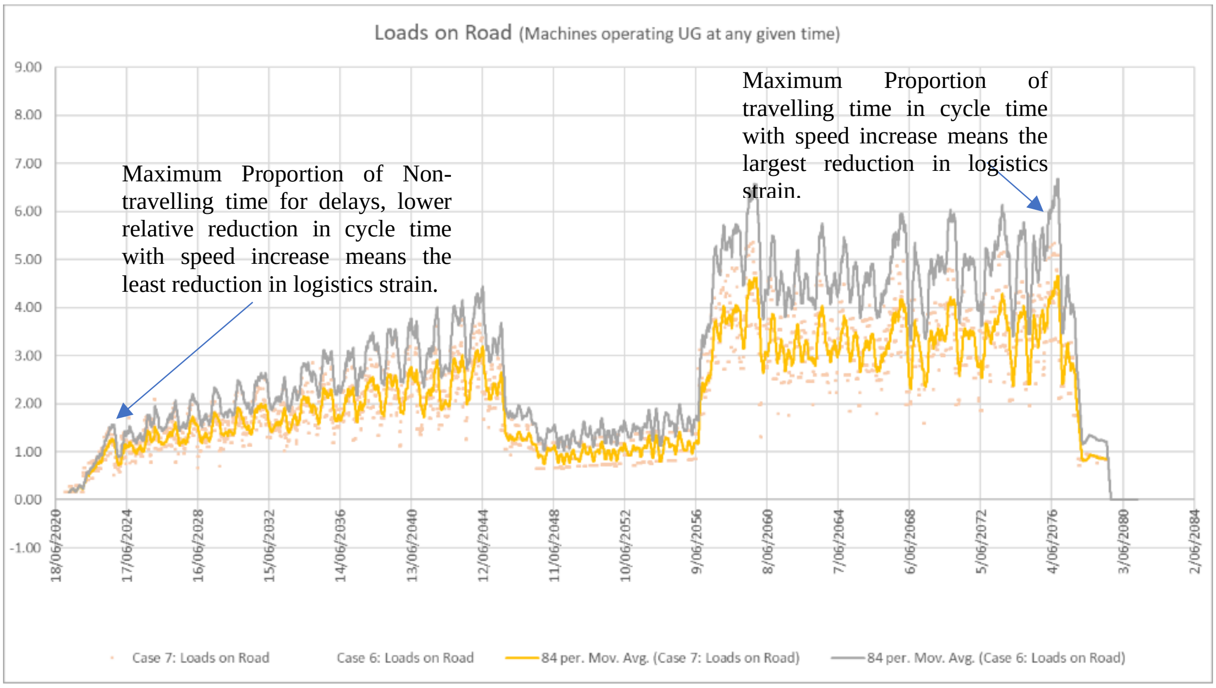


Figure 4-87: Case 7 vs Case 6 loads on road.

Speed has no impact on combined distance or required loads per day. It directly affects loads on road through cycle time as the underground pit design is constant and the required deliveries for each location also remains the same. Increasing speed has the greatest impact on reducing logistics strain when other delays including loading and unloading and other non-travelling delays (e.g., light section delays) are minimised so that the actual travelling is the dominant proportion of the cycle time. Recalling from Case 6a, the installation of a portal at the commencement of the Northeast Extension will reduce the impact of speed on logistics strain because the cycle time will revert to a higher proportion of fixed time. It may therefore be uneconomic to immediately concrete roads and install lighting (unless for reasons of safety) immediately as the reduction in logistics strain by doing so will be minimal. Therefore, a staged approach to the management of logistics strain should be implemented with each compounding step studied for its respective cost-benefit. As industry would say "there are multiple levers to pull" many of which we are exploring in this thesis, but do not pull them all at once.

4.11 Case 8: Increased Payload

With the exact schedule of Case 6 and Case 7, Case 8 builds on from Case 7 by doubling the load capacity of each delivery LHD. For example, if a delivery vehicle was taking one trailer per trip, then increasing the payload by road train setup of two trailers is the impact that Case 8 attempts to explore.

4.11.1 Loads per Day

The total loads per day, shown in Figure 4-88, have reduced from a peak of 44.8 to 22.4 from Case 8 to Case 7 for the obvious reason, the payload has been doubled.

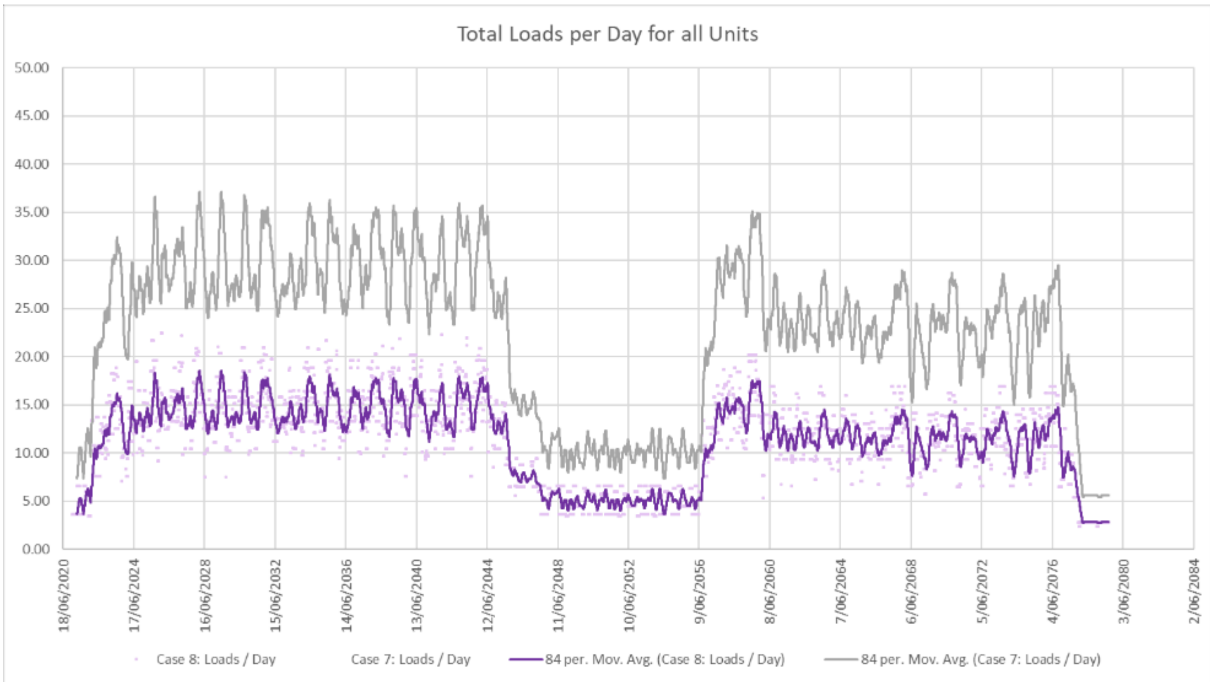


Figure 4-88: Loads per day between Case 8 and Case 7. NB A load for Case 8 is double a load for Case 7.

4.11.2 Loads on road

With the same fixed non-travelling time as in Case 7, loads on road/logistics strain is halved, as shown in Figure 4-89, from an incremental peak of 3.7 to 1.9 and 5.4 to 2.7 delivery vehicles underground at any time for the Northeast and Northeast Extensions Area/domains, respectively. There remains a crossover point that if doubling the payload either decreases the average speed of the vehicle or increases the loading and unloading time or both may outstrip the benefit of increased payload. For example, if in a particular operation, double payload vehicles needed to travel at half speed if interacting with personnel transport on the same road compared with a single payload vehicle, then consideration of a high-speed heavy haulage road without the risk of interaction may need to be studied for a particular operation. Alternatively, if in another operation, the level of delays due to loading, unloading and other travel time delays offset the gain in double payload then opportunities need to be found to reduce these delays on a case-by-case basis which is outside the scope of this thesis.

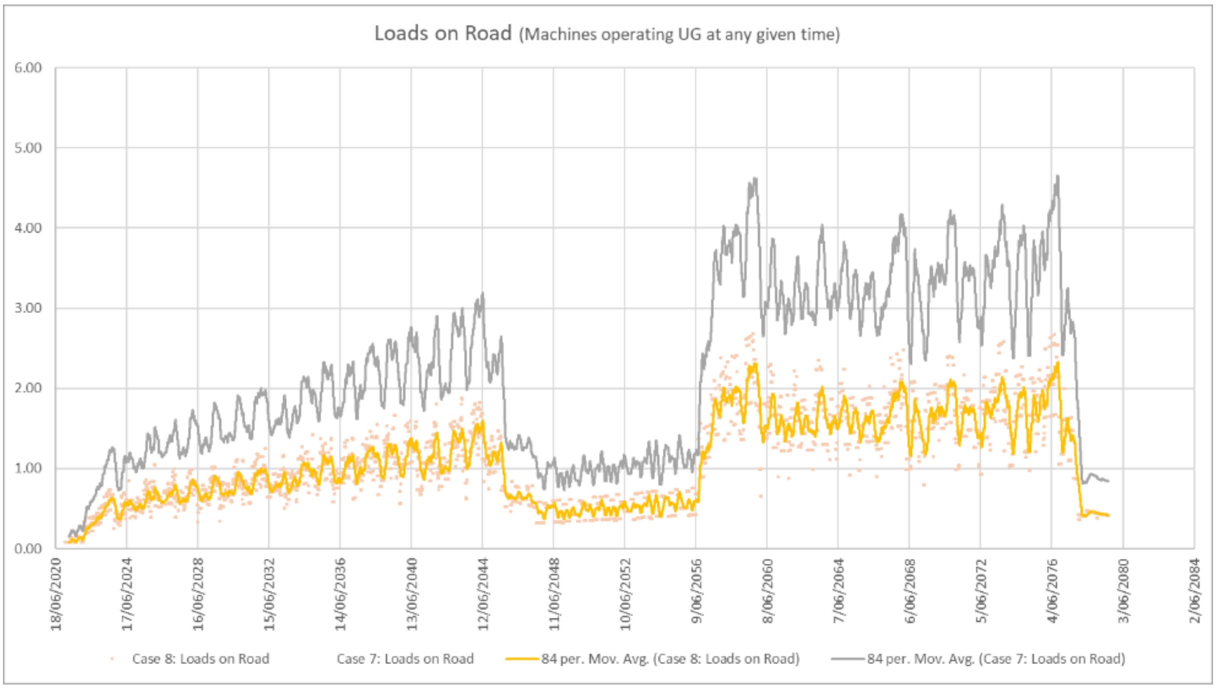


Figure 4-89: Case 8 vs Case 7 Loads on road.

All things being equal, increasing payload presents a significant opportunity to reduce loads on road/logistics strain for the lowest investment. It likely requires the same number of logistics personnel but will need some form of towing capacity upgrade in the machines for both power and safety reasons. Nevertheless, compared with the installation of a new portal, or upgrades to existing roads to increase speeds, the investment in increasing payload is comparatively cheap. Mine-by-mine considerations such as steep declines or drifts may need to be considered due to the risk of runaways which should occur in due course of logistics planning. Even in this case, if double payloads were only delivered partially within the operation, a proportional decrease in logistics strain will still occur so long as the proportion of travel time outweighs the proportion of fixed delays.

4.12 Case 9: Reducing Delivery Window Times

In many operations, getting personnel to and from production panels takes priority. This is turn may limit when large delivery vehicles are able to operate to minimise interaction with crews, preventing them from slowing down by being caught behind a delivery vehicle. Some operations manage this through delivery windows. These are the time ranges throughout the mine's day that have minimum interaction with other prioritised machines or personnel. For example, deliveries may only occur between the hours of 8:00 AM and 12:30PM on dayshift, 4:00PM and 8:30PM for afternoon shift or 12:00AM to 4:30AM for night shift. The reduction of the delivery window does not change the schedule. It therefore does not change the combined distance or the loads per day required at each productive place. However, it does increase the intensity of those deliveries because there is less time to deliver the same total loads per day without capping productivity of the continuous miners or longwall. Therefore, like Case 7 with speed, delivery window and therefore delivery intensity directly affect loads on road/logistics strain only.

As per the example in the previous paragraph, Case 9 has reduced the delivery window from 24 hours to 13.5 hours to represent three shifts of 4.5-hour windows to test the impact of intensity on logistics strain. Its impact to loads on road is demonstrated in Figure 4-90.

4.12.1 Loads on road

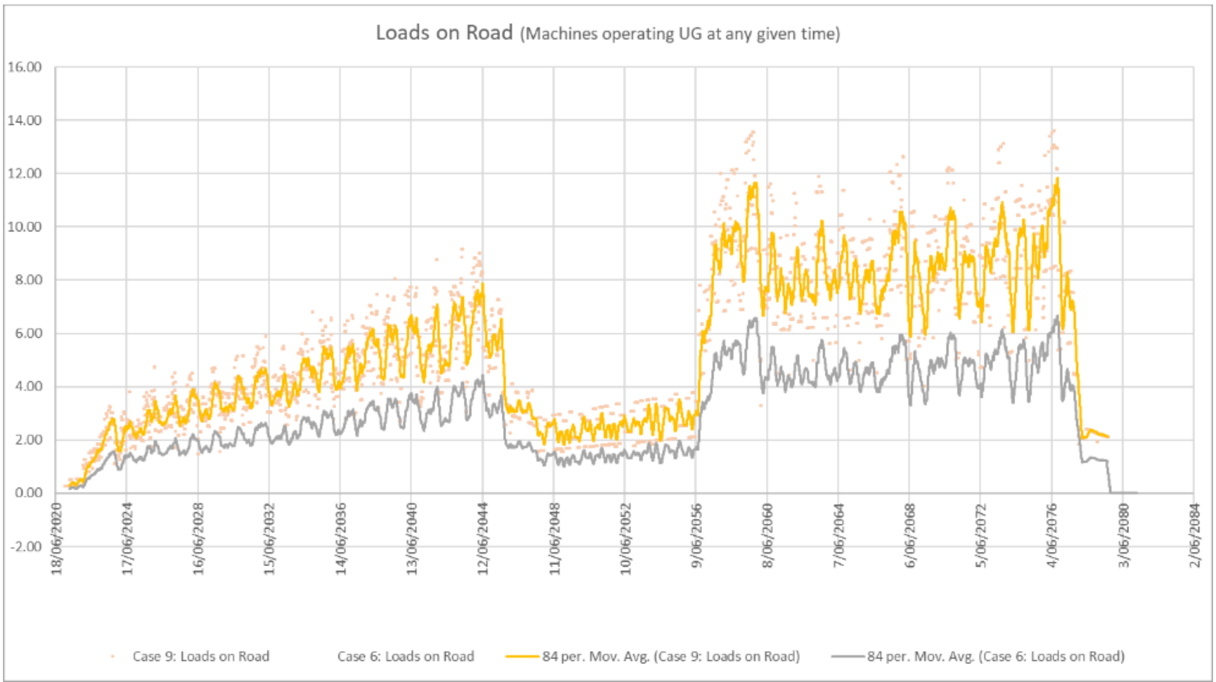


Figure 4-90: Case 9 vs Case 6 Loads on road.

With the delivery window now reduced to 13.5 hours the loads on road logistics strain sees an almost immediate increase that grows proportionally with distance from the portal. The peak logistics strain increases from Case 6 to Case 9 from 5.2 to 9.2 and 7.7 to 13.6 delivery LHDs in transit for the Northeast and the Northeast Extension Area/domains respectively. Payload increase will likely alleviate this challenge as discussed in Case 8 or for an inbye shaft in Case 6a which will reduce overall strain and growing logistics strain divergence as distances to the portal will be smaller. Another option is to consider reduction of interaction using dedicated heavy haulage roads which would minimise vehicular interaction and therefore likely increase the delivery time window.

4.13 Case 11: Increased development rates

Case 11 is designed to analyse the impact of an increased development rate and is essentially the opposite of Case 1a for all five Area/domains which slows development. In this case development has increased by about 47% for all primary support types in both main headings and gateroad development. For example, green support in gateroads has increased from 150 metres per week to 220 metres per week and in mains from 100 metres per week to 147 metres per week. The period plot for Case 11 is shown in Figure 4-91. Compared to Case 6, Case 11 now finishes ten years earlier because the development rates are higher which leads to lower discontinuity between the Northeast domain and the Northeast Extension.

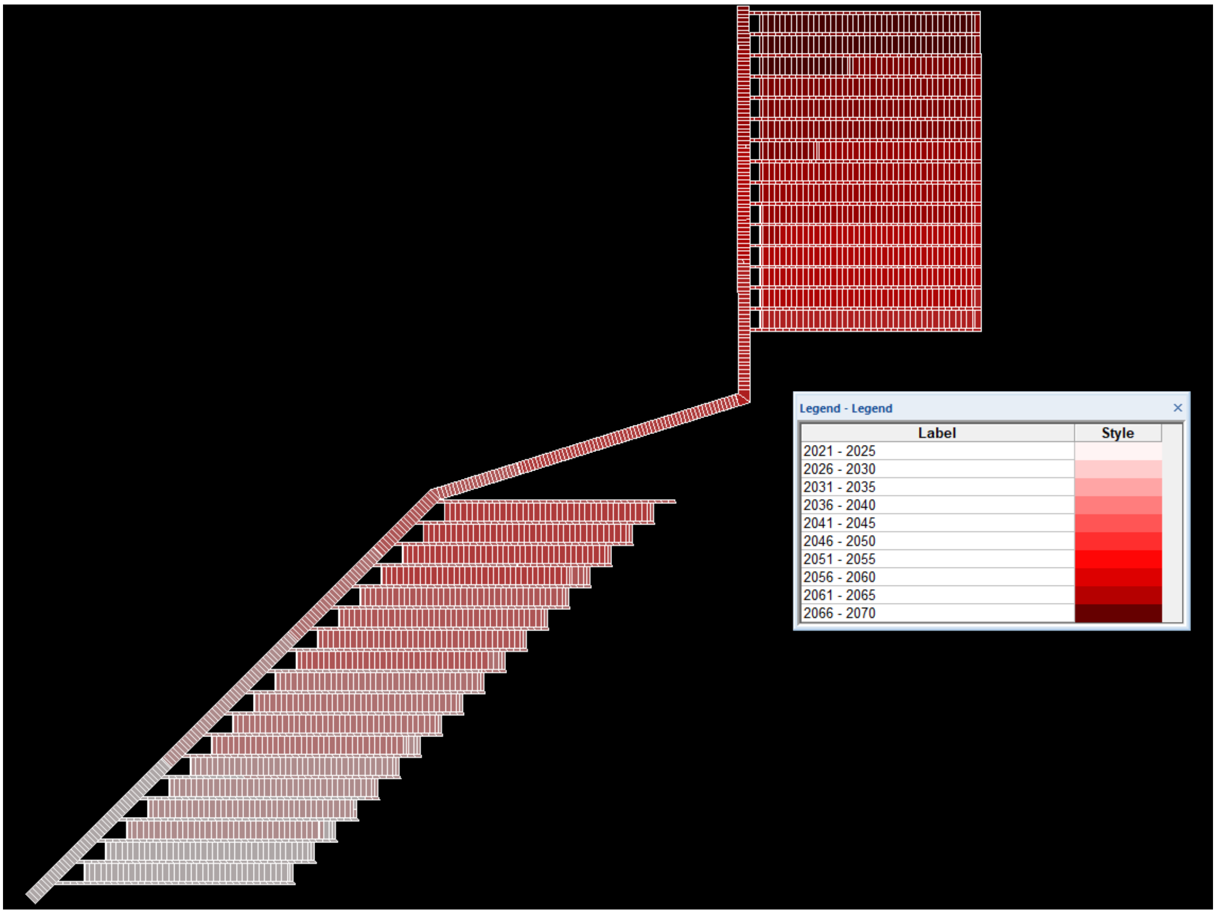


Figure 4-91: Period Plot of Case 11.

4.13.1 Combined Distance

Increasing the development rate means the combined distance per day gradient is higher because development reaches inbye sooner. Added to this, the shorter the longwall discontinuity between area/domains means that the maximum combined distance is reached sooner in Case 11 than for Case 6 as shown in Figure 4-92 and Figure 4-93.

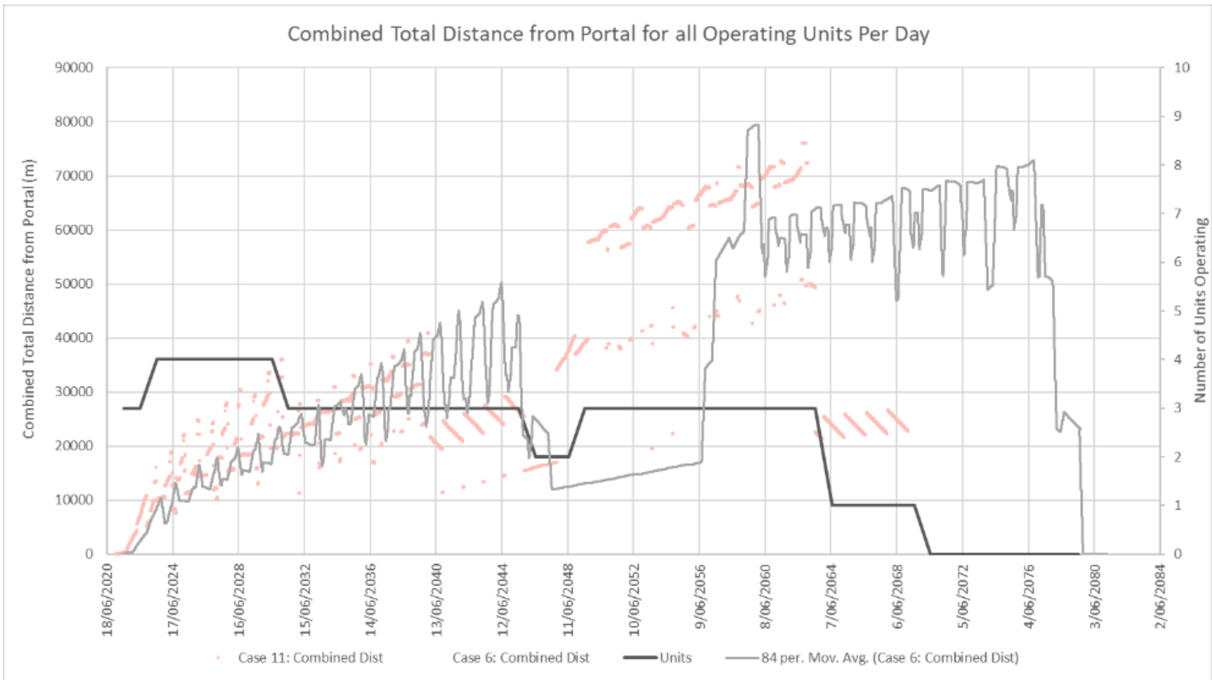


Figure 4-92: Case 11 vs Case 6 daily combined total distance from the portal for all productive units.

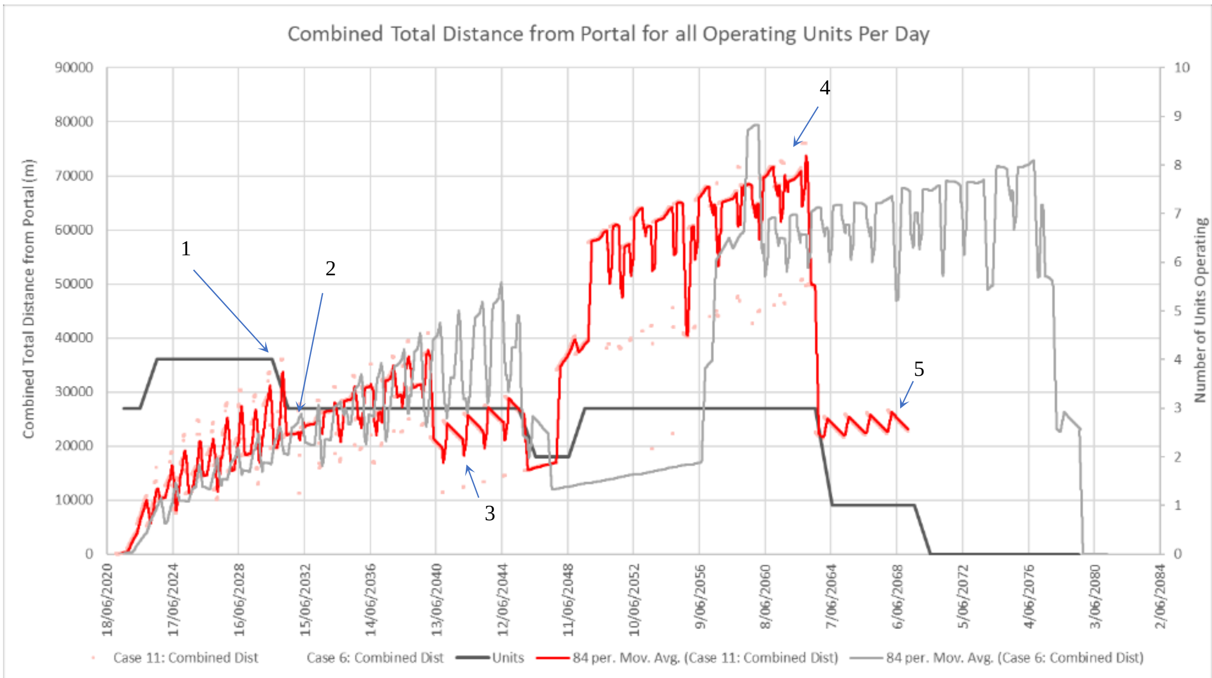


Figure 4-93: Case 11 vs Case 6 daily combined total distance from portal for all productive units with a 12-week rolling average trendline.

Milestone 1, shown in Figure 4-94, advances through the Northeast domain at a faster rate. At the same time in 2030 Case 6 has just commenced MG107 whereas Case 11 is 25% through MG110. Therefore, the combined distance gradient is higher for Case 11.

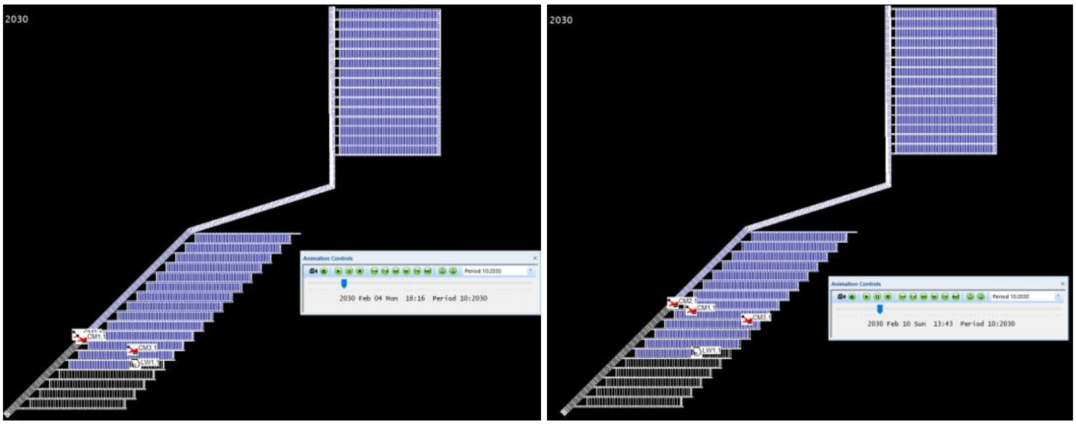


Figure 4-94: Milestone 1 left (Case 6) and right (Case 11). Case 11 is significantly ahead.

As development in advance continues to build, Milestone 2, shown in Figure 4-95, in Case 11 attempts to rein this in through the standing down of the 3rd development unit. This in turn causes a reduction in combined development metres for Case 11. Even so the combined distance of Case 11 with only two development units operating at a higher rate and a longwall combined with already established further inbye distances means that the combined distance and its growth rate is equal to the combined distance of three development units and a longwall in Case 6 for the remainder of the Northeast Area/domain.

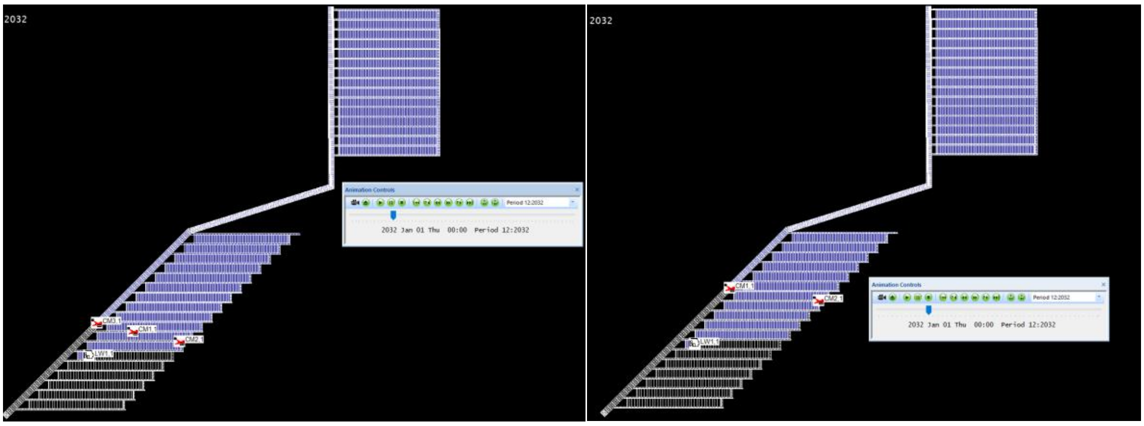


Figure 4-95: Milestone 2 left (Case 6) and right (Case 11). Case 11 has demobilised a development unit to reduce development inventory in advance

Milestone 3 sees development revert to slower production for super unit main headings driving out to the Northeast Extension Area/domain for Case 11. There is no longer the pit room to re-introduce the third continuous miner now until the Northeast extension gateroads are available to be driven. Case 6 is still within the productive drivage of Northeast Area/domain as shown in Figure 4-96.

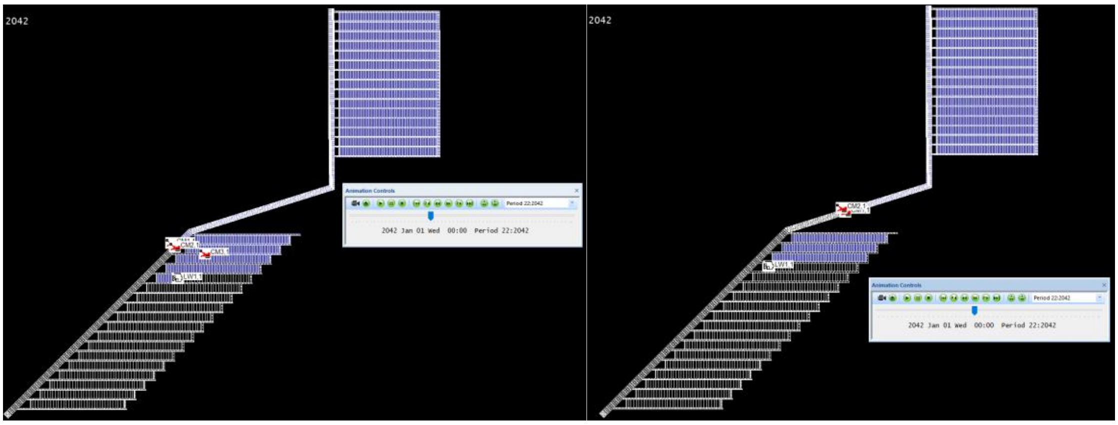


Figure 4-96: Milestone 3 left (Case 6) and right (Case 11). Case 11 has stood down a unit to rein in development inventory in advance.

Milestone 4, in Figure 4-97, shows development nearing completion for Case 11 in the Northeast Extension Area/domain. The longwall in Case 6 is at LW3, whereas Case 11 is at longwall 10. This is entirely due to the smaller discontinuity between Area/domains in Case 11 allowing the longwall to restart and therefore advance through sooner as the longwall rates for both cases are the same.

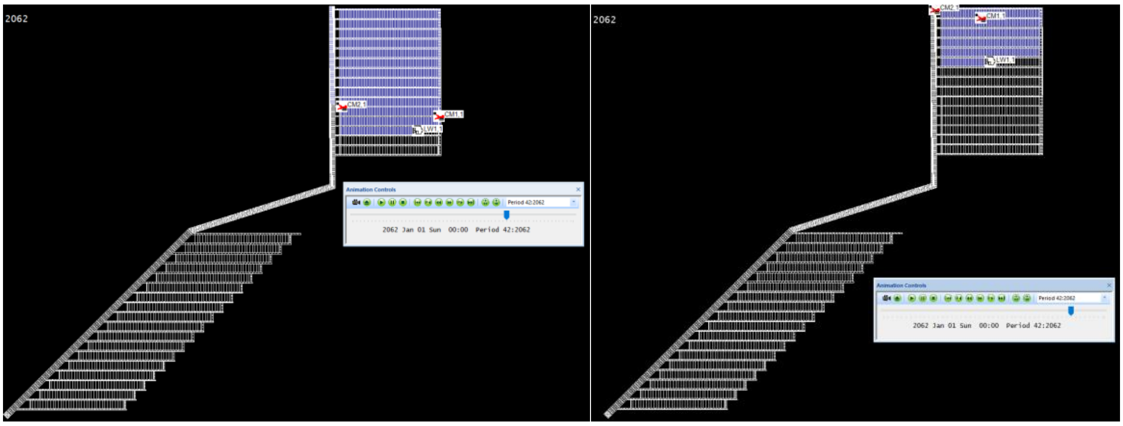


Figure 4-97: Milestone 4 left (Case 6) and right (Case 11). Longwall advancement between cases is due to higher development rates in Case 11 leading to lower discontinuity between Area/domains.

Milestone 5, in Figure 4-98, shows the completion of the development for Case 11 with the longwall still operating which suggests some development inventory in advance could be reined in much like Case 1b.

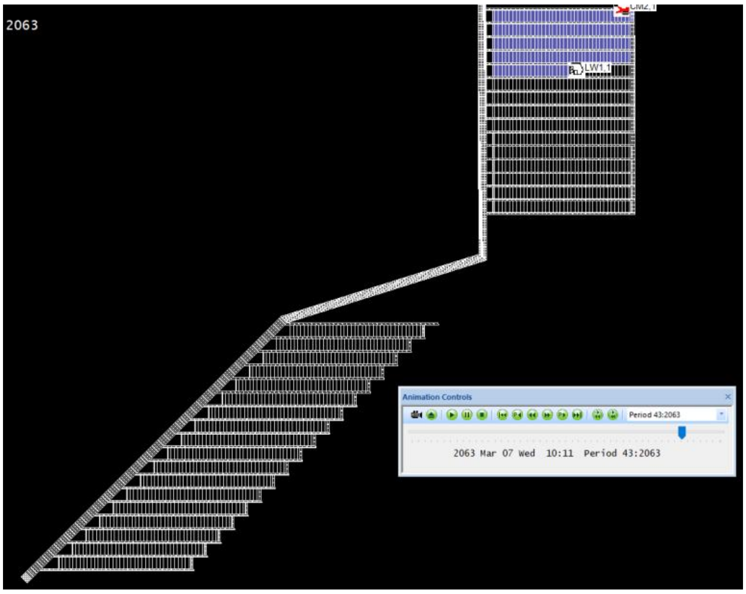


Figure 4-98: Case 11 Milestone 5. Development is almost complete for Case 11 with significant inventory in advance.

4.13.2 Loads per Day

Case 11 has development rates about 46% higher which means that loads per day peak at 64.0 compared to 44.8 for Case 6 as shown in Figure 4-99. This peak occurs early within the schedule whilst three development units and one longwall are all operating. As per the combined distance when the third development unit was stood down in 2031 the loads per day requirement dropped, but it only drops to what was required for Case 6 which has an additional continuous miner. It is only when drivage occurs out to the Northeast Extension that the loads per day drops below Case 6.

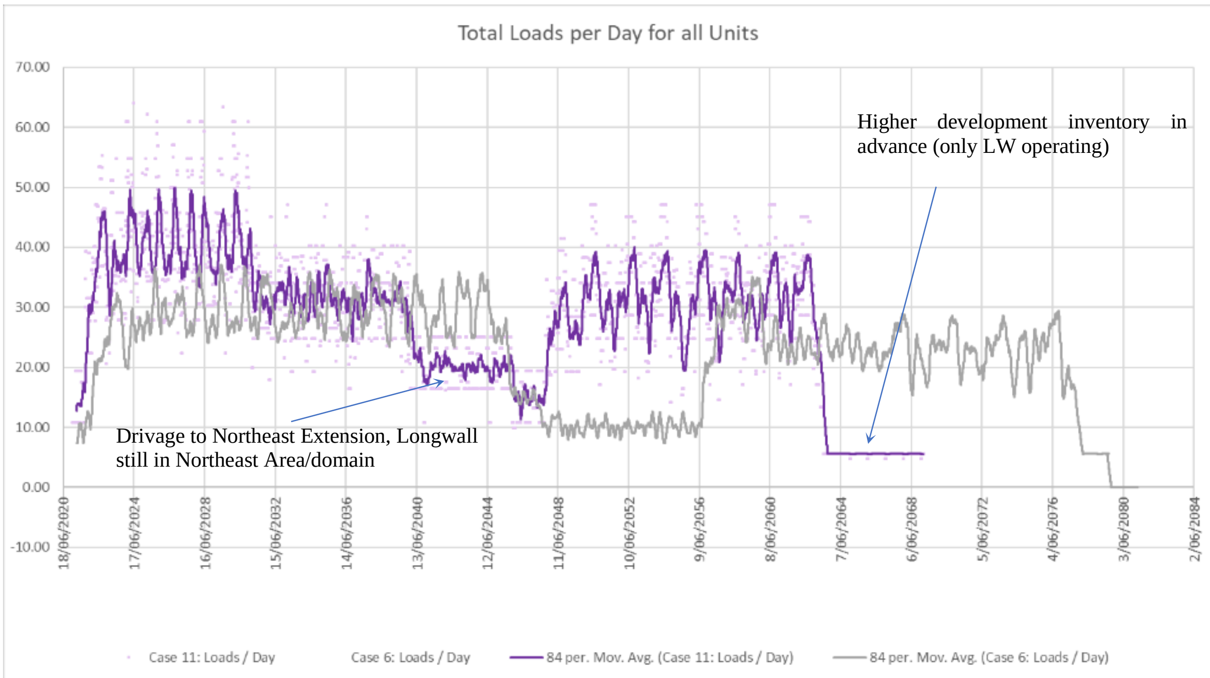


Figure 4-99: Loads per day between Case 11 and Case 6.

4.13.3 Loads on road

Case 11 loads on road is shown in Figure 4-100. As to be expected a higher development rate can have a compounding negative effect on logistics strain. Higher development rates mean that combined distances become larger sooner. Higher development rates also mean that there is an increase in deliveries per day. Therefore, Case 11 with a 46% higher development rate is expected to have higher logistics strain loads on road / logistics strain, which it does, with the peak logistics strain increasing from Case 6 to Case 11 from 4.2 to 5.4 and 7.7 to 10.5 delivery LHDs in transit for the Northeast and the Northeast Extension area/domains, respectively.

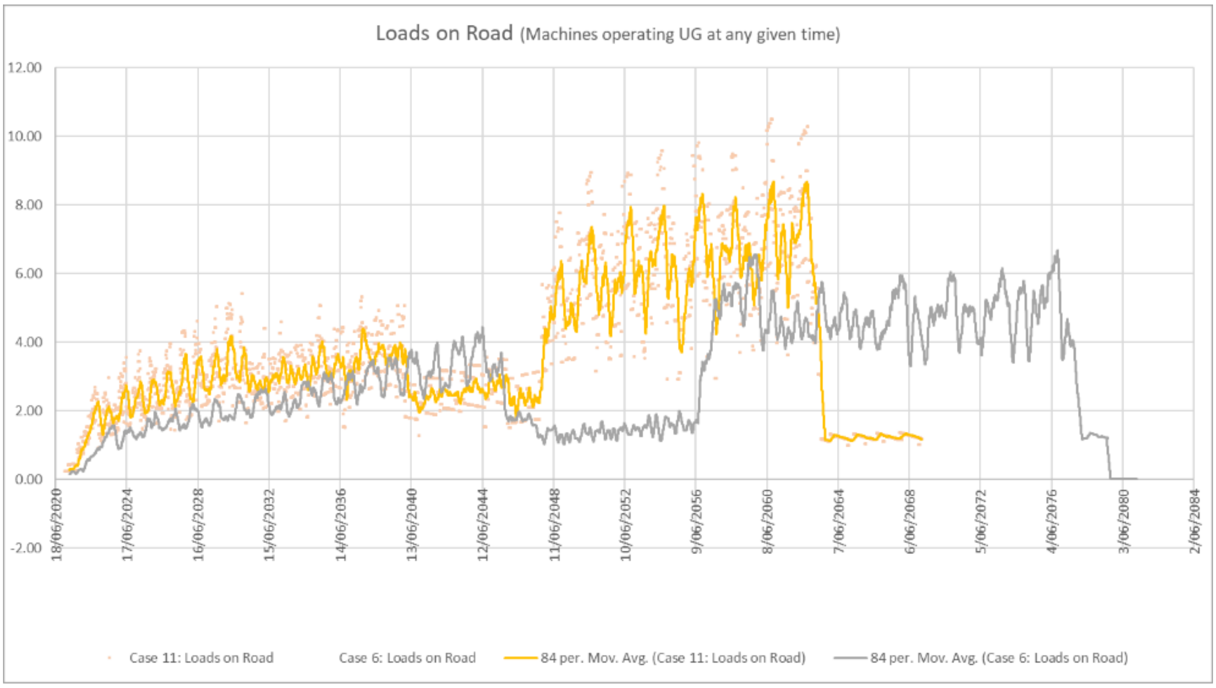


Figure 4-100: Case 11 vs Case 6 Loads on road.

After consultation with the outbye services coordinator and if the logistics breaking strain is greater than nine machines, that being the peak 12-week rolling average, which caps development productivity, at any given time operating underground then you have a valid schedule. If not, loads on road needs to be reduced through infrastructure or the schedule demand reduced otherwise the plan can never be achieved.

4.14 Case 12: Capping Production to Logistics Breaking Strain

Considering Case 11 a hypothetical scenario was presented where after typical consultation with management and the operation’s mining logistics department, it was established that six loads on road is the breaking strain. That is, where no more than six vehicles travelling in either direction can feasibly operate at full capacity without delays and it is not possible to increase payload, decrease cycle time or install a new inbye portal, then the last alternative is to target the schedule to meet but not exceed the logistics breaking strain. The system developed in this thesis can do this. Capping of logistics strain is known as Case 12 and is an iterative optimised schedule to meet but not exceed logistics breaking strain and maximise production whilst doing so. The system developed in this thesis took four iterations of 15 minutes each to optimise the schedule to meet the logistics breaking strain.

For Case 12 to be optimised there was a need to absorb any development inventory in advance in the Northeast extension. Sufficient development inventory must be ensured between the Northeast and Northeast Extended area/domains so that there is no longer any discontinuity by building development inventory in advance. If logistics breaking strain is exceeded, then a downgrade in development is then required which may or may not downgrade longwall production depending on inventory for that period.

Annual ROM tonnes and development metres are shown in Figure 4-101. Point 1 shows how in Case 12 the discontinuity has been recovered and longwall production has been maintained compared to Case 11 (in grey). This was achieved through building development inventory in advance in the Northeast Area/domain shown in the date ranges shown by “2”. Total LW production is tapered off shown by “3” and development inventory is also reduced through reduction in development metres compared to Case 11 to match the logistics breaking strain of eight loads on road.

Figure 4-101: Case 12 vs Case 11 annual ROM tonnes (top) and annual development metres (bottom).

A useful tool in planning is the use of cumulative graphs to understand the time value impact of cost and revenue. Figure 4-102 shows Case 11 and Case 12 cumulative ROM tonnes and development metres. Longwall tonnage is higher for Case 12 shown at point "5" and development metres is higher earlier in shown by point 6 capitalising on the buffer between current logistics strain at that point in time and logistics breaking strain. However where logistics breaking strain does occur later in the schedule, development metres and tonnages are reduced in Case 12 to remain below threshold as shown at point "7" and point "8".

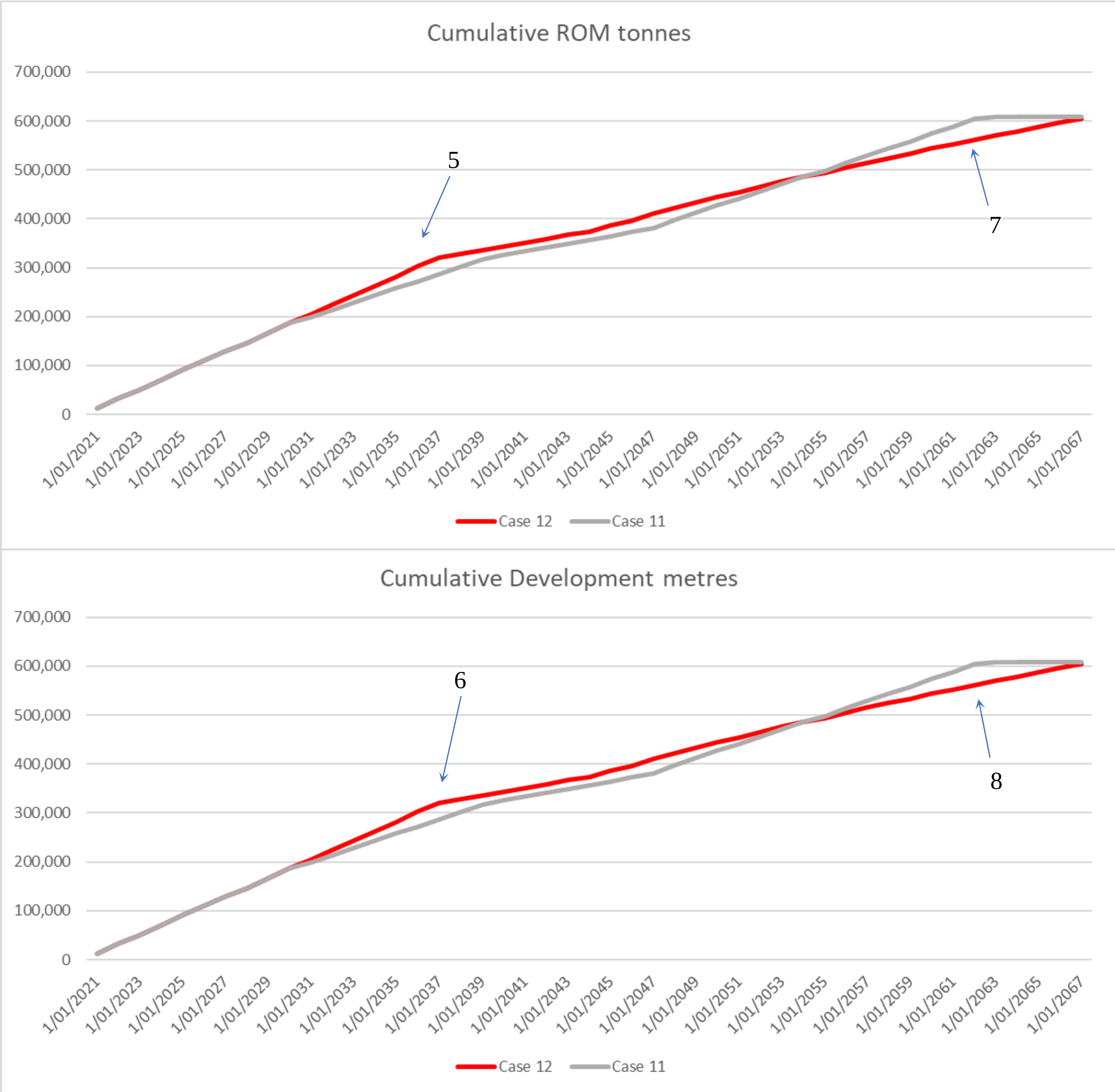


Figure 4-102: Case 12 vs Case 11 cumulative ROM tonnes (top) and development metres (bottom).

4.14.1 Loads on road

Logistics strain is shown in Figure 4-103. The absolute maximum logistics strain on any given day for Case 11 was 10.5 and this has been reduced in Case 12 to 7.3. What might be asked here is 7.3 exceeds the maximum of six loads on road stipulated by the mining logistics department in the example given. This is where the 12-week rolling average smooths the peaks and for the same peak period the 12-week average loads on road is just below

6, meaning that if loads on road for the 12 weeks around the peak requirement day is maintained but does not exceed the logistics breaking strain there will be sufficient materials delivered and stockpiled to not cap production. Therefore, management of logistics breaking strain should be implemented using a smoothed average “loads on road” otherwise the schedule could be seriously undervalued.

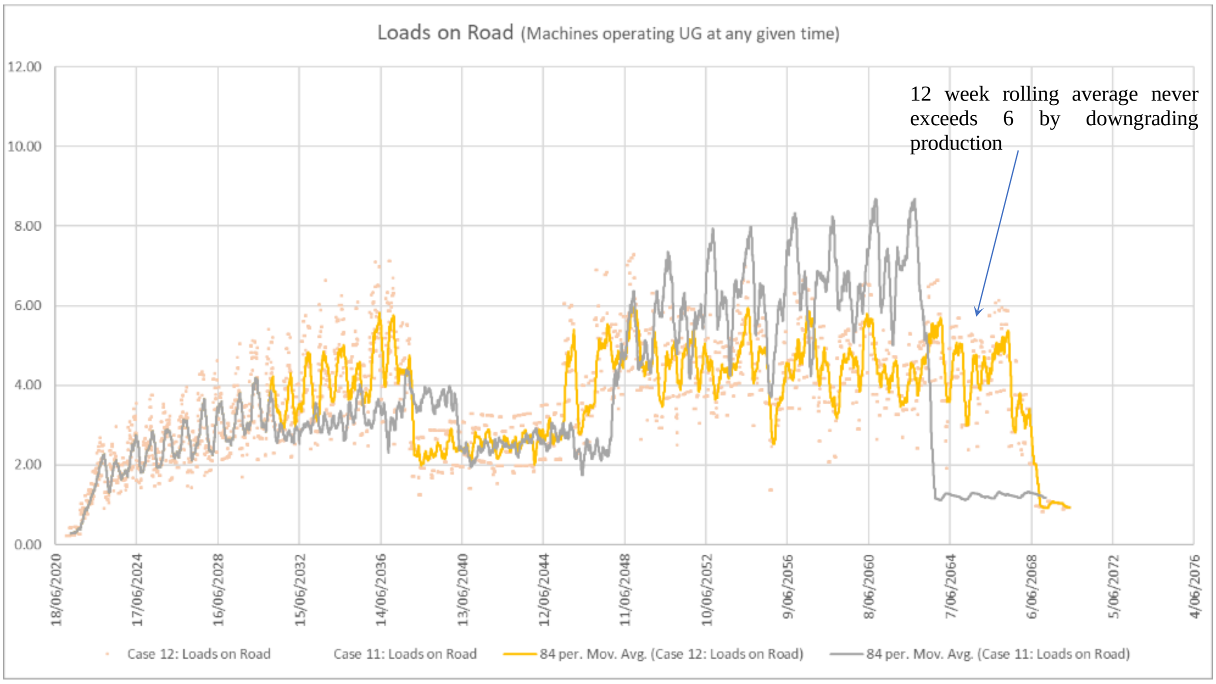


Figure 4-103: Case 12 vs Case 11 loads on road. Case 12 never exceeds six loads on road for the 12-week rolling average.

Although a downgrade in production might be considered a last resort, the mine’s licence to operate may dictate this, so that additional infrastructure or portals cannot be installed perhaps due to lack of regulatory approval, and if the logistics breaking strain is capped at six loads on road, Case 11 is incorrect and in certain circumstances provides an overestimate of value that could mislead investment.

4.15 Case 13: Splitting the Logistics System

All other cases up to this point were based upon delivery to the production district. Typically, these larger machines cannot go further inbye due to face ventilation constraints and so deliveries are stored outbye and then transferred to smaller 4-cylinder lower powered machines that deliver to the face. Recalling from Section 3.3.2 that outlined ventilation restrictions a single unit can travel up and down a gateroad at any given time. Therefore, there is an opportunity to store deliveries with larger machines outbye at the start of a gateroad and transfer to the face machine which travels up and down the gateroad typically with minimal interference compared to outbye gateroads.

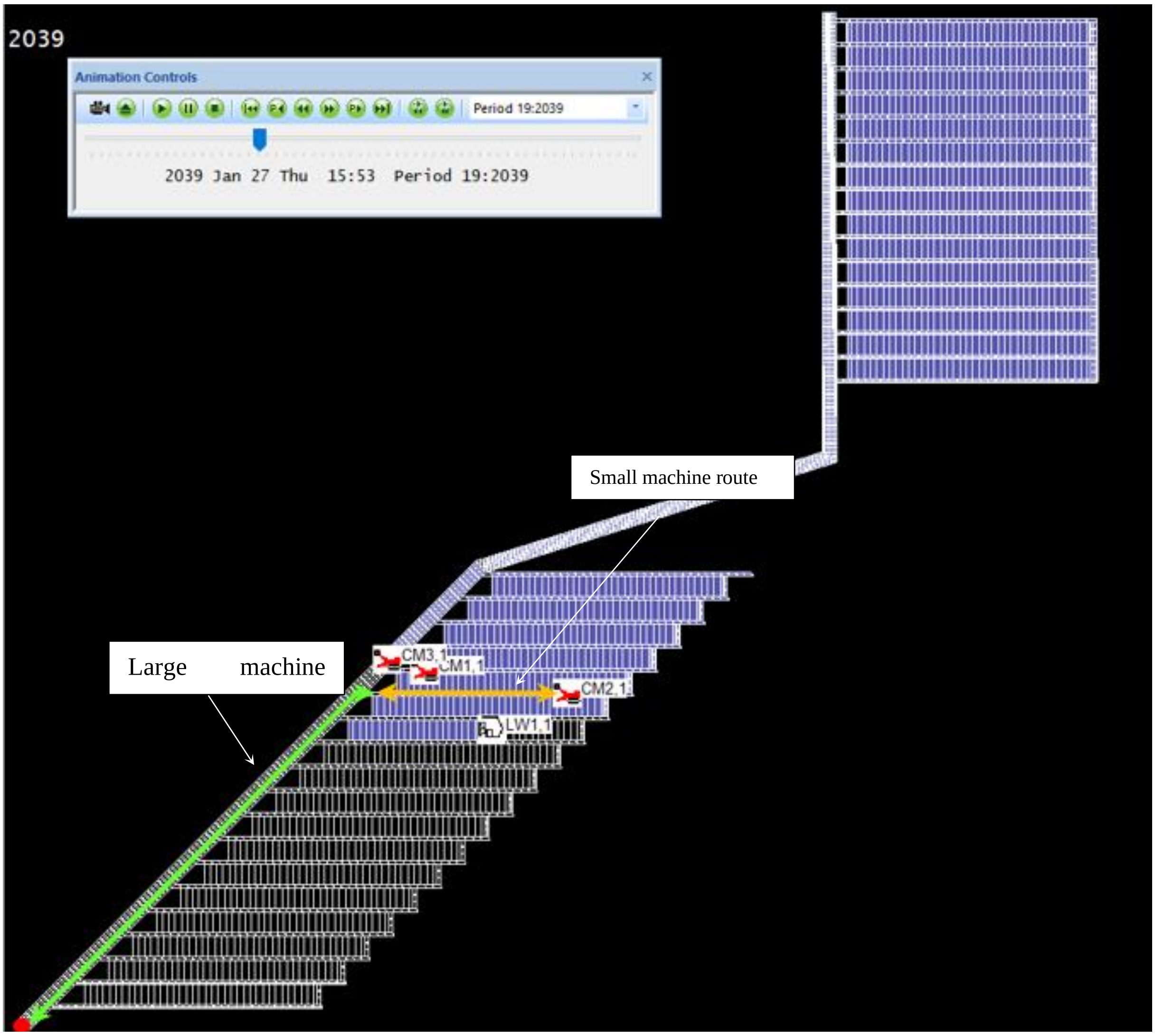


Figure 4-104: Case 13, small vs large machine route for CM2 in MG13.

The schedule for Case 13 is identical to that of Case 6 schedule, but the combined distance is split into two components. These split route cycles are shown in Figure 4-104 where orange is the smaller panel machine cycle operating between 1 cut through (ct) and the productive face large machine and green is the delivery cycle of the large outbye logistics machine. Therefore, the green route continues to grow as the mine migrates away from the portal, and the orange fluctuates depending on the status of distance inbye from the maingate turn for each respective machine down each gateroad.

Figure 4-105 shows the combined distance for Case 13 compared to Case 6 and it can be immediately seen that this is up to 13.6 km which occurs in mid-2044.

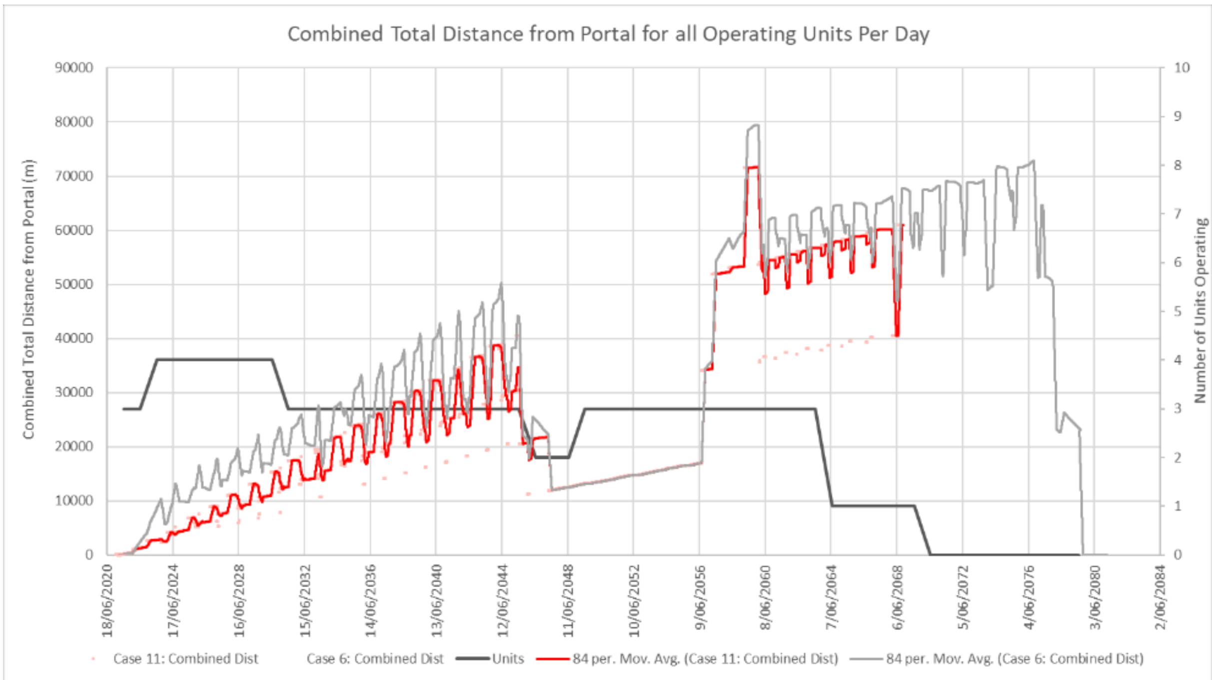


Figure 4-105: Combined distance of Case 13 vs Case 6 where Case 13 is only always delivering to the first cut through of each gateroad. (Green route).

As can be seen in Figure 4-105, the combined distance for Case 13 continues to grow but is less than that for Case 6 as this graph represent portal to first cut through (green route) and not the distance from 1ct inbye. There are still fluctuations in combined distance albeit with smaller amplitude. At first glance this is unexpected as each time a development unit or longwall moves inbye there is no alleviation of distance by finishing a gateroad and starting another. In other words, if you are at MG12 at 4,200 m inbye or MG13 at 200 m inbye the combined distance of MG13 is larger because the distance is only to 1ct for MG12 and MG13 and MG13 1ct happens to be around 320 m further inbye. The fluctuations that occur are a result of continuous miner flits from one panel to another, super units, and longwall changeouts.

4.15.1 Loads per Day

Loads per day are the same as Case 6 as shown in Figure 4-106. However, these requirements are now for two fleets (green and orange) In mains drivage it is only green cycles. Loads per day per panel should be scrutinised with peak combined loads of 45 loads on the 10/1/2026 broken down into: -

- MG102 Block 35 orange support requiring 13 loads that day.
- MG103 Block 15 yellow Support requiring 14 loads that day.
- MHNE Block 15 yellow Support requiring 12 loads that day.
- LW102 Block 2 requiring six loads.

Remembering delivery inbye from 1ct is done by the smaller LHD it is vital that not only the above loads can be met from the portal to 1ct, but the panel must also be able to supply from 1ct to the production face the same. Individual panel delivery maxima should also be studied as this may not occur in the combined maximum. The model developed in this thesis allows the maximum delivery per day per productive unit/panel for the entire life of mine which happens in this case to be 14 deliveries per 24 hours period and occurs on a range of dates throughout the entire life of the schedule.

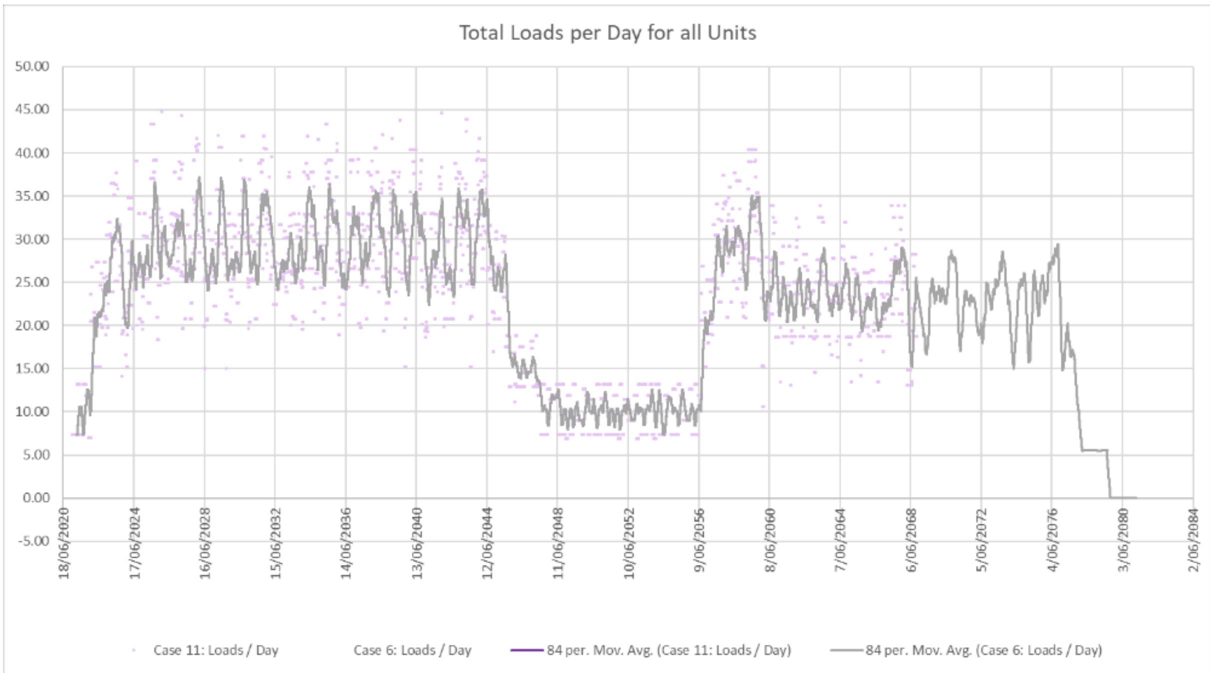


Figure 4-106: Case 13 vs Case 6 loads per day.

4.15.2 Loads on road

The loads on road logistics strain has been reduced as shown in Figure 4-107. For the Northeast Area/domain the peak loads on road have been reduced from 5.2 to 4.3 and for the Northeast Extension Area/domain from 7.7 to 6.9 from Cases 6 to 13, respectively. Therefore, if logistics breaking strain is encountered by a single LHD from pit bottom to production district, utilising the production district's LHD for part of the delivery journey can defer and perhaps, depending on remaining life of the mine, eliminate it.

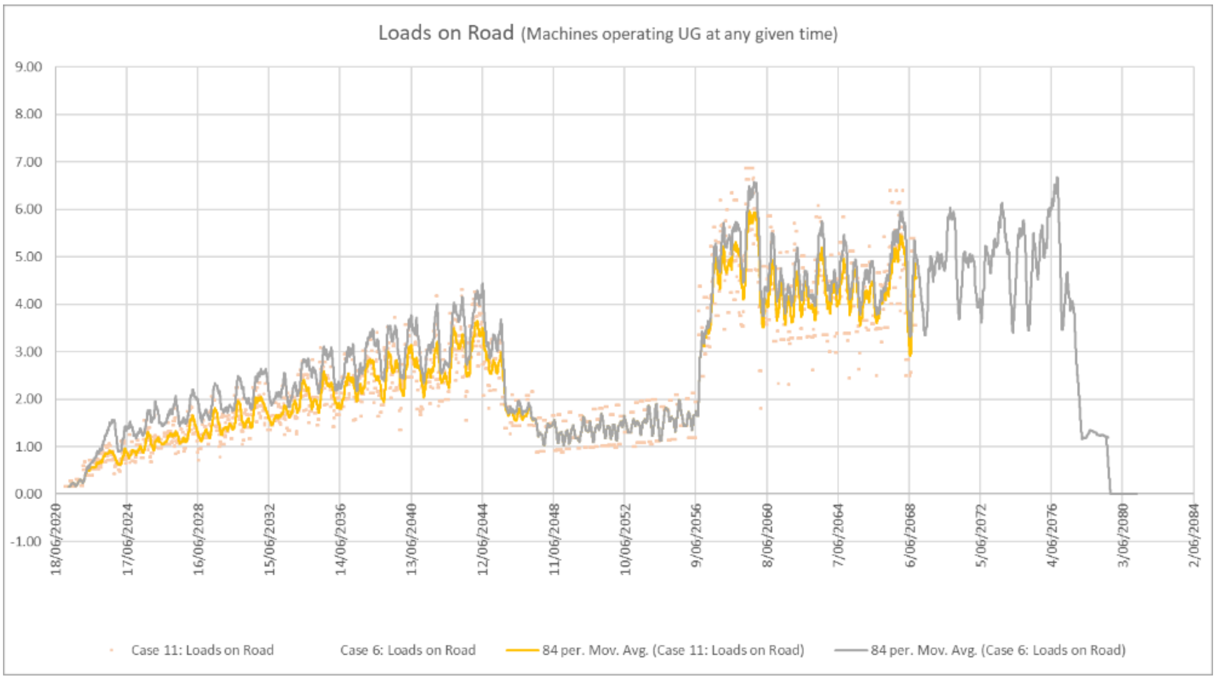


Figure 4-107: Case 13 vs Case 6 loads on road.

4.16 Drilling Down into the Logistics Strain Phenomena with FlexSim.

As XPAC fulfills identification of the strategic plan, FlexSim is utilised at a relative microscopic level taking daily peaks from XPAC outputs and watching how the actual day of deliveries would be executed in simulation. XPAC Cases 6 and 6a were selected because, Case 6 showed the impact of lack of inbye infrastructure and large distances out to the Northeast Extension Area/domain and Case 6a would show the alleviation of distance but the same deliveries per day requirements with the installation of the inbye shaft.

After loading into FlexSim, sensitivity analyses were conducted to evaluate the impact of changes to, the delivery time window, the number of delivery LHDs including capping, speed, payload, dedicated directional haulage roads and if the XPAC model could be verified independently.

4.16.1 Case 6a Peaks to be Studied

Case 6 and 6a combined distances, loads per day and loads on road are found in Figure 4-108, Figure 4-109, and Figure 4-110, respectively.

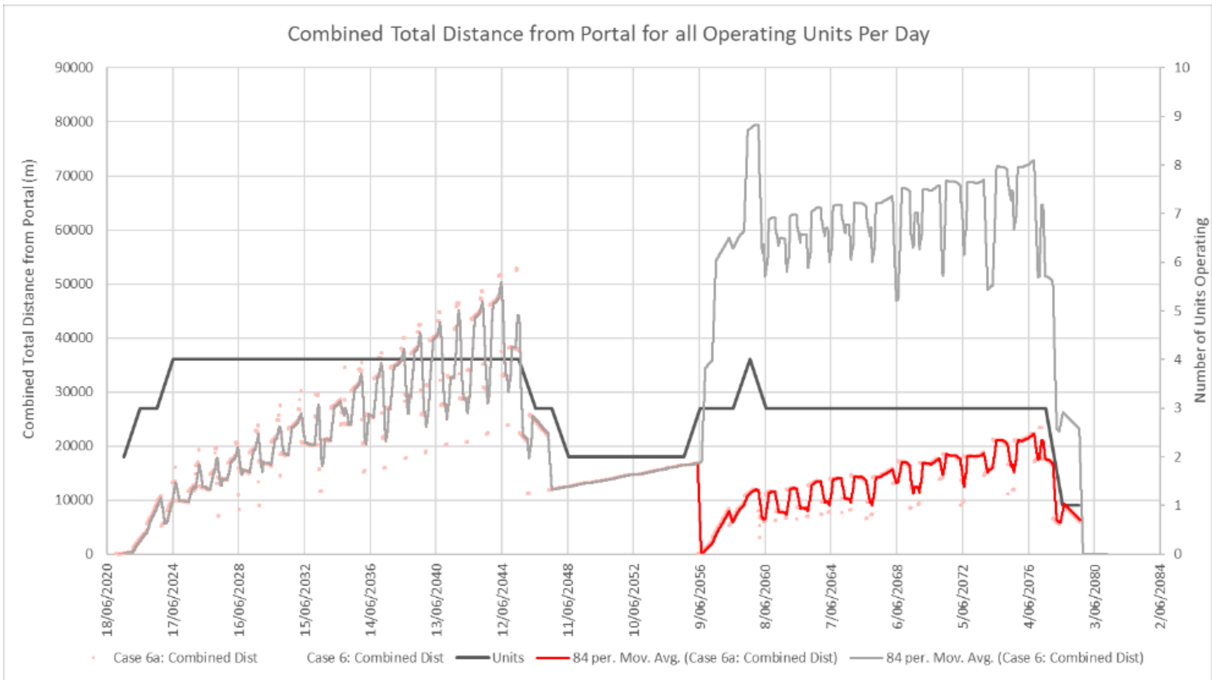


Figure 4-108: Case 6 and 6a Combined Distances

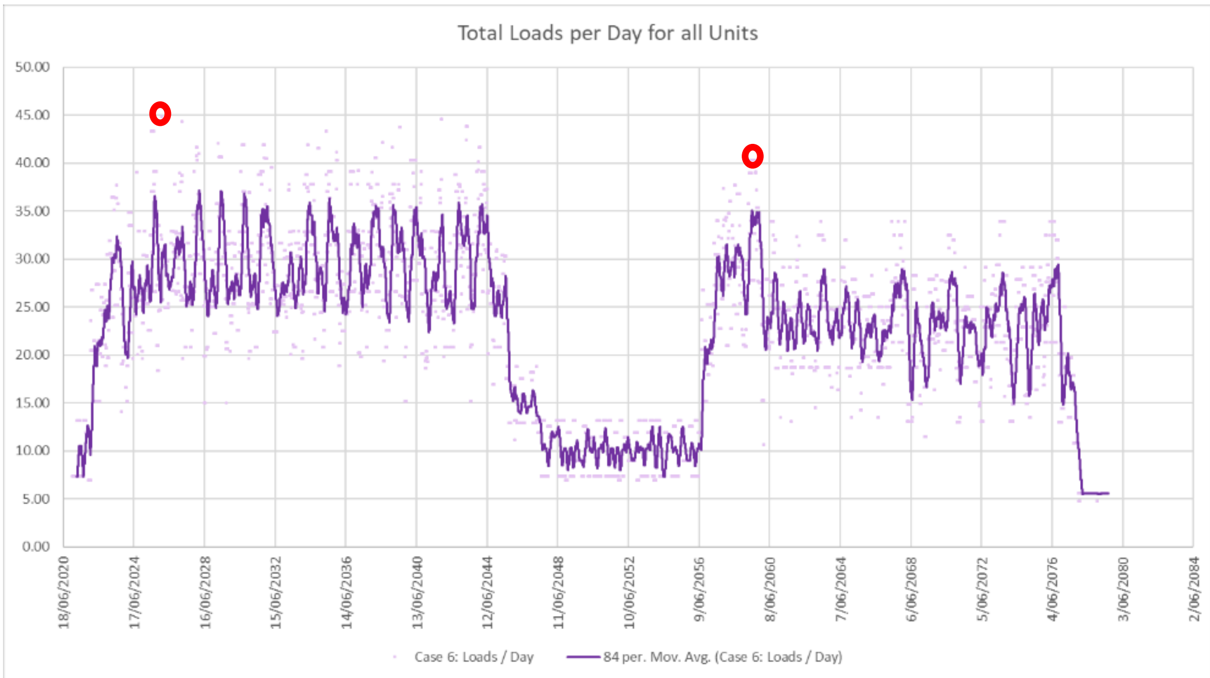


Figure 4-109: Case 6 and 6a Loads per Day

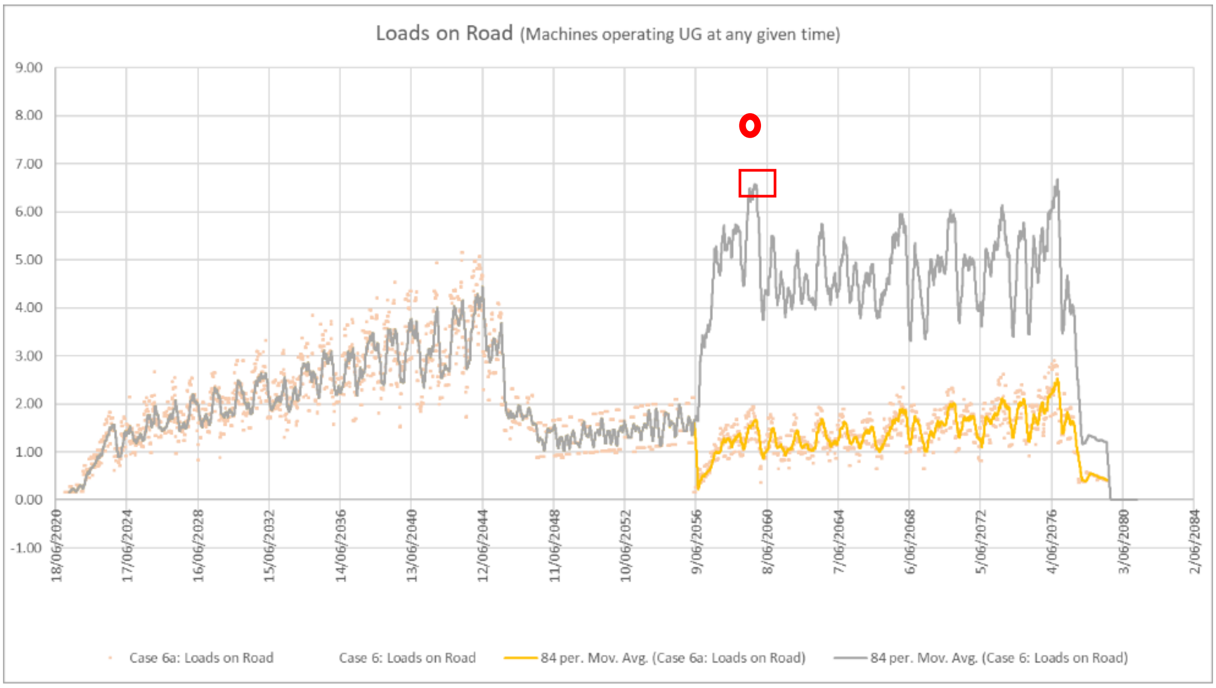


Figure 4-110: Case 6 and 6a loads on road.

There are two periods that warrant investigation. Firstly, the peak deliveries per day which occurs on the 17th of January 2026, as shown in Figure 4-111 Figure 4-112, at 45 loads per day where in the Northeast Area/domain:

- MG102 requires 13 deliveries on this day.
- MG103 requires 14 deliveries on this day.
- Northeast Mains requires 12 loads on this day.
- Longwall 102 requires six loads on this day.

This is because the combined distance reduces the logistics strain because it is so early in the schedule. Nevertheless, it is still prudent to see if this peak in deliveries can occur so early in the mine whilst at a stage where there is low travelling room, and the risk of a traffic jam is higher. As Cases 6 and 6a are identical at this point only one FlexSim model was necessary.

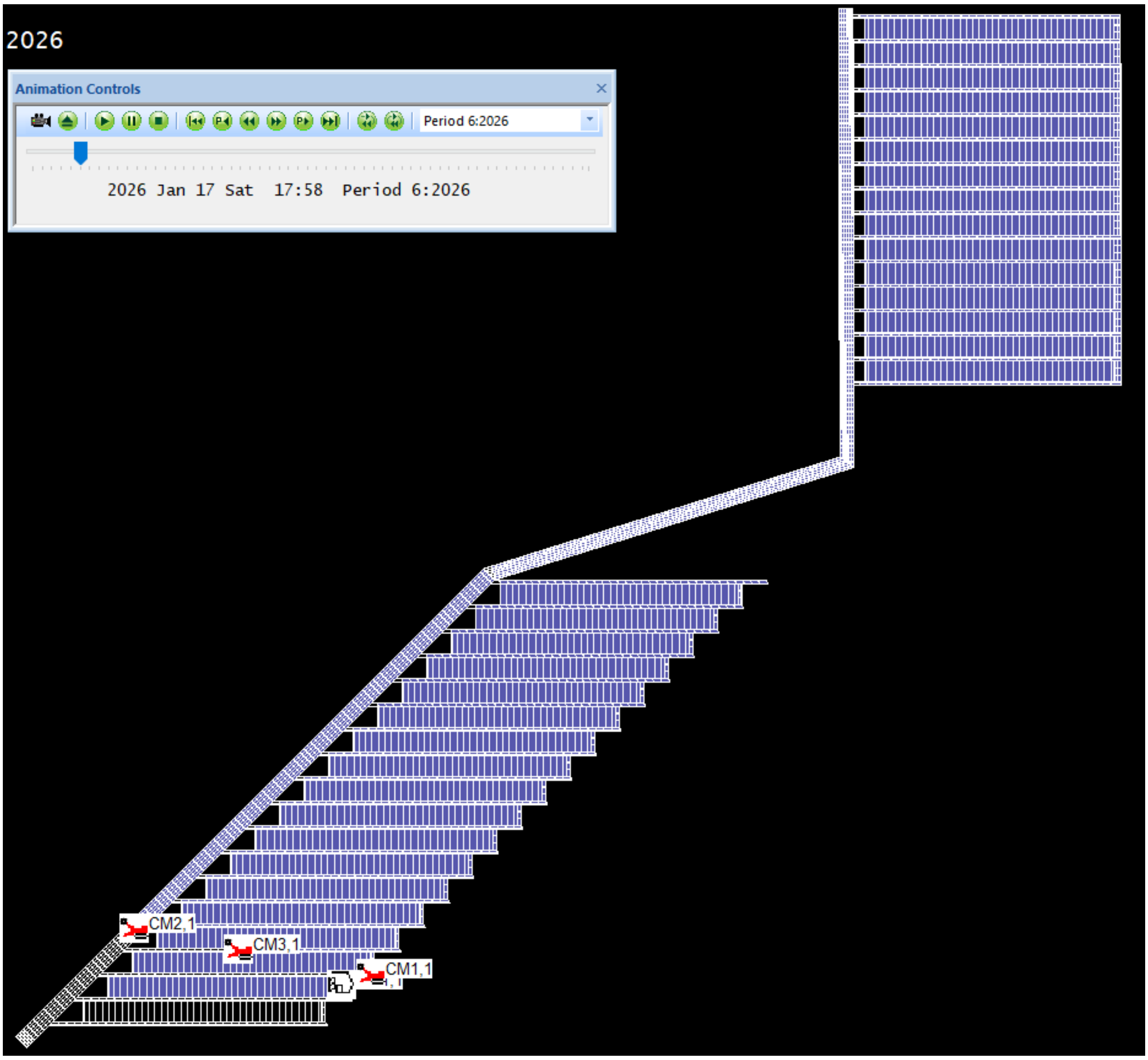


Figure 4-111: Case 6 "Peak 1" 1⁷ʰ January 2026 in XPAC.

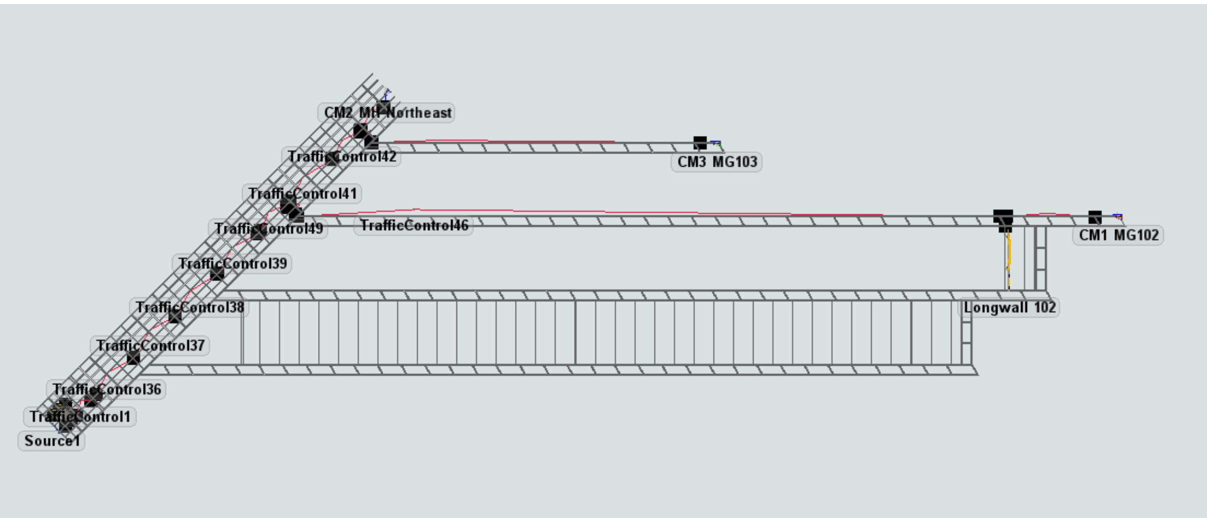


Figure 4-112: Replication of the XPAC face positions in Case 6 "Peak 1" 1⁷ʰ January 2026 in FlexSim.

The second peak warranting investigation is related to Loads on Road and occurs on the 20th of August 2059 as shown in Figure 4-113 and Figure 4-114. On this date there are 40.3 deliveries required and at any given time there are 7.6 loads on road where in the Northeast Extended Area/domain: -

- MG102 14 deliveries per day, 2.8 loads on road at any given time.
- MG103 14 deliveries per day, 2.6 loads on road at any given time.
- MHNE_EXT six deliveries per day, 1.1 loads on road at any given time.
- LW101 six deliveries per day and one load on road at any given time.

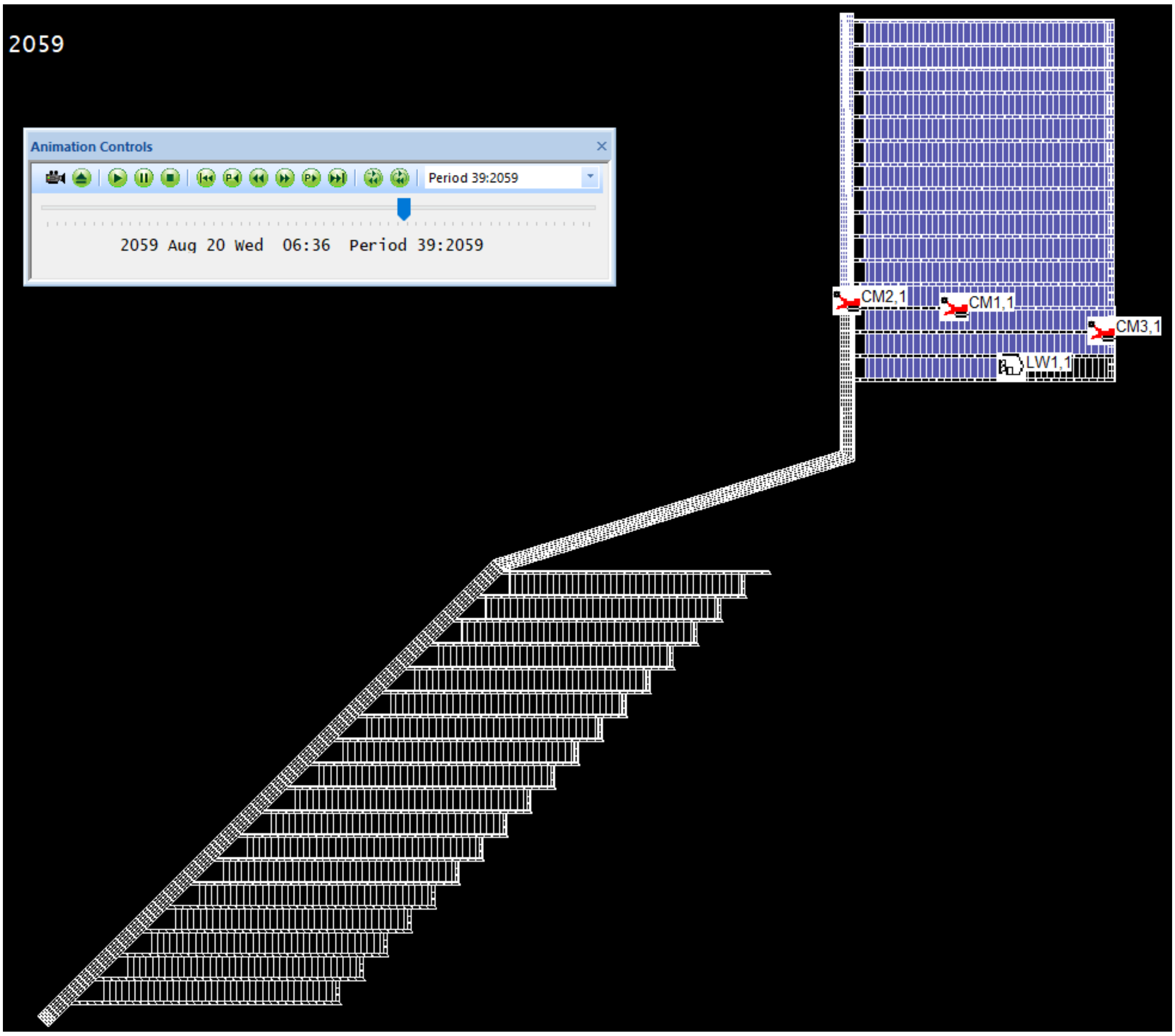


Figure 4-113: Case 6 "Peak 2" 20th August 2059

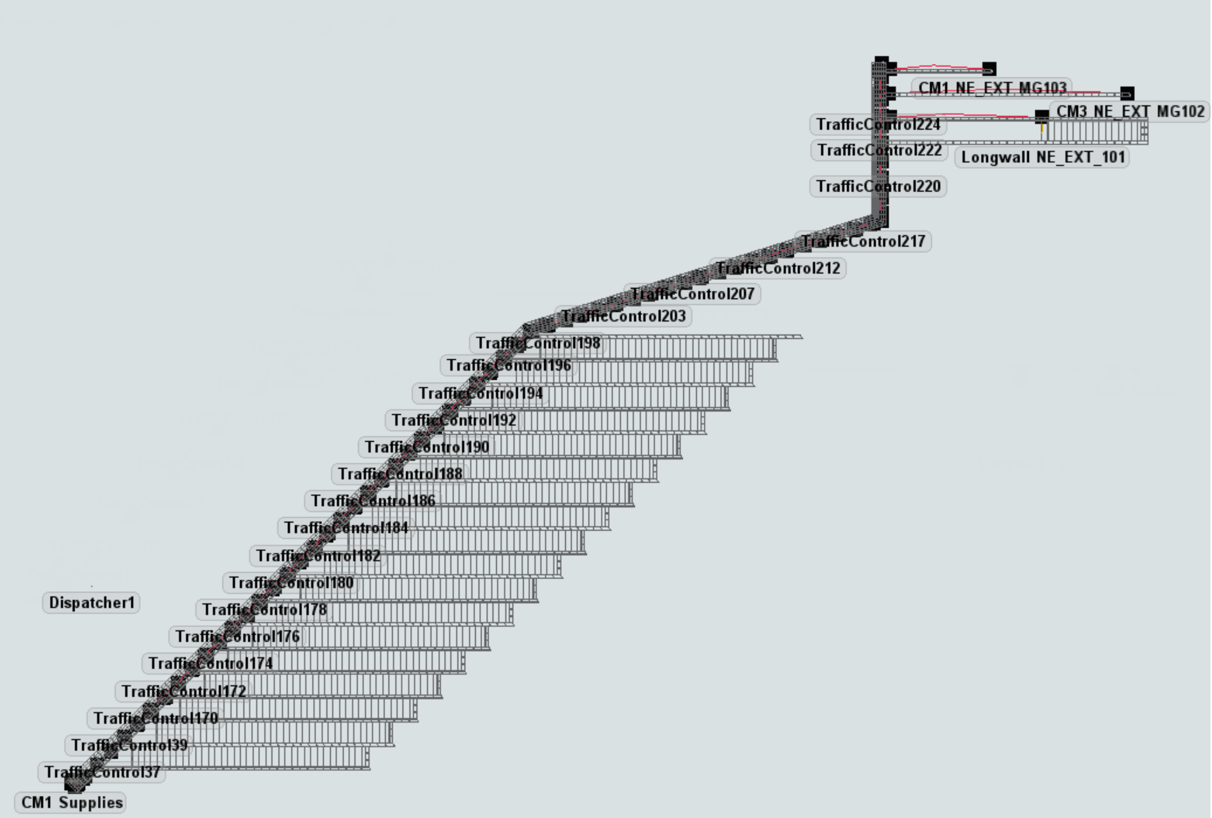


Figure 4-114: Replication of the XPAC face positions in Case 6 "Peak 2" 2⁰th August 2059 in FlexSim.

If the above loads per day can be achieved, then logistics breaking strain has not been reached, if loads per day cannot be achieved then alleviation is required.

4.16.1.1 Cases 6 and 6a "Peak 1" 2026

The key performance indicators from FlexSim for 2026 for a two and three LHD scenario are shown in Table 4-1. XPAC "loads on road" calculation on this day required 2.66 machines operating (the 0.66 could be for example operating only on afternoon and night shift) to fulfil the total of 45 deliveries correctly proportionally distributed across the production panels.

Table 4-1: FlexSim models 1 and 2 of the 2026 delivery peak

File Name	FlexSim Case	Panel	XPAC Deliveries required per day	XPAC Loads on Road	FlexSim Deliveries Per Day	FlexSim loads on Road	Satisfies Logistics Requirement?	*Verifies XPAC Identified Requirement*
1.0 2026 Status 2 loaders.fsm	Case 6: 2026 2 Loaders	MG102	13	2.66	10	2	No	Yes
		MG103	14		11			
		NE Mains	12		9			
		LW 102	6		5			
2.0 2026 Status 3 loaders.fsm	Case 6: 2026 3 Loaders	MG102	13	2.66	13	3	Yes	
		MG103	14		16			
		NE Mains	12		14			
		LW 102	6		7			

As can be seen two delivery LHDs operating achieve 35 deliveries per day and is a shortfall of ten deliveries. Three delivery LHDs exceed delivery requirements by four deliveries at 49 loads. Therefore, the LHDs required are somewhere between two and three delivery LHDs and closer to three delivery LHDs which coincidently independently verifies for this date the logistics strain calculation of the XPAC model.

Table 4-2 shows the average breakdown in time for each LHD. The expected delivery timetable between two and three delivery LHDs is shown per panel. Even though two delivery LHDs cannot reach the delivery quota for the day, three delivery LHDs are slightly less efficient as there is a higher risk of vehicle interaction and the need for shunting which is reflective of the 4.2% average increase in traffic delay.

Table 4-2: The Fleet average of time breakdown between two and three delivery LHDs on 1^{7}th January 2026.

% Average breakdown of time on each task for the Delivery Machine fleet.		
Task	**2 Delivery Machines**	**3 Delivery Machines**
Travel Loaded	32.2	30.9
Travel Unloaded	31.0	29.7
Loading	18.7	17.8
Unloading	17.3	16.7
Traffic Delay	0.8	5.0

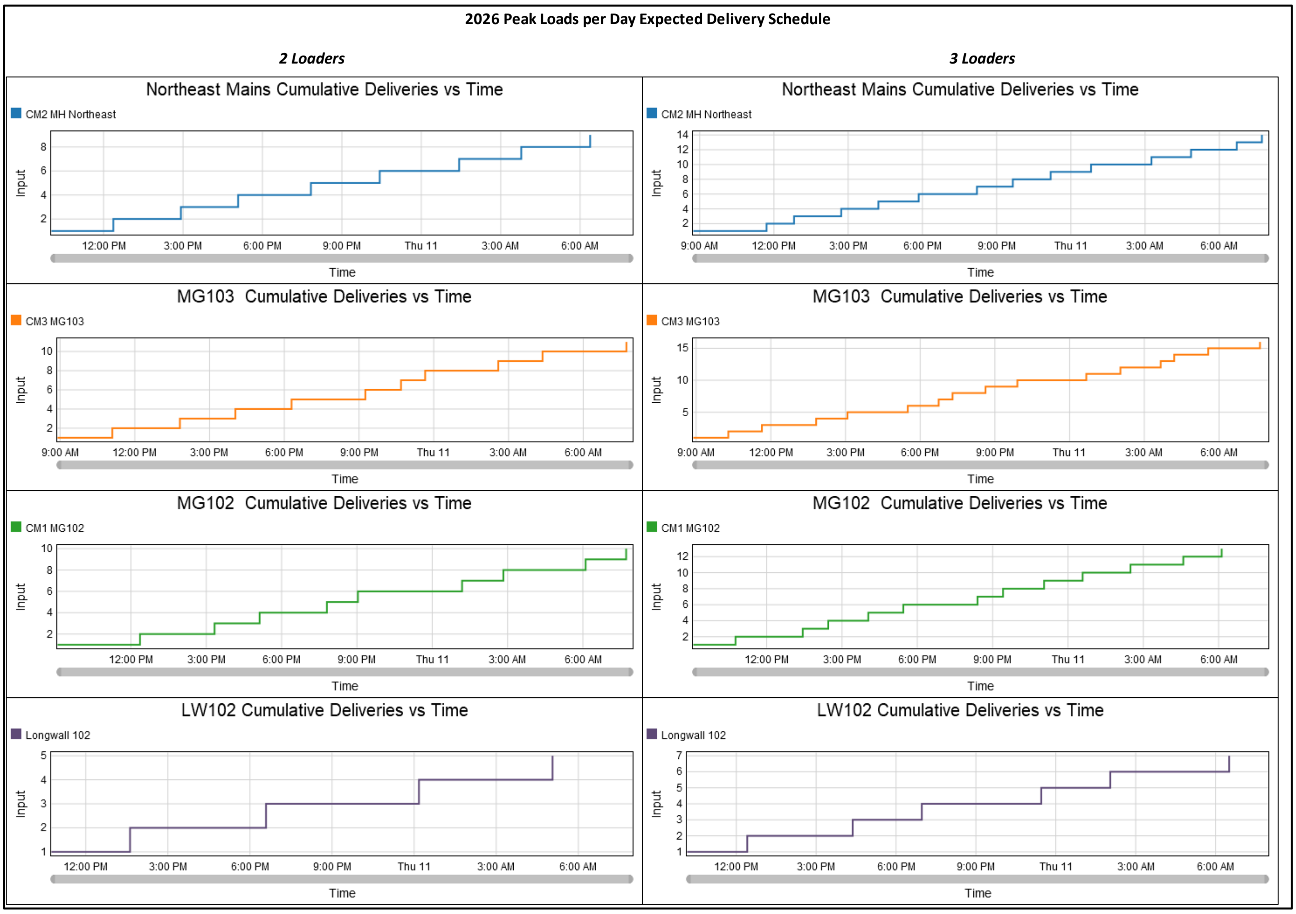


Figure 4-115: Delivery Schedule throughout 1^{7}th January 2026.

4.16.1.2 Case 6 "Peak 2" 2059

On the 20th of August 2059 there is a peak "loads on road". It was different to 2026 because this is a combination of distance and loads required. The XPAC output predicted 7.6 loads on road were required to maintain deliveries for each production panel. This is presented in Table 4-3. Firstly, three LHDs deployed were studied to evaluate the impact on productivity if nothing changed from 2026 and that LHDs were limited. It found that with three LHDs, total productivity would be estimated to be at or slightly above 37.5% of LoM target. Secondly, with seven LHDs deployed on the same day, a 10% reduction on required deliveries would occur. Thirdly, at eight LHDs all deliveries were met.

Table 4-3: The Fleet average of time breakdown between two and three delivery LHDs on 2^0th August 2059.

File Name	FlexSim Case	Panel	XPAC Deliveries required per day	XPAC Loads on Road	FlexSim Deliveries Per Day	FlexSim loads on Road	Satisfies Logistics Requirement?	*Verifies XPAC Identified Requirement*
3.0 2059 Status 3 loaders.fsm	Case 6: 2059 3 loaders	NE_EXT MG102	approximately 37.5%	7.6	4	3	No	
		NE_EXT MG103	14		5			
		NE_EXT MAINS	6		4			
		NE_EXT LW102	6		2			
4.0 2059 Status 7 loaders.fsm	Case 6: 2059 7 loaders	NE_EXT MG102	14	7.6	13	7	No	Yes
		NE_EXT MG103	14		12			
		NE_EXT MAINS	6		6			
		NE_EXT LW102	6		5			
5.0 2059 Status 8 loaders.fsm	Case 6: 2059 8 loaders No transport interruption from other vehicles	NE_EXT MG102	14	7.6	14	8	Yes	
		NE_EXT MG103	14		14			
		NE_EXT MAINS	6		6			
		NE_EXT LW102	6		6			

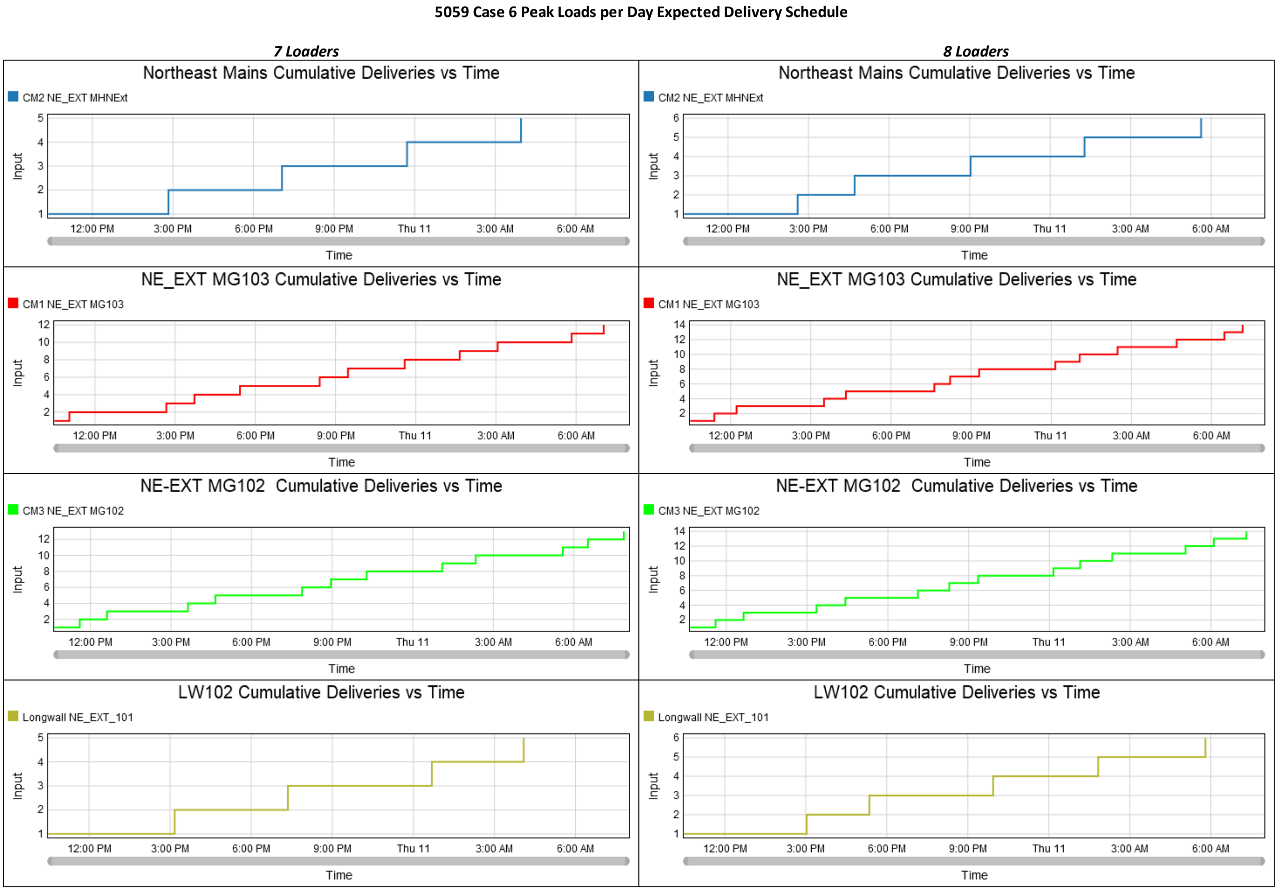


Figure 4-116: Delivery schedule throughout 2^0th August 2059.

Figure 4-116 shows the delivery schedule throughout the day. As can be seen eight LHDs achieve the required breakdown in deliveries. This is within the range for the XPAC estimate for "loads on road" required of 7.6 for this day, with seven LHDs in FlexSim delivering less and eight LHDs delivering the set target. Logistics breaking strain for this day would therefore be anything less than approximately 7.6 LHDs operating which would result in a write down in productivity for that day. It is important to note that anxiety about a specific day in planning reality into the future is futile and this is not what this thesis is about, but enables trust in the XPAC model, and does give a clear requirement of what machines will need to be deployed as a slow growing trend to meet LoM production requirements. Therefore the 12-week rolling average is very important in that daily outlier delivery requirements can be managed through logistics planning forethought. However, studying individual peaks in FlexSim and solving them will eliminate anomaly days surrounding those peaks.

Table 4-4 shows the average breakdown in time for each delivery LHD for three, seven, eight and a grossly overestimated 20 LHDs (assuming ventilation capacity is unlimited). Inefficiencies grow with the number of delivery LHDs as more shunting is required. Twenty LHDs were selected to demonstrate that delivery capacity rises from 40 required (with eight LHDs) to 77 deliveries, but with significant inefficiencies as roadways excessively block with shunting with the average of traffic delay / idle increasing to 25%.

Table 4-4: Case 6 fleet average of time breakdown between two and three delivery LHDs on 2^{0}th August 2059.

% Average breakdown of time on each task for the Delivery Machine fleet.				
Task	**3 Delivery Machines**	**7 Delivery Machines**	**8 Delivery Machines**	**20 Delivery Machines**
Travel Loaded	46.6	44.7	43.6	34.3
Travel Unloaded	42.2	40.5	40.8	31.2
Loading	6.0	6.0	5.8	4.6
Unloading	4.9	5.3	5.3	4.1
Traffic Delay / Idle	0.3	3.5	4.4	25.8

4.16.1.3 Case 6 "Peak 2" 2059

The installation of the portal/shaft at the Northeast Extension Area/domain pit bottom was then replicated in FlexSim for the 2059 peak. The face positions for 2059 remains the same but Figure 4-117 shows the position of the new materials delivery portal/shaft where deliveries are in this case loaded. XPAC estimated on this day, that for Case 6a the "loads on road" reduces to 1.91 and therefore FlexSim should fail at one LHD and just pass at two LHDs.

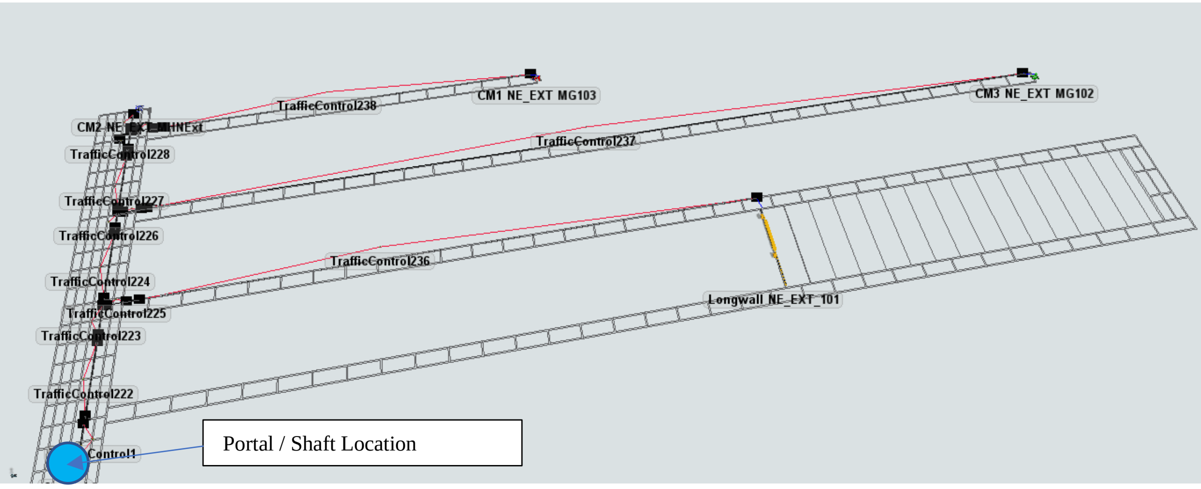


Figure 4-117: Case 6a location of shaft in FlexSim.

Table 4-5: FlexSim results for one, two and three delivery LHDs.

File Name	FlexSim Case	Panel	XPAC Deliveries required per day	XPAC Loads on Road	FlexSim Deliveries Per Day	FlexSim loads on Road	Satisfies Logistics Requirement?	*Verifies XPAC Identified Requirement*
6.0 2059 Status (6a inbye shaft) 1 loader.fsm	Case 6a: 2059 1 loader	NE_EXT MG102	14	1.9	7	1	No	Yes
		NE_EXT MG103	14		7			
		NE_EXT MAINS	6		3			
		NE_EXT LW102	6		3			
7.0 2059 Status (6a inbye shaft) 2 loaders.fsm	Case 6a: 2059 2 loaders	NE_EXT MG102	14	1.9	14	2	Yes	
		NE_EXT MG103	14		14			
		NE_EXT MAINS	6		6			
		NE_EXT LW102	6		6			
8.0 2059 Status (6a inbye shaft) 3 loaders.fsm	Case 6a: 2059 3 loaders	NE_EXT MG102	14	1.9	20	3	Yes	
		NE_EXT MG103	14		20			
		NE_EXT MAINS	6		9			
		NE_EXT LW102	6		8			

As can be seen in Table 4-6, inefficiencies are significantly less with less machines on road meaning that going to between one and two delivery LHDs doubles the delivery output from 20 loads with one delivery LHD per day to 40 loads with two, due to relatively little interaction between the machines. Increasing to three machines introduces a slight 5% inefficiency as rather than a fully efficient 60 machines with zero interaction, actual delivery is 57 which is to be expected with more likelihood of minor vehicle interaction and shunting. In any case as always, a new portal / shaft is the general panacea for logistics strain that reduce the priorities of solving all other inefficiencies, as long as regulator approvals permit them.

Table 4-6: Case 6a fleet average of time breakdown between one, two and three delivery LHDs on 2^{0t}h August 2059.

% Average breakdown of time on each task for the Delivery Machine fleet.			
Task	**1 Delivery Machine**	**2 Delivery Machines**	**3 Delivery Machines**
Travel Loaded	29.9	28.9	28.6
Travel Unloaded	28.3	27.6	28.2
Loading	22.3	21.8	20.4
Unloading	19.5	19.5	19.0
Traffic Delay / Idle	0.0	2.2	3.8

As travel time is so much less than for Case 6, the proportion of fixed time components of the delivery cycle is much higher. In Case 6 the combined loading and loading time amounted to 11.1% of the time in the day for the predicted eight delivery LHDs. In Case 6a for two delivery LHDs this has increased to 41.3%. Therefore, to reduce loads on road for a short distance delivery cycle, there is more benefit to be gained through finding efficiencies in loading and unloading time. For longer distances such as in Case 6, finding efficiencies during the travelling loaded or unloaded phases (such as higher speed roadways) is the priority.

Therefore, it could be argued that newer mines close to the portal / shaft should concentrate on maximising efficiencies of loading and unloading. As the mine gets older there is a crossover point where more focus on travel time is necessary to reduce logistics strain. It may not be a priority to concrete and light roads in an early mine life, rather to retrospectively do this at the crossover of focus between the importance of fixed components (loading and unloading) to variable components (speed) of cycle time. In other words, and as shown in Figure 4-118, optimise the efficiencies of non-travel while the mine is considered new, then take these efficiencies into the future as the mine gets larger to allow the planner to concentrate on optimising the efficiencies of travel time to minimise the risk of logistics breaking strain.

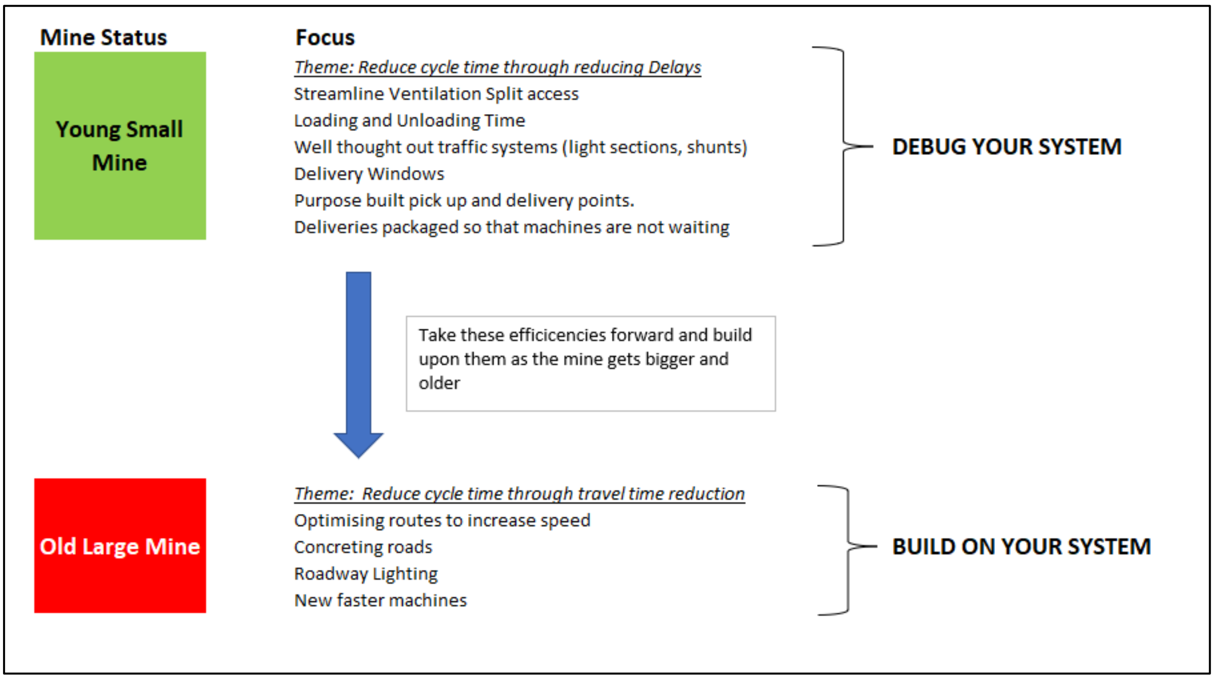


Figure 4-118: Mine status and logistics priorities

4.16.2 Other Methods to Reduce Logistics Strain through FlexSim Analysis

FlexSim has verified the strategic identification of logistics strain using XPAC independently at multiple dates (2026 and 2059) and multiple scenarios (Case 6a). It also evaluates vehicle interaction, whereas at the strategic level, XPAC can only use total delay. FlexSim was utilised in this thesis to: -

- Fulfill Case 6 delivery obligations and drop one delivery LHD back to seven delivery LHDs.
- Understand for Case 6, the durability of eight delivery LHDs to a range of small vehicle or pedestrian interaction delays.
- The impact of capping LHDs to a tradition four loads on road Case 6 scenario.

4.16.2.1 Case 6 Delivery Obligations with Seven Delivery LHDs.

Multiple scenarios limiting Case 6 to seven delivery LHDs were examined. These included the use of an inbye and outbye heavy haulage road, sensitivity of increasing payload with four or five double delivery LHDs using road trains, sensitivities on increasing the speed or delivery by 10% and 20%, and a combination of speed and payload increase. Increasing payload also required increasing loading time from 15 minutes to 20 minutes to hitch on the additional trailer. Table 4-7 highlights the key outcomes for all these scenarios.

Table 4-7: Case 6 FlexSim results for seven delivery LHD scenarios.

File Name	Isolating	Panel	XPAC Deliveries required per day	XPAC Loads on Road	FlexSim Deliveries Per Day	FlexSim loads on Road	Satisfies Logistics Requirement?
4.0 2059 Status 7 loaders.fsm	Base Case	NE_EXT MG102	14	7.6	13	7 single load time 15mins	No
		NE_EXT MG103	14		12		
		NE_EXT MAINS	6		6		
		NE_EXT LW102	6		5		
4.5 2059 Status 7 loaders + 12kmhr.fsm	20% increase in speed	NE_EXT MG102	14	7.6	15	7 single load time 15mins	Yes
		NE_EXT MG103	14		14		
		NE_EXT MAINS	6		6		
		NE_EXT LW102	6		6		
9.0 2059 Status 7 loaders - inbye outbye road.fsm	Inbye and Outbye dedicated one way travel roads	NE_EXT MG102	14	N/A	13	7 single load time 15mins	No
		NE_EXT MG103	14		12		
		NE_EXT MAINS	6		6		
		NE_EXT LW102	6		6		
10.0 2059 Status 7 loaders - inbye outbye road + 4 x road train(2 loads).fsm	Inbye and Outbye dedicated one way travel roads + 4 delivery machines with double payload	NE_EXT MG102	14	N/A	14	7 total delivery machines, 4 doubled. Single load time 15mins, double load time 20mins.	Yes
		NE_EXT MG103	14		14		
		NE_EXT MAINS	6		6		
		NE_EXT LW102	6		6		
11.0 2059 Status 7 loaders - inbye outbye road loader 11kmhr.fsm	Inbye and Outbye dedicated one way travel roads + 10% increase in speed	NE_EXT MG102	14	N/A	13	7 single load time 15mins	No
		NE_EXT MG103	14		13		
		NE_EXT MAINS	6		6		
		NE_EXT LW102	6		6		
12.0 2059 Status 7 loaders - inbye outbye road loader 12kmhr.fsm	Inbye and Outbye dedicated one way travel roads + 20% increase in speed	NE_EXT MG102	14	N/A	15	7 single load time 15mins	Yes
		NE_EXT MG103	14		14		
		NE_EXT MAINS	6		6		
		NE_EXT LW102	6		6		

As can be seen seven delivery LHDs are only able to meet delivery obligations with a 20% increase in speed, or four out of the seven LHDs carrying double payload. Dedicated inbye and outbye haulage roads alone meets delivery criteria even with 11 delivery LHDs but it is expected from anecdotal evidence from research conducted in Chapter 2 that as more light vehicles or pedestrians are added to the system speed alone (Case 4.5) would be a significantly less robust solution than a combined solution of speed and dedicated directional roadways.

4.16.2.2 Interaction Delays

Additional to shunting between delivery vehicles, there are inevitably going to be times when a LHD must shunt or be delayed due to light vehicle or pedestrian interaction. A single inbye outbye travel road with eight delivery LHDs known as "5.0" was selected as the base case. The case was then flexed with 30 mins, 60 minutes, and 120-minute additional delay to achieve delivery obligations by reducing the productivity window in FlexSim from 24 hours x 3600secs = 86400 seconds, to for example for a one-hour additional delay 86400 – 3600 = 82800 seconds and so. These are shown in Table 4-8.

Table 4-8: Case 6 FlexSim results for additional interaction delays.

File Name	Isolating	Panel	XPAC Deliveries required per day	XPAC Loads on Road	FlexSim Deliveries Per Day	FlexSim loads on Road	Satisfies Logistics Requirement?
5.0 2059 Status 8 loaders.fsm	Base Case	NE_EXT MG102	14	7.6	14	8	Yes
		NE_EXT MG103	14		14		
		NE_EXT MAINS	6		6		
		NE_EXT LW102	6		6		
13.0 2059 Status 8 loaders with 0.5 hour interaction delay.fsm	30mins additional delay	NE_EXT MG102	14	7.6	14	8	Yes
		NE_EXT MG103	14		14		
		NE_EXT MAINS	6		6		
		NE_EXT LW102	6		6		
14.0 2059 Status 8 loaders with 1 hour interaction.fsm	60mins additional delay	NE_EXT MG102	14	7.6	14	8	Yes
		NE_EXT MG103	14		14		
		NE_EXT MAINS	6		6		
		NE_EXT LW102	6		6		
14.1 2059 Status 8 loaders with 1.5 hour interaction.fsm	90mins additional delay	NE_EXT MG102	14	7.6	13	8	No
		NE_EXT MG103	14		13		
		NE_EXT MAINS	6		6		
		NE_EXT LW102	6		6		
15.0 2059 Status 9 loaders with 2 hour interaction delay	9 delivery machines + 2 hours delay	NE_EXT MG102	14	7.6	14	9	Yes
		NE_EXT MG103	14		14		
		NE_EXT MAINS	6		6		
		NE_EXT LW102	6		6		
15.1 2059 Status 9 loaders with 2.5 hour interaction delay	9 delivery machines + 2.5 hour delay	NE_EXT MG102	14	7.6	13	9	No
		NE_EXT MG103	14		13		
		NE_EXT MAINS	6		6		
		NE_EXT LW102	6		6		

As the original estimate from XPAC was 7.6 delivery LHDs to meet the daily obligation there is some additional capacity in an 8- delivery LHD fleet. This capacity allows the absorption of 60 minutes of additional delay for a 24-hour period. Any longer and there is a shortfall in materials supply. An additional LHD, therefore, nine LHDs, allows approximately another 60 minutes of additional delay on top of the 8-LHD capacity.

4.16.3 The Effect of a Capped Fleet.

The last scenario is to evaluate the capacity for delivery in a fixed fleet size, and then only to operate that fleet in low traffic times, for example for 13.5 hours per day to represent back shift (afternoon and night shifts) operating times only. In this case a nominal four units was selected. This is a method to demonstrate to management what would occur if appropriate resources or time were not planned for and included within the valuation of the model much like the write down in productivity to a capped "loads on road" as discussed in the XPAC "Case 12".

If the daily breakout logistics was eight "loads on road" but the 12-week rolling average was four, then with pre-planned inventory management productivity would not be compromised. However, if the 12-week rolling average required eight "loads on road" then logistics breaking strain has occurred because of the 4-LHD capping as shown in Table 4-9.

Table 4-9: Case 6 FlexSim results for capped and capped + operating hours reduction.

File Name	Isolating	Panel	XPAC Deliveries required per day	XPAC Loads on Road	FlexSim Deliveries Per Day	FlexSim loads on Road	Productivity on this day*
5.0 2059 Status 8 loaders.fsm	Base Case	NE_EXT MG102	14	7.6	14	8	100%
		NE_EXT MG103	14		14		
		NE_EXT MAINS	6		6		
		NE_EXT LW102	6		6		
16.0 2059 Status 4 loaders.fsm	4 loader cap	NE_EXT MG102	14	7.6	7	4	50%
		NE_EXT MG103	14		7		
		NE_EXT MAINS	6		3		
		NE_EXT LW102	6		3		
17.0 2059 Status 4 loaders with 13.5 hour operating window.fsm	4 loader cap + 13.5 hour operating time in a 24 hour period.	NE_EXT MG102	14	7.6	4	4	70%
		NE_EXT MG103	14		4		
		NE_EXT MAINS	6		2		
		NE_EXT LW102	6		2		

4.16.4 FlexSim application conclusion

The bulk of logistics bottleneck identification is done within XPAC and scheduling. XPAC enables strategic solutions to be undertaken with significant forward planning. However, FlexSim adds more detail to that plan by drilling down to the tactical level for better microscopic understanding of machine movements and interactions. It is most importantly a powerful tool in that it forms part of the software suite in the research particularly during time periods where short-term logistics strain spikes and has the potential to be alleviated or at least the alternatives are exhausted, and a productivity downgrade further justified.

4.17 Chapter Conclusion

Two generic mines were constructed and scheduled implementing the logistics system developed in this thesis as discussed in Chapter 3. One mine plan represented migration and return to a portal using five area/domains which included Northeast, Northwest, Southeast, Southwest, and Northeast Extended. The other mine plan represented a migration away in a general direction from an adit/box cut/ cut and cover mine and comprised the Northeast and the Northeast Extended area/domains. In total 15 LoM schedule cases were modelled and built up from a reference model to isolate a singular difference from the previous model. Starting from the base case (Case 1) the following impacts could be summarised: -

- Mine design (Case 1 Migration away and return and Case 6): - Proved that the centroid of production face location travel distance from pit bottom was directly proportional to logistics strain. There was a steady increase in logistics strain through a domain as it migrated away from pit bottom and then rapid relief when a new closer domain was transferred to.
- Development inventory in advance (Case 1b vs Case 1): - The further development was ahead of the longwall (development inventory) the higher the peaks of logistics strain. If development was kept closer to the longwall face and not allowed to build too much inventory in advance, it smoothed and importantly lowered and delayed the onset of logistics strain.
- Changes to productivity (Case 1a vs Case 1 and Case 11): - Proportionally changed the deliveries per day per production district which in turn changed the logistics strain. Generally, the higher or lower the

productivity will increase or decrease logistics strain respectively, but it is ***not*** proportional as the progression through the mine will be different. For example, sometimes there will be travel distance relief sooner as a new domain closer to pit bottom is reached sooner with higher productivity but logistics strain can in some circumstances be reduced by the reduction in travel time more than offsetting the deliveries per day.

- The impact of a large step around to a new domain (Case 2 vs Case 1 and Case 6): - Transferring to a new mining area / domain with significant mains drivage between the original and new domain without changing the location of the portals / pit bottom for materials delivery created an immediate and detrimental effect on logistics strain.
- The impact of primary support (Case 3 vs Case 2): - Moving from a homogenous primary support to a more realistic heterogenous primary support impacting development rate in each individual development panel increased the day-to-day differences in loads per day and logistics strain. It highlighted that depending on the combination of primary support at each production district a "perfect storm" of very high logistics strain or logistics breaking strain could occur for short periods of time that was much higher than the rolling average logistics strain. The tool that this thesis has produced can predict these "perfect storms" ahead of time which may allow a build-up of materials inventory (if storage permits) prior allowing a smoothing of logistics strain through this period.
- Mine progression e.g., Rehanding vs one sided (Case 4 vs Case 3 and Case 6): - Changes to the way mine extraction progresses has an immediate impact on the frequency or logistics strain relief. Taking one side of a domain which requires all mains drivage to be done up front resulted in an increase in the rate of change of logistics strain but quicker relief to the strain as the production districts returned closer to pit bottom to take the other side of the domain in half the time. In contrast taking both sides of the domain by alternating / rehanding the longwall and progressing away from pit bottom resulted in a slower rate of change of logistics strain but higher logistic strain peaks as all production faces were further away from pit bottom at the same time towards the end of that domain.
- Introduction of inbye portals (Case 5 vs Case 4, Case 6a vs Case 6): - Provided immediate step change logistics strain relief. The introduction of closer portals smoothed the number of machines throughout the life of mine simplifying the fleet requirements and utilisation of them. Deliveries per day did not change but the cycle time was significantly reduced meaning less delivery LHDs were required.
- Speed of delivery (Case 7): - Reduced delivery LHD travel time proportionally to the distance away from pit bottom portals which in turn reduced logistics strain. The advantage of the speed of delivery was realised when the significant component of the delivery LHD cycle time was travelling (i.e., longer distances) compared with fixed time loading. Loading time should therefore be the focus on productivity improvement for operations that are close by and then speed surpasses this as priority as the production districts migrate away. When the operations are close focus on reducing fixed time delay and then take that forward to reduce the total cycle time and hence logistics strain for the remainder of the life of mine.
- Changes to Payload (case 8): - Reduced deliveries per day per production district proportionally to the increase in payload which reduced logistics strain. This is based on the condition that there are sufficient storage areas either at an inbye delivery hub or at the production district. It is important that logistics strain gains could be lost if the fixed loading time component is excessive for the additional payload.

- Variation of dedicated delivery time through the day (Case 9): - Whilst there is no change to delivery per day or total distance, reducing the delivery windows in any given day will increase the number of delivery vehicles required on the road in the time permitted to travel according to the formula:

$$Delivery\ machines\ required\ in\ permitted\ delivery\ window = \frac{Delivery\ machines\ required\ per\ 24\ hour\ period \times 24}{Total\ Permitted\ Delivery\ Window\ Time}$$

- Shaping productivity to avoid logistics breaking strain (Case 12): - As a last resort capping production enables the mine planner to understand if logistics breaking strain is reached and nothing can be done about it, capping the production output to reach but not exceed the logistics breaking strain threshold enables a "truth in value" proposition.
- The use of delivery hubs and splitting delivery (Case 13): - If there is spare capacity of panel LHDs that could take material delivery from the start of a ventilation district to the production face, this can reduce logistics strain. The reduction in logistics strain is larger with a higher proportional distance of gateroad travel as compared with mains distance from pit bottom. This case is also very important when ventilation constrains the movements of high-powered delivery LHDs into a panel with insufficient ventilation quantity to abide by legislative requirements or there is a high risk of unplanned delay to the cycle time of the delivery LHDs at a diesel tag board, waiting on inbye production face machines to be shut down.

Therefore, the hypothesis in Chapter 1 on logistics strain behaviour was proven. Other discoveries included diseconomies of scale being identified when introducing a unit that may push logistics strain over into logistics breaking strain and the impact of capping production to a logistics breaking strain threshold to be able to get a more accurate value of a LoM project.

CHAPTER 5

REAL MODEL CALIBRATION AND VALIDATION

This chapter is focussed on transferring the generic model developed and experimented upon in Chapters 3 and 4 to a real-world life of mine plan to calibrate and history match the model. The bolt on nature of the algorithms developed in this thesis remains independent and does not compromise the schedule in totality.

"SC02" is a metallurgical coal mine on the east coast of Australia. Historically, it is a 2 million tonne per annum (Mtpa) operation and is scheduled to continue to produce at 2.6 Mtpa until end of life. It is serviced by a 1,650 m drift at a gradient of 1:3.4 and id used for personnel and material transportation. The materials are unloaded at the bottom of this drift and transferred around a very well-lit pit bottom area into specific fit for purpose storage locations that would be considered best practice.

The mine operates five continuous miners and one longwall. Currently, two continuous miners and the longwall operate in the near depleted Southeast Area/Domain. Three other continuous miners are developing a new area/domain with longwall operations scheduled to start there in late 2022. The new domain is considerably closer to the main drift access.

The period plot for SC02 is shown in Figure 5-1. The near depleted domain is in the Southeast with 2.5 longwalls remaining, then the Central Domain is extracted and afterward the Northern Domain. This mine is considered appropriate for validation and calibration of the generic model developed in this thesis because it is anticipated that logistics strain relief will occur when wholly transferred to the new area/domain and it also possesses two brand new domains that migrate away from the portal which should show logistics strain building and then relieve upon return closer to drift bottom.

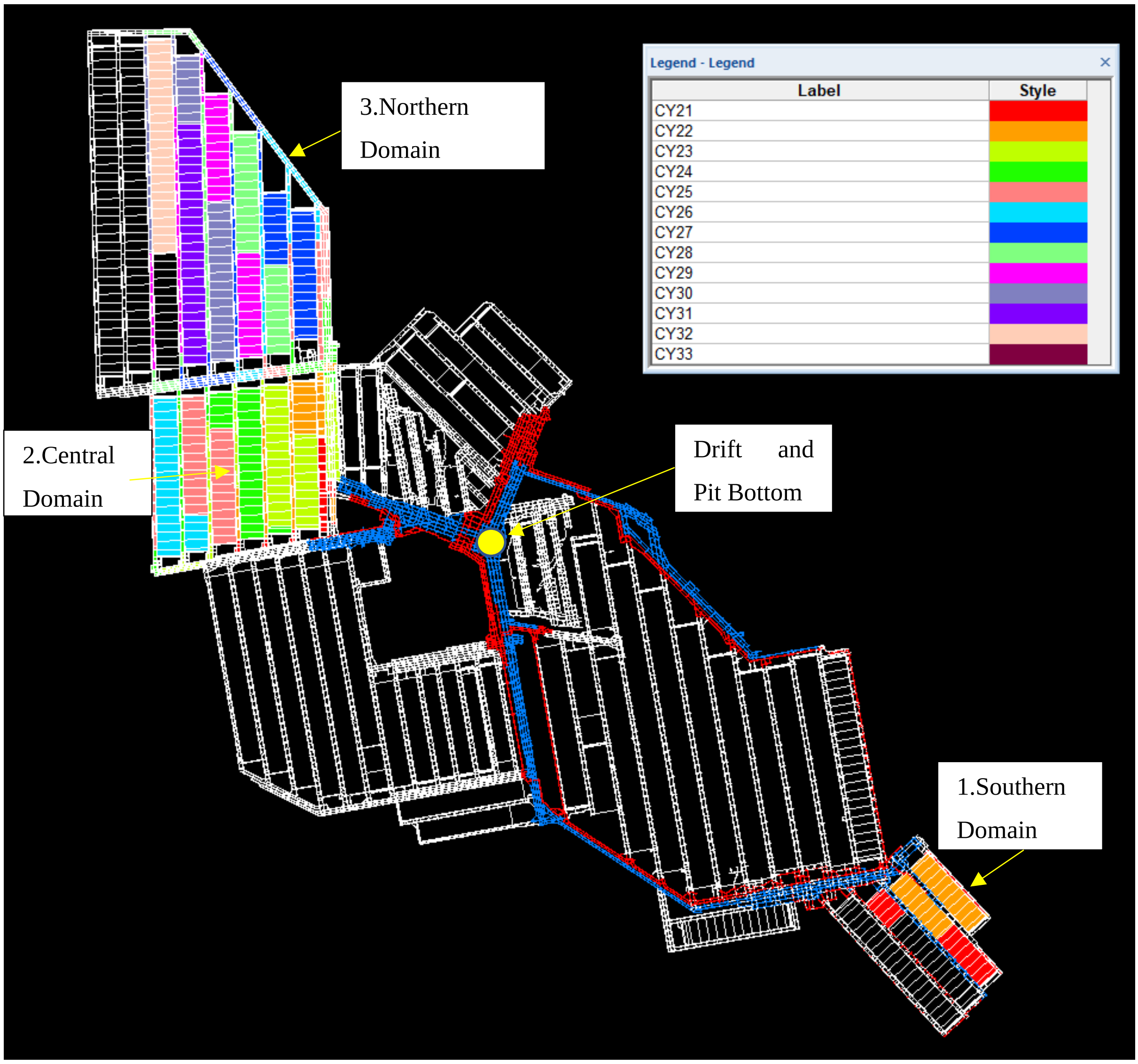


Figure 5-1: SC02 life of mine period plot.

5.1 Cumulative Distance per Panel from Drift Bottom

During the life of the operation, face positions were selected and distances from the base of the drift were compared between the algorithm developed in this thesis and actual distance as per the AutoCAD mine plan. Figure 5-2, Figure 5-3 and Figure 5-4 shows three face positions for different dates within the life of mine schedule and compares the XPAC algorithm developed in this thesis compared to the true distance. All travel roads are highlighted in green for contrast purposes because traditional “brown” is difficult to distinguish.

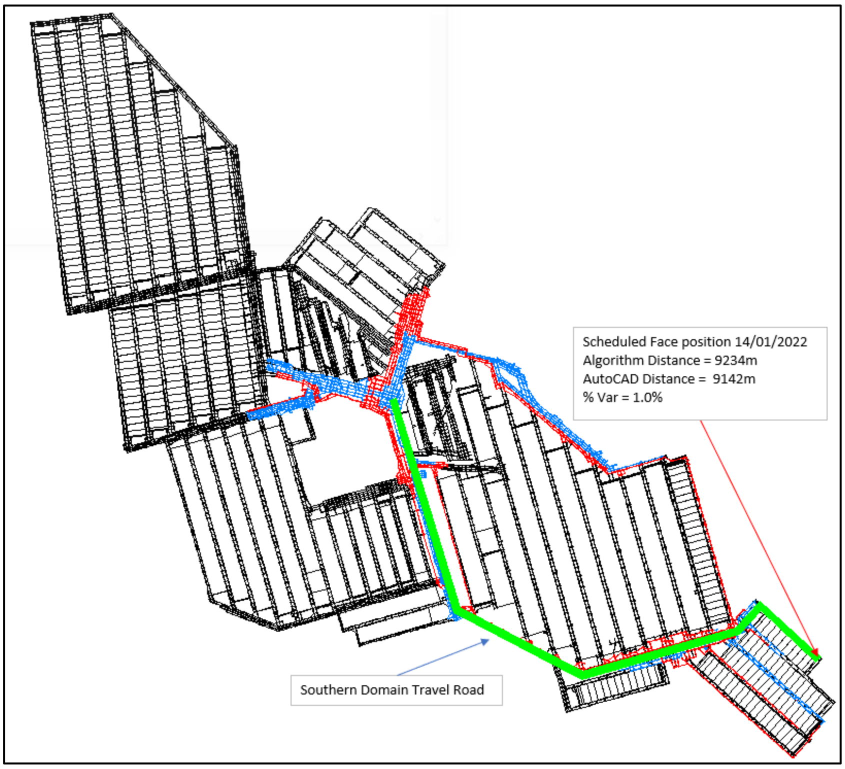


Figure 5-2: Comparison between actual vs model calculated face distances from drift base for 14th Jan 2022.

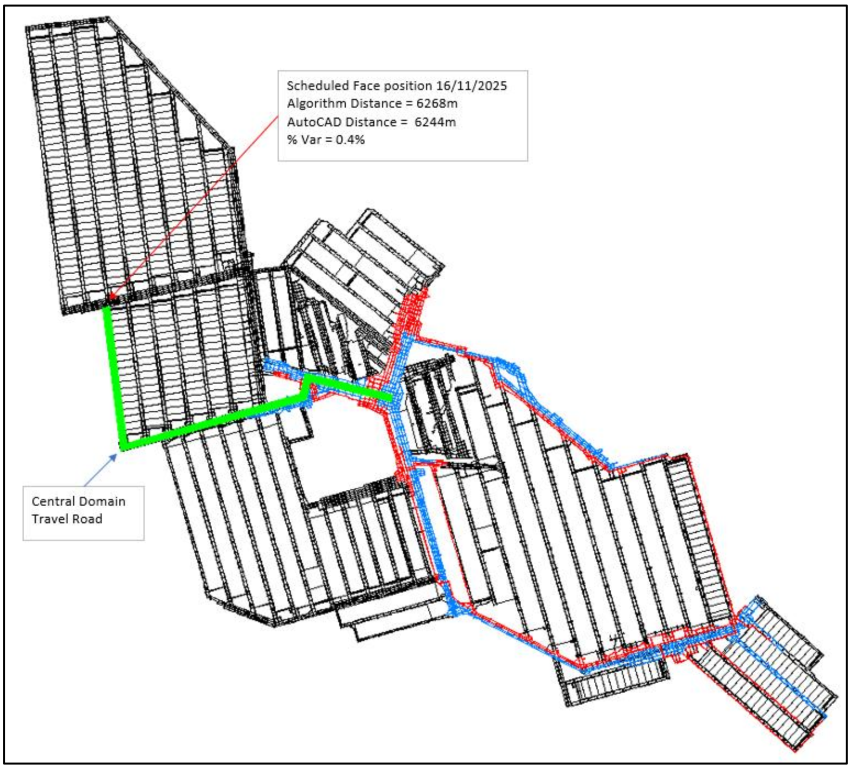


Figure 5-3: Comparison between actual vs model calculated face distances from drift base for 16th Nov 2025.

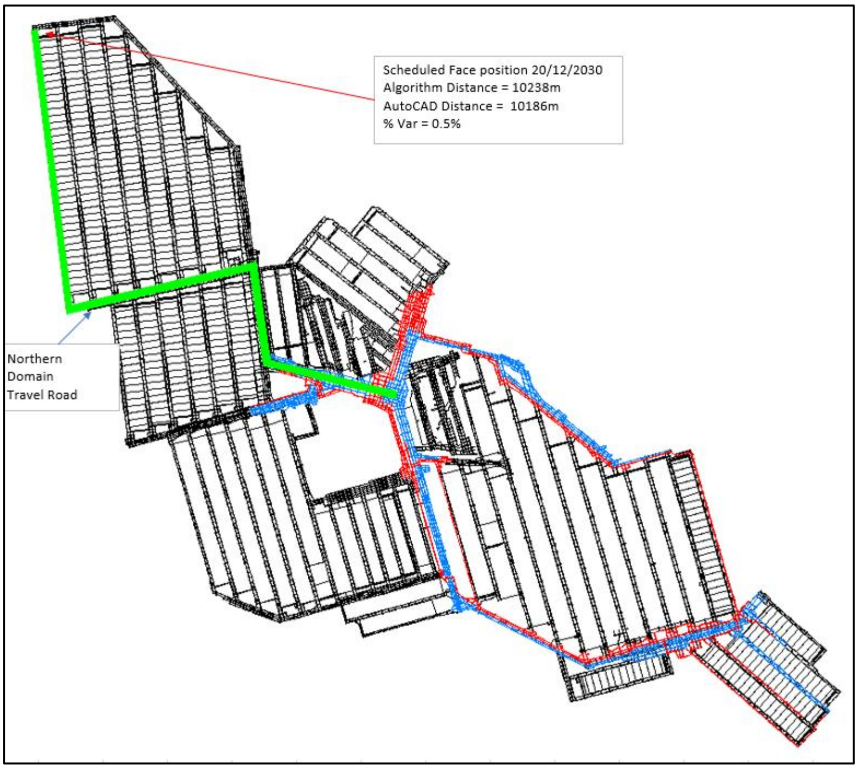


Figure 5-4: Comparison between actual vs model calculated face distances from drift base for 20th Dec 2030.

As can be seen for each random face position, the percentage difference between actual and calculated distance is less than 1% for all cases.

5.1.1 Combined Cumulative Distance Check

To check the combined distance that is reported in the combined cumulative distance graphs a random date was selected which was 29th June 2027. The previous single panel checks are for the travel distance back to the drift bottom. This check ensures/compares:

- Combined cumulative distance to the bottom of the drift for all panels on any given day.
- The continuing integrity of the VBA combination algorithms and final data pivoting after the data has been dumped out of XPAC and into Excel.

The results for this are shown in Figure 5-5:-

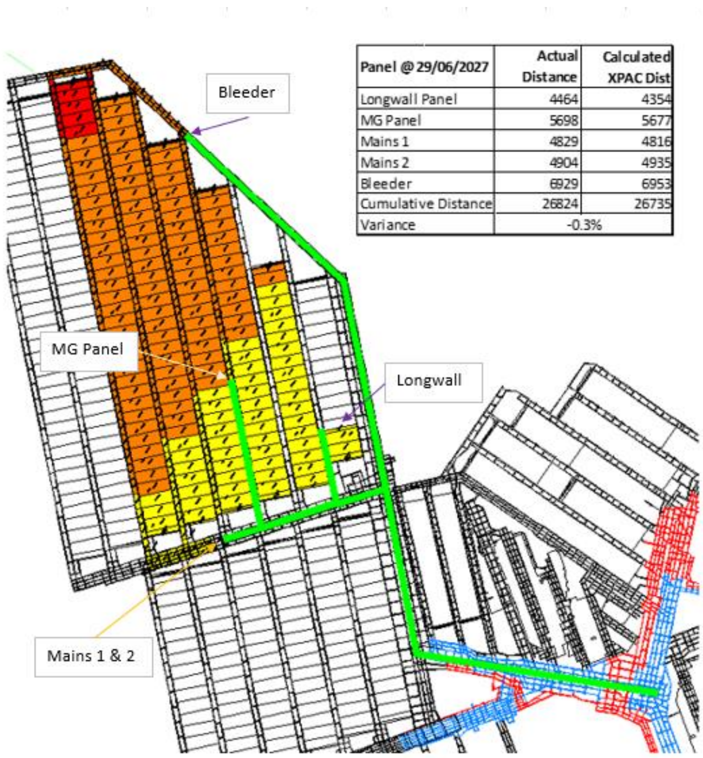


Figure 5-5: Comparison between actual vs model calculated face distances from drift base for 20th Dec 2030.

As can be seen even with multiple calculation stages and a transfer to a secondary application the total percentage difference for combined cumulative distance to portal bottom is 0.3% between actual and calculated.

5.1.2 Combined Cumulative Distance

With the transition of operations from the Southern domain to the Central domain there is immediate relief with respect to the combined distance in mid-late 2022 which in turn will create downward pressure on logistics strain. This is partially because of a reduction in development units required after the first longwall in the central domain is developed and that the early central domain is considerably closer to drift bottom, which is not dissimilar to the impact on combined distance from the migration and return generic model developed in this thesis. Combined distance peaks in 2027 and 2028 which are both in the Northern Domain. Combined distance relief occurs with the reduction of development units as sufficient development inventory in advance is built and the development rate ahead of the longwall is sufficient to maintain a float from 2028 until the end of the scheduled mine life.

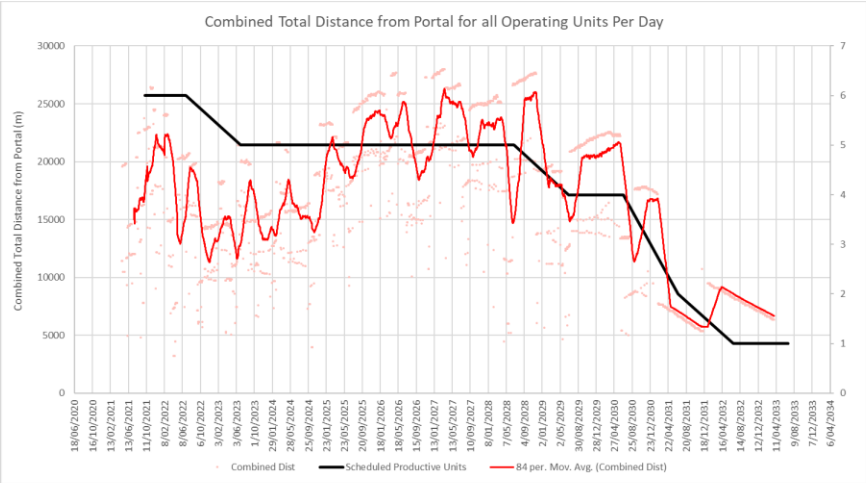
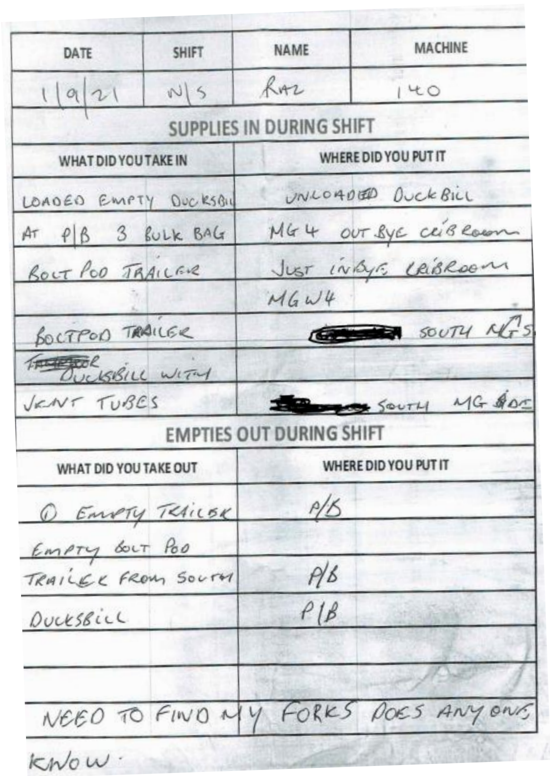


Figure 5-6: Combined cumulative distance for SC02 Mine.

5.2 Loads per Day

To calibrate deliveries per day, actual data from SC02 was required. Optimal data obtained would be for longwall and development deliveries per shift and metres per shift, and additionally for development, primary support per shift, and metres per shift. This would enable the most accurate prediction of metres by geotechnical regime. Delivery tracking was sporadic and only kept for 11 weeks (1/9/21 to 17/11/21) which based on this thesis' mine visits and would still be considered reasonably good in comparison to other sites. Development metres per shift was well understood which is always to be expected. Deliveries per shift were reported back to the development coordinator and were in the form shown in Figure 5-7.



DATE	SHIFT	NAME	MACHINE
1/9/21	N/S	RAZ	140

SUPPLIES IN DURING SHIFT	
WHAT DID YOU TAKE IN	WHERE DID YOU PUT IT
LOADED EMPTY DUCKSBILL	UNLOADED DUCKBILL
AT P/B 3 BULK BAG	MG 4 OUT BYE CRIB ROOM
BOLT POD TRAILER	JUST INBYE CRIBROOM
	MGW4
BOLTPOD TRAILER	[redacted] SOUTH MGS
DUCKSBILL WITH	
VENT TUBES	[redacted] SOUTH MG 8 DT

EMPTIES OUT DURING SHIFT	
WHAT DID YOU TAKE OUT	WHERE DID YOU PUT IT
① EMPTY TRAILER	P/B
EMPTY BOLT POD	
TRAILER FROM SOUTH	P/B
DUCKSBILL	P/B

NEED TO FIND MY FORKS DOES ANYONE KNOW.

Figure 5-7: Typical shift materials delivery report

These reports were sporadic depending on the shift with night shift being the most thorough reporting shift and its reports exceeded the combined number of reports for weekday dayshift, afternoon shift and weekend day shift. Therefore, the data was combined with actual consultation with the development coordinator and technical services manager. This conversation led to the following outcomes: -

- The data spanned from the 1st of September 2021 to 17th November 2021.
- The data received was to only one development panel in the current critical Southern Domain and could nominally be applied to all panels.
- Deliveries were scheduled for Monday to Thursday for day, afternoon and night shifts equating to 12 x 8 hour (effective) shifts per week and Friday to Sunday 12-hour day shift, equating to three shifts.
- The average of the reported shifts is to be applied to unreported shifts.
- Delivery machine availability was 70%.
- The longwall delivery data was consistent with the data that Prow (2018) used in longwall delivery calculations at 0.654 deliveries per retreat metre.
- Deliveries and metres should be spread across the full recorded period.
- LHD speed was 15 km/hour.

Average deliveries per shift for Monday to Thursday was 2.05 and for weekend day shift was 3.5 as these were 30% longer shifts. Therefore, nominal deliveries per week was 35.1 (12 shifts x 2.05 + 3 shifts x 3.5). The 70% availability was applied to estimate final deliveries per week at 24.6 (0.7 x 35.1). During this same time the total metres for this panel was 945.9 m which over 11 weeks equated to 86 metres per week. Deliveries per metre was then estimated to be 0.286 (24.6 deliveries per week / 86 metres per week) which is more aggressive than the green support figure used in the generic model (0.367 deliveries per metre), noting that if the arbitrary availability obtained anecdotally to be 70% is increased to 90% then the exact green support figure used in this thesis is achieved. This figure was applied across all development for the duration of the life of mine to calculate loads per day and loads on road.

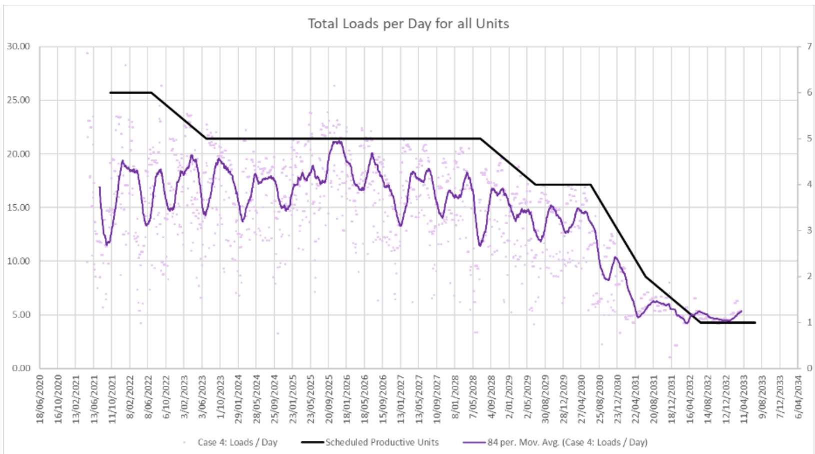


Figure 5-8: SC02 loads per day

It should be noted that due to lack of data, the cumulative distance, which is already an excellent indicator of logistics strain is still valid and proven already to be very accurate. A shift in thinking is required for "loads per day" and "loads on road" to treat it as a strain factor rather than an exact predictor. Figure 5-8 suggests a peak of loads per day occurs in late 2025 which is around 15% higher than present peaks in a relative sense even if the foundational data is not entirely accurate for an exact estimate. If a development unit is demobilised in 2023 (all other things being equal), then deliveries per day are reasonably stable. The positive news is that when this prediction is used as a factor, it may warrant closer scrutiny of delivery data to get a more accurate prediction which could now through this thesis be calibrated much the same as metres, utilisation, qualities, and tonnages which are reconciled and calibrated back into the schedule with each planning cycle.

5.3 Loads on road

Loads on road can be calculated in two ways. Firstly, that the capacity to deliver is underutilised and that system can deliver more with the same fleet and able to operate around the clock with minimal delay or secondly that the current capacity to delivery is maximised with the current delivery LHD fleet size and therefore cannot deliver more without an increase in fleet size. If loads on road is treated as a factor rather than as an absolute measure, that is, known as a logistics strain factor then it is acceptable as you are only seeking trends from the present day forward. The true prediction is somewhere between Scenario 1 and Scenario 2 and can continue to be reconciled and calibrated as delivery tracking receives more scrutiny.

5.3.1 Scenario 1 – Underutilised Delivery LHDs.

Delivery machines can increase their capacity to work around the clock, with 30 mins delay for loading/unloading and average travel speeds at 15 km/hr. This scenario is driven only by the cumulative distance from the drift bottom and the deliveries per development metre and therefore is considered an optimal scenario if delivery was the priority. In this scenario we would expect to see very low loads on road, but the relative logistics strain ratio would remain the same as Scenario 2, just that the amplitude of the graph would be lower.

5.3.2 Scenario 2: All Future Performance is Capped at Current Performance in the Southern Domain

Scenario 1, whilst a good relative logistics strain factor, is not an actual estimate. Scenario 2 attempts to give an estimate based upon what the LHD is currently achieving and the assumption that this is the maximum productivity and whilst it is still able to achieve the deliveries required for the Southern Domain development panel, it is expected it cannot do anything additional. The delivery window and delay time per cycle (for loading and unloading and other ancillary delays) must therefore be calibrated to meet the current LHD capacity. The current LHD capacity for the Southern Domain development panel is a single LHD per shift with 70% availability. Calibrated loads on road are therefore 0.7 LHDs for this one panel between 1/09/21 and 17/11/21. Knowing the estimated average speed of the LHD is 15 km/hr, the total delay is calibrated to ~ 1.5 hours per cycle with an 18-hour delivery window per day. If this is applied for the timeframe 1/9/21 to 17/11/21 then the average loads on road is 0.7. The speed of 15 km/hour, 1.5 hours total delay per cycle and 18-hour delivery window is then applied to the entire schedule to get a new calibrated “loads on road”. Table 5-1 shows how the calibration is calculated. The schedule received from SC02 included the calibration period from September 2021 to November 2021 and therefore this could be used to calibrate loads on road for future projection to the end of mine life.

In Table 5-1 the blue columns are the delay time per cycle in hours and delivery window in hours per 24-hour period to match 0.7 LHDs. The two numbers 1.48 hours (delay) and 18 hours (delivery window) are then implanted into the remainder of the Life of Mine schedule to get an estimate of loads on road per day for Scenario 2.

Table 5-1: Calculation to calibrate.

South Development Panel											
ROW		Cum Dist from Portal Bottom	Speed of Loader	Operating Time (Wheels turning)	Loads per Day	Scenario 1: Loads on Road	Scenario2: Delay Time CALIBRATION INPUT	Scenario 2: Util time	Scenario 2: Delivery Window CALIBRATION INPUT	Loads on Road	Actual Loads on Road Calibrator
	Column	A	B	C	D	E	F	G	H	I	J
	Calculation	Algorithm	NSW02 Anecdotal	(A x 2) x 1000 / B	Algorithm using NSW02 (0.286 del/m)	Algorithm	GoalSeek I1 = 0.7	C + F	GoalSeek I1 = 0.7	D x G / H	Average(I1:I73)
	Date / Units	m	km/hr	Hours	/day	Delivery Machines	Hours	Hours	Hours	Delivery Machines	Delivery Machines
1	1/09/2021	8325	15	1.11	4.03	0.27	1.48	2.59	18.00	0.58	0.7
2	2/09/2021	8325	15	1.11	4.03	0.27	1.48	2.59	18.00	0.58	
3	4/09/2021	8426	15	1.12	4.94	0.33	1.48	2.61	18.00	0.72	
4	5/09/2021	8426	15	1.12	4.94	0.33	1.48	2.61	18.00	0.72	
5	6/09/2021	8426	15	1.12	4.94	0.33	1.48	2.61	18.00	0.72	
6	7/09/2021	8426	15	1.12	4.94	0.33	1.48	2.61	18.00	0.72	
7	8/09/2021	8426	15	1.12	4.94	0.33	1.48	2.61	18.00	0.72	
8	9/09/2021	8426	15	1.12	4.94	0.33	1.48	2.61	18.00	0.72	
9	10/09/2021	8426	15	1.12	4.94	0.33	1.48	2.61	18.00	0.72	
10	11/09/2021	8426	15	1.12	4.94	0.33	1.48	2.61	18.00	0.72	
11	12/09/2021	8426	15	1.12	4.94	0.33	1.48	2.61	18.00	0.72	
12	13/09/2021	8426	15	1.12	4.94	0.33	1.48	2.61	18.00	0.72	
13	14/09/2021	8426	15	1.12	4.94	0.33	1.48	2.61	18.00	0.72	
14	15/09/2021	8426	15	1.12	4.94	0.33	1.48	2.61	18.00	0.72	
15	16/09/2021	8426	15	1.12	4.94	0.33	1.48	2.61	18.00	0.72	
16	23/09/2021	8527	15	1.14	4.85	0.33	1.48	2.62	18.00	0.71	
17	24/09/2021	8527	15	1.14	4.85	0.33	1.48	2.62	18.00	0.71	
18	25/09/2021	8527	15	1.14	4.85	0.33	1.48	2.62	18.00	0.71	
19	26/09/2021	8527	15	1.14	4.85	0.33	1.48	2.62	18.00	0.71	
20	27/09/2021	8527	15	1.14	4.85	0.33	1.48	2.62	18.00	0.71	
21	28/09/2021	8527	15	1.14	4.85	0.33	1.48	2.62	18.00	0.71	
22	29/09/2021	8527	15	1.14	4.85	0.33	1.48	2.62	18.00	0.71	
23	30/09/2021	8527	15	1.14	4.85	0.33	1.48	2.62	18.00	0.71	
24	1/10/2021	8527	15	1.14	4.85	0.33	1.48	2.62	18.00	0.71	
25	2/10/2021	8527	15	1.14	4.85	0.33	1.48	2.62	18.00	0.71	
26	3/10/2021	8527	15	1.14	4.85	0.33	1.48	2.62	18.00	0.71	
27	4/10/2021	8527	15	1.14	4.85	0.33	1.48	2.62	18.00	0.71	
28	5/10/2021	8527	15	1.14	4.85	0.33	1.48	2.62	18.00	0.71	
29	6/10/2021	8527	15	1.14	4.85	0.33	1.48	2.62	18.00	0.71	
30	8/10/2021	8628	15	1.15	4.85	0.33	1.48	2.63	18.00	0.71	
31	9/10/2021	8628	15	1.15	4.85	0.33	1.48	2.63	18.00	0.71	
32	10/10/2021	8628	15	1.15	4.85	0.33	1.48	2.63	18.00	0.71	
33	11/10/2021	8628	15	1.15	4.85	0.33	1.48	2.63	18.00	0.71	
34	12/10/2021	8628	15	1.15	4.85	0.33	1.48	2.63	18.00	0.71	
35	13/10/2021	8628	15	1.15	4.85	0.33	1.48	2.63	18.00	0.71	
36	14/10/2021	8628	15	1.15	4.85	0.33	1.48	2.63	18.00	0.71	
37	15/10/2021	8628	15	1.15	4.85	0.33	1.48	2.63	18.00	0.71	
38	16/10/2021	8628	15	1.15	4.85	0.33	1.48	2.63	18.00	0.71	
39	17/10/2021	8628	15	1.15	4.85	0.33	1.48	2.63	18.00	0.71	
40	18/10/2021	8628	15	1.15	4.85	0.33	1.48	2.63	18.00	0.71	
41	19/10/2021	8628	15	1.15	4.85	0.33	1.48	2.63	18.00	0.71	
42	20/10/2021	8628	15	1.15	4.85	0.33	1.48	2.63	18.00	0.71	
43	22/10/2021	8729	15	1.16	4.87	0.34	1.48	2.65	18.00	0.72	
44	23/10/2021	8729	15	1.16	4.87	0.34	1.48	2.65	18.00	0.72	
45	24/10/2021	8729	15	1.16	4.87	0.34	1.48	2.65	18.00	0.72	
46	25/10/2021	8729	15	1.16	4.87	0.34	1.48	2.65	18.00	0.72	
47	26/10/2021	8729	15	1.16	4.87	0.34	1.48	2.65	18.00	0.72	
48	27/10/2021	8729	15	1.16	4.87	0.34	1.48	2.65	18.00	0.72	
49	28/10/2021	8729	15	1.16	4.87	0.34	1.48	2.65	18.00	0.72	
50	29/10/2021	8729	15	1.16	4.87	0.34	1.48	2.65	18.00	0.72	
51	30/10/2021	8729	15	1.16	4.87	0.34	1.48	2.65	18.00	0.72	
52	31/10/2021	8729	15	1.16	4.87	0.34	1.48	2.65	18.00	0.72	
53	1/11/2021	8729	15	1.16	4.87	0.34	1.48	2.65	18.00	0.72	
54	2/11/2021	8729	15	1.16	4.87	0.34	1.48	2.65	18.00	0.72	
55	3/11/2021	8729	15	1.16	4.87	0.34	1.48	2.65	18.00	0.72	
56	5/11/2021	8830	15	1.18	4.54	0.32	1.48	2.66	18.00	0.67	
57	6/11/2021	8830	15	1.18	4.54	0.32	1.48	2.66	18.00	0.67	
58	7/11/2021	8830	15	1.18	4.54	0.32	1.48	2.66	18.00	0.67	
59	8/11/2021	8830	15	1.18	4.54	0.32	1.48	2.66	18.00	0.67	
60	9/11/2021	8830	15	1.18	4.54	0.32	1.48	2.66	18.00	0.67	
61	10/11/2021	8830	15	1.18	4.54	0.32	1.48	2.66	18.00	0.67	
62	11/11/2021	8830	15	1.18	4.54	0.32	1.48	2.66	18.00	0.67	
63	12/11/2021	8830	15	1.18	4.54	0.32	1.48	2.66	18.00	0.67	
64	13/11/2021	8830	15	1.18	4.54	0.32	1.48	2.66	18.00	0.67	
65	14/11/2021	8830	15	1.18	4.54	0.32	1.48	2.66	18.00	0.67	
66	15/11/2021	8830	15	1.18	4.54	0.32	1.48	2.66	18.00	0.67	
67	16/11/2021	8830	15	1.18	4.54	0.32	1.48	2.66	18.00	0.67	
68	17/11/2021	8830	15	1.18	4.54	0.32	1.48	2.66	18.00	0.67	

Note:

- “del/m” means deliveries per metre of development.
- “Util time” mean s utilisation time

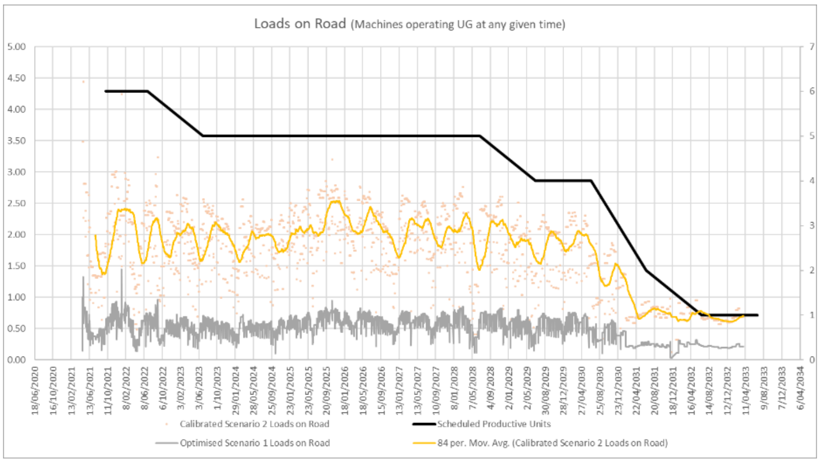


Figure 5-9: Loads on road for Scenario 1 (grey) and Scenario 2(gold)

It can be seen in Figure 5-9 that three operating delivery LHDs at any given time onward should be sufficient for this life of mine if 0.286 deliveries per metre for development can be achieved.

The maximum productivity is going to be somewhere between Scenarios 1 and 2, but Scenario 2 would be considered a best estimate until consistent and managerial focussed real time data is able give a projection with higher confidence or there is immediate opportunity for delivery productivity improvement. It must again be remembered that even if the number is absolutely wrong the relativity of the changes to the loads on road over time still enables management and the mine planner to scrutinise the risk of logistics breaking strain into the future which is precisely the purpose of this thesis.

5.4 Chapter Conclusion

The generic model has been successfully transferred to a real-world life of mine plan for Mine NSW 02. What is more is that it is a “bolt on” model and no changes to the schedule need to occur and therefore schedule integrity is maintained giving confidence to the mine planner that nothing insidious has occurred to the schedule during this application. Cumulative distances from drift bottom have been validated, deliveries per day have been historically matched and calibrated and sensitivities of logistics strain / loads on road have been successfully undertaken. More so, even if the delivery data is compromised, which most operations that have been interviewed during the ACARP commissioned project seem to be affected by, combined cumulative distance, a vital component of logistics strain remains uncompromised, and loads per day and loads on road can still be reviewed as factors rather than as absolutes for the planner to target.

Chapter 6

CONCLUSION AND RECOMMENDATIONS

This thesis has successfully quantified the number of delivery LHDs to be operating at any given time to sustain production in a dynamic environment where destinations are constantly changing. Unlike the static nature of typical logistics modelling between a fixed location and a fixed customer, the system developed estimates the logistics requirements for material delivery to one or more moving targets in the form of advancing and retreating production districts with flexible timeframe granularity (daily, weekly, monthly, quarterly) throughout the life of mine plan.

During the ACARP research face-to-face interviews with key personnel from coal mines up and down the east coast of Australia, not one operation had given any thought to what may be needed for logistics management to happen in the medium to long-term (Walker et al.,2020). Therefore, as discussed in Chapter 1, the maturity of logistics planning within Australian underground coal mining operations is short-term at best. Every mine site interviewed continues to undertake life of mine operations with a base assumption that for whatever we produce in either metres or tonnes, logistics will simply keep up be it with technology, infrastructure, or another shaft. If there is no logistics considered in the strategic planning of the operation, then the general underlying assumption is that the supply chain can keep up with the planned production rate of the operation and the life of mine plan and subsequent valuation model accounts for enough:

- Transport roads to be able to manage the supply chain movement safely and reliably.
- Personnel to deliver the supplies.
- Suitable machinery fit for purpose.
- Ventilation to support diesel machinery movements.
- Speed of delivery can counter the distance from a portal to a productive area.

The problem with respect to the above assumption is that even when it is true, there is never a true understanding of the risk to productive work being inhibited, and constraints would be rarely identified early enough to eliminate the risk of lost production. Such thinking leads to retrospective implementation which in turn leads to a capping of production until rectification works to raise the threshold of logistics breaking strain can be executed. This means that with all things, since the mine inception, being equal (same financial and production inputs) an **<u>unrecoverable loss in value at that point in time will be realised</u>**.

Current best practice in logistics management in Australian coal mining operations would be to: -

- Standardise equipment used in supply delivery. This reduces complexity and distraction, searching for implements that are suitable so that machines are “on road” undertaking core tasks rather than ancillary work or undergoing maintenance delays.
- Track all machine and material movements into, around and out of the mine. This information is imperative so that the prediction of logistics strain into the future is accurate.

- Use computer-based inventory management that is triggered directly from the production face to ensure that the right deliveries are made at the right time and that inventory management systems for the "perfect storms" are ensuring no capping of production due to logistics breaking strain.
- Travel road lighting increases safety and that higher speed can be maintained with better visibility ahead.
- Concreting increases travel speeds and consistency of those speeds by eradicating mud build-up which slows machine speed. It prevents flooded, bumpy, and broken floors that could injure the driver or passengers or bottom out the machines or trailers and damage the actual supplies. It was found however that speed of loading and unloading should be given preference in short haulage newer mines over concreting as the proportion of travel time is less in the total cycle. That way once haulage times become critical within the cycle the system for loading and unloading is optimised.
- Minimise interruption to the haulage cycle through, inbye and outbye dedicated transport roads so that equipment is only ever required to shunt if a faster machine has priority. Machine tracking ensures that when machines are operating, a machine is not delayed at a diesel tag board awaiting access.
- The use of large road trains with braked trailers within mains and unloading at supply hubs for panel machines to continue to take to the production district in gateroads. These hubs should be purpose built to optimise unloading time, minimisation of rehandling and systemised storage to cater for multiple deliveries at once.

6.1 Strategic Long Range Logistics Planning

This thesis has built a new system for early identification of logistics breaking strain which can be completely integrated within the life of mine plan. The system allows for fast understanding of issues re: -

- The dynamic nature of delivery locations that can change on a day-to-day basis.
- Mine design.
- Productivity.
- Infrastructure.
- Delivery machine fleet size.
- Payload.
- Delivery LHD speed.
- Schedule path.
- Primary support.
- The impact to value if logistics breaking strain is reached after all other solutions are exhausted.

This thesis identifies at a macro level within a life of mine plan, trends or spikes in logistics strain / "loads on road". This can then be further examined by drilling down into FlexSim for a better day-to-day tactical understanding with the inclusion of delivery LHD interaction to give a robust solution or at the very least robust investigation into ways to defer logistics breaking strain. The overall system in this thesis is shown in Figure 6-1 (also in Chapter 3) and highlights the three phases of integrated logistics into the life of mine plan.

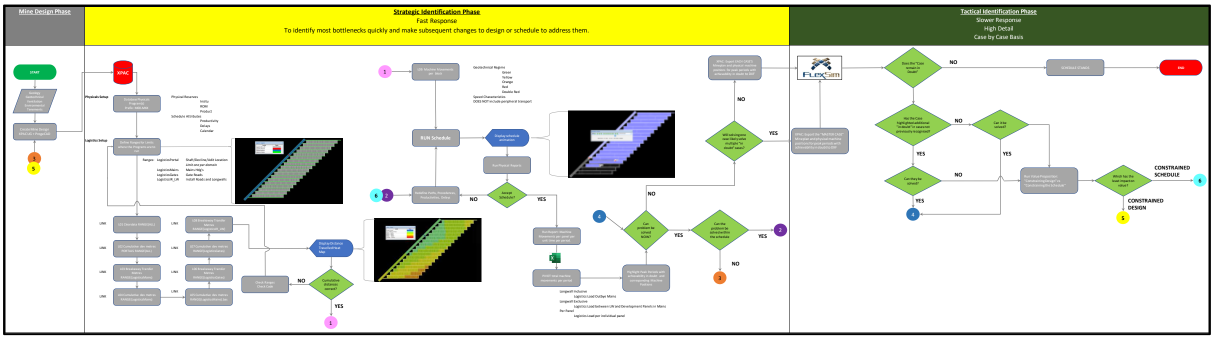


Figure 6-1: The system developed in this thesis to identify and then attempt to solve or defer logistics breaking strain.

Early identification means that countermeasures can be planned at a significantly lower cost to overall value and production than a reactive retrospective solution. This integration within the widelyused commercial scheduling software XPAC allows for seamless integration of long-term data in logistics requirements, and with the algorithms presented in this thesis can be, with slight modifications be transferred to any scheduling package.

6.1.1 Proposition 1: Migration Away From and Return to a Portal.

In Chapter 1, it was anticipated that over the life of mine logistics strain would increase with time. Firstly, with a central shaft or portal logistics strain would increase as the mining operations migrated away and then be alleviated when operations in that domain ceased and a new domain commenced closer back to pit bottom.

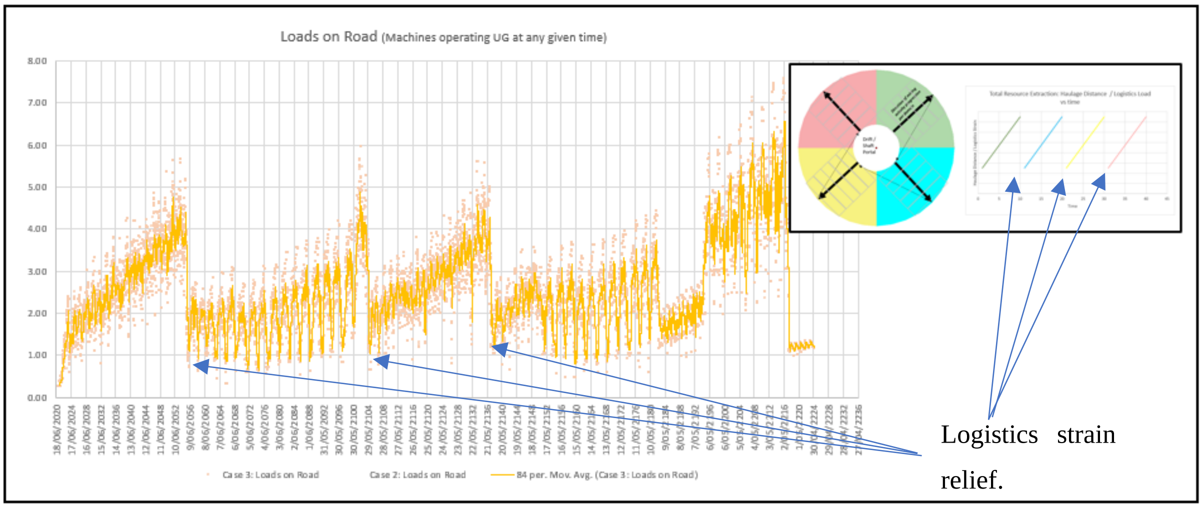


Figure 6-2: Central portal migrating away and returning Case 3 loads on road (inset Chapter 1 Figure 1-3)

6.1.2 Proposition 2: Migration Away in a General Direction.

Mines which had portals that tended to expand only away from portals, such as cut and cover, adits or box cuts would accelerate faster towards a logistics breaking strain threshold and that the installation of an inbye shaft would give significant relief to the operation's logistics strain as shown in Figure 4-84 and Figure 6-3:

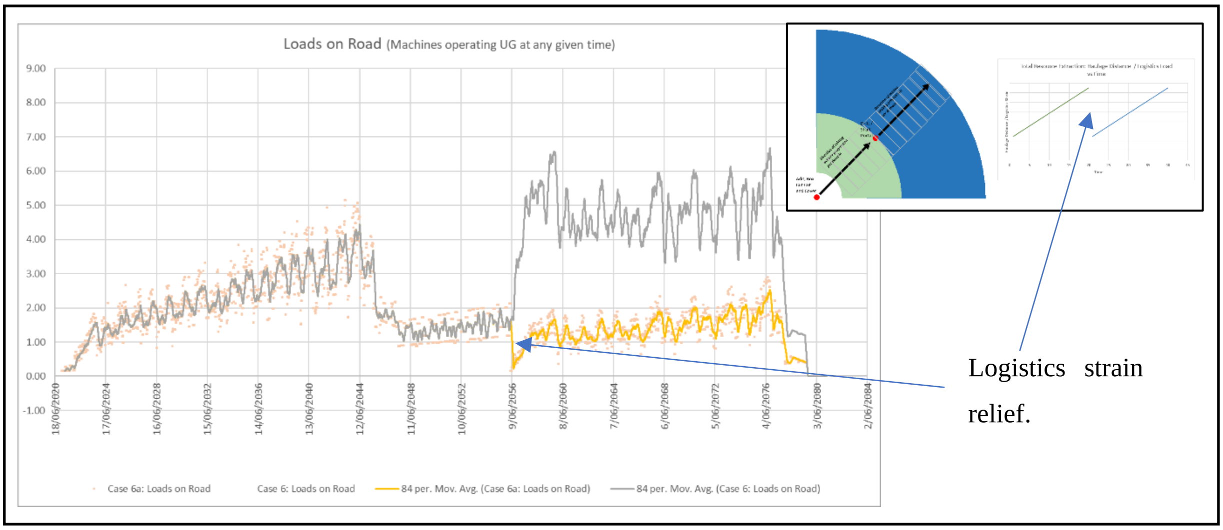


Figure 6-3: Case 6a vs Case 6 loads on road (Inset Chapter 1 Figure 1-5).

6.1.3 Proposition 3: Unique Events that Create Logistics Strain

It was also established that unique events such as the geotechnical regime combined, machine productivity and additional development units all posed a risk of exceeding logistics breaking strain threshold. To specifically look beyond the noise of daily fluctuations in logistics strain that may on one day exceed breaking strain and on another be well below, and therefore supplies can be managed through inventory within the production panel. Twelve week / 84-day rolling average of loads on road was nominated where exceedance of logistics breaking strain within this timeframe could not be managed through inventory. If the rolling average spiked above logistics breaking strain, then this must be addressed through changes to logistics infrastructure or the mine plan. Figure 6-4 confirms the incidence of unique events, with every peak and trough being a combination of machine positioning, primary support requirements, number of productive units, and productivity in contrast to the simplified proposition of unique event effects in Chapter 1.

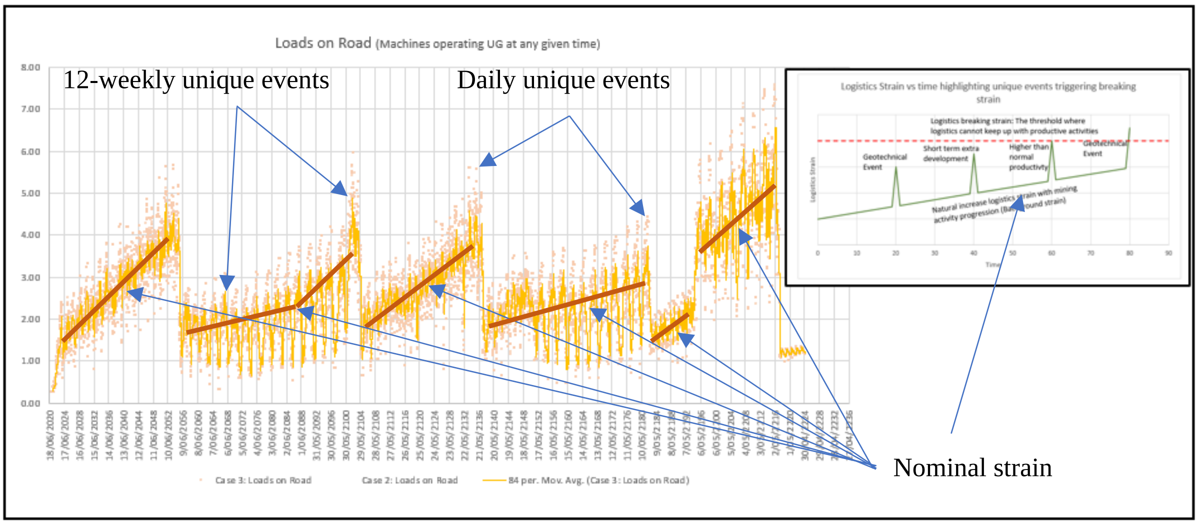


Figure 6-4: Central portal migrating away and returning Case 3 loads on road (inset Chapter 1 Figure 1-7)

The proposed term of logistics nominal strain was also confirmed which was the general trend upward as operations migrated away from portals. The gradient of nominal strain would allow triggers into the future to manage the deferral of logistics breaking strain.

6.1.4 Proposition 4: Logistics Breaking Strain

It was established in this thesis that logistics breaking strain is quantified by external factors such as ventilation capacity, personnel limitations, other operational practicalities defined logistics breaking strain rather than it being defined by the XPAC or FlexSim model itself as shown in Figure 6-5. It was found that with the larger mine, which is associated with higher logistics strain, there is also more room albeit incredibly inefficiently for delivery LHDs to operate. Using FlexSim, 20 delivery LHDs were employed to see if there was a reduction in deliveries due to the significant increase in traffic to that compared to the nominal eight development units. It was found that whilst traffic delays and idle time increased 600%, deliveries increased meaning that ventilation limitations will define the threshold of logistics breaking strain well before machine interaction does. Even with a reduction in hours of delivery operation to 13.5 hours to represent operations only within afternoon and night shift, it was found that the delivery reduction was essentially directly proportional to the reduction in hours meaning that an increase in delivery LHDs would defer logistics strain, which re-introduces legislative limits due to ventilation.

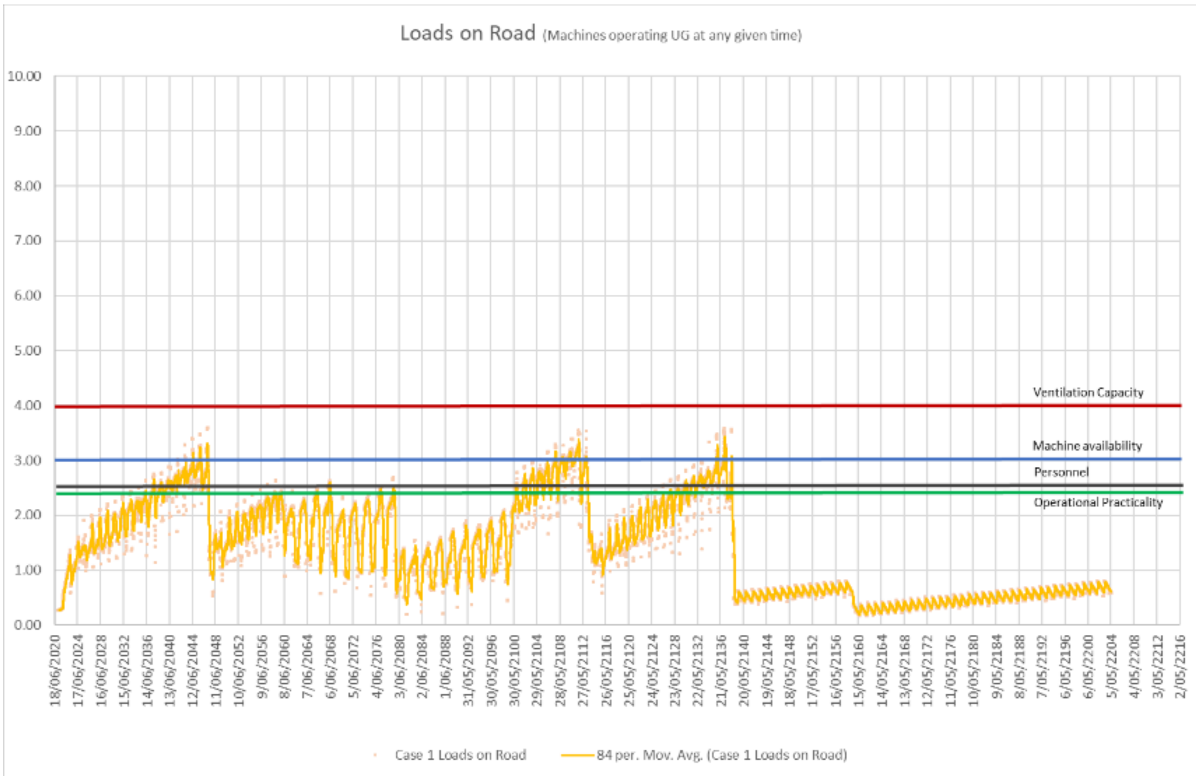


Figure 6-5: An example of bottlenecks that bring about logistics breaking strain.

The most prominent problem for meeting ventilation requirements was the limitation of air quantities particularly down development production panels. This in turn meant that usually only one large delivery LHD could be used at a time. However, most development panels have their own smaller LHD that demands less ventilation allocation, and therefore limitations in ventilation could be addressed by running the large delivery LHDs to the first cut through of the panel (a delivery hub), unloading and letting the smaller machine run up and down the panel continuously delivering to the productive face from the hub.

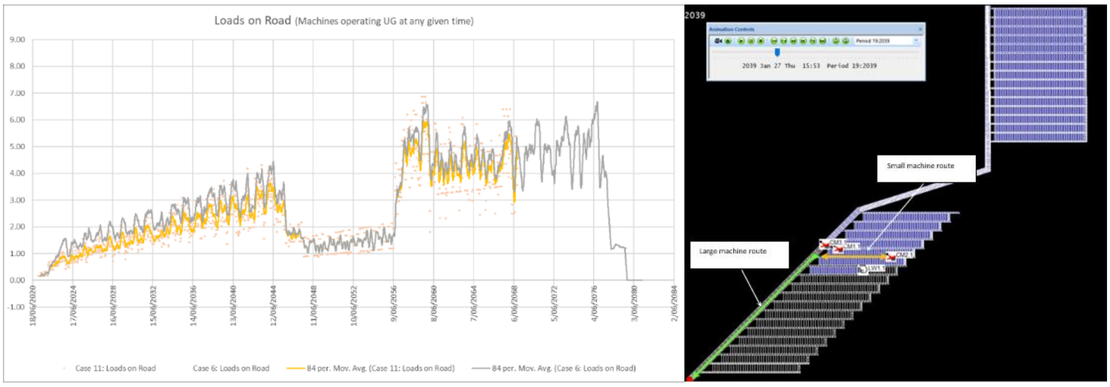


Figure 6-6: Reduction in logistics strain with the application of hubs to address ventilation capacity in gates.

Capping the fleet due to machine or personnel availability was also examined. Simply put, this with ventilation limitations will immediately initiate a logistics breaking strain event. The machines will be highly productive with very little interaction delay due to shunting, but units simply cannot meet demand and therefore production is capped.

6.1.5 Proposition 5: More Units, More Problems

For every instance of the introduction of a new unit into the delivery system there was a step change in inefficiency. Whilst incredibly inefficient, more units are an answer to defer logistics strain and as discussed previously 20 units will deliver more but at a cost of 600% inefficiency. This rise in inefficiency is shown in Table 6-1:-

Table 6-1: The negative return of more delivery LHDs on direct operating hours per machine.

Number of delivery vehicles	Delay / Idle Time (minutes)
3	4.5
7	50.5
8	63.5
20	371.5 (6.2 hours)

Human utilisation plummets with more machines due to significantly higher waiting times, meaning less hours undertaking useful work, in turn leading to significant operational cost. The ratio of direct operating hours vs capital expenditure for the delivery fleet also will fall significantly.

6.1.6 Proposition 6: Identification of Perfect Storms

When there is a step change increase in delivery requirements, with very little reduction in productivity such as yellow support actual mine data collected for Chapter 3 there are times albeit very infrequent when every production unit aligns in combination of high productivity and high delivery. Perfect storms are typically absorbed through good inventory management within the 12-week delivery window, but this thesis allows for the identification of these events, as shown in Figure 6-7, and then pre-deliveries can commence to ensure inventory is sufficient to maintain production. If it does put 12-week logistics strain above the logistics breaking strain threshold, critical development would be prioritised to continue and redeployment of lower prioritised drivage to lower delivery requirement areas, which can be monitored and addressed early to prevent such events capping production.

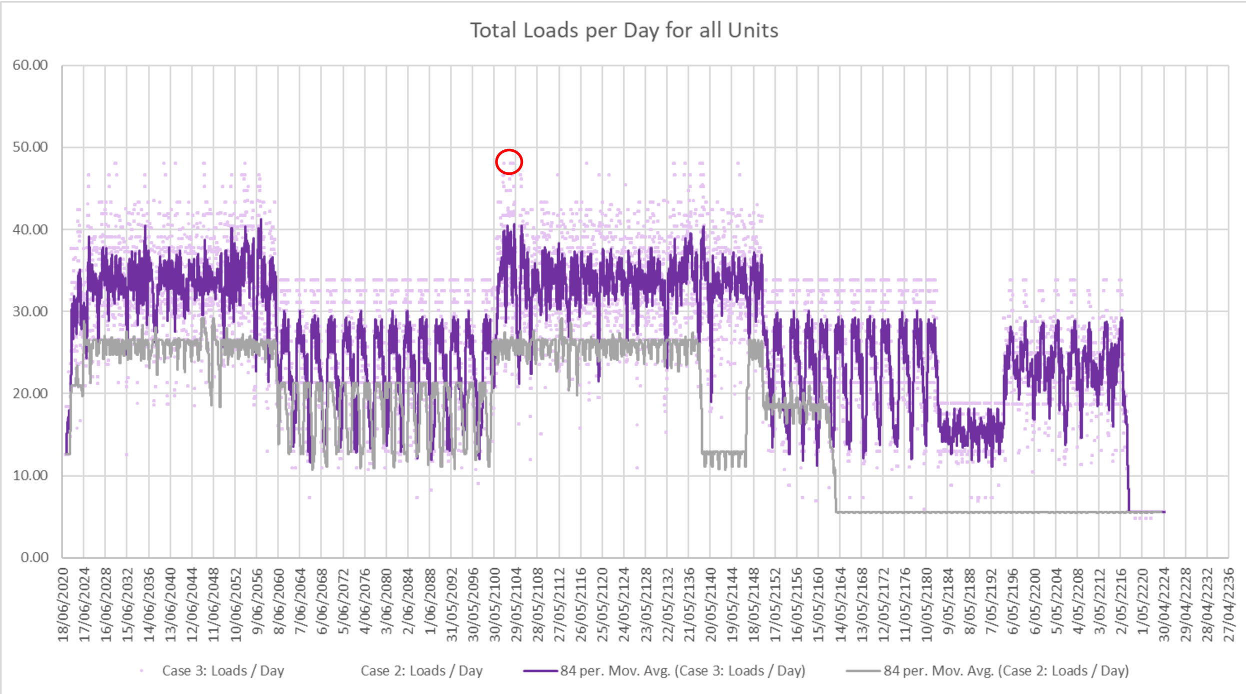


Figure 6-7: Case 3 loads per day (purple) circling a "perfect storm" of an "all yellow support" event.

6.2 Findings in Summary

The development of integrated logistics requirements into a life a life of mine schedule enabled multiple scenarios to be examined. Table 6-2 has the strategic summarised findings from the XPAC component of the research. Table 6-3 shows the findings from drilling down on specific peak days from XPAC into FlexSim.

Table 6-2: Summarised strategic findings of XPAC scenarios and sensitivities.

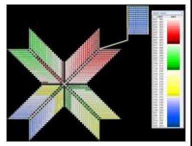
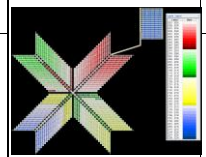
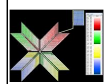
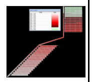
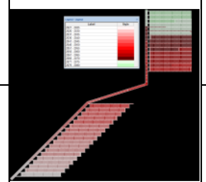
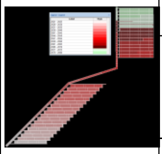
System	Case	Comment	Platform	Mine Design	Finding
XPAC	1	Base Case radiate away and return - all green support	N/A	Generic 4 Areas/Domains 	Migrating away will increase logistics strain Return to commence a new domain near the supplies portal/shaft will create logistics strain relief Demonstrates logistics strain relief with:- Super Units Standing down a unit Quantifies diseconomies of scale through the addition of development units through a step change in logistics breaking strain.
	1a	50% reduction in production.	Case 1		Slower development rates reduce the peak logistics strain but increase the time between relief from it.
	1b	Case 1 Dev rates but absorbing excessive longwall float by reducing development unit operating time.	Case 1		Reduction of development inventory in advance, or less longwall float reduces and defers peak logistics strain.
	2	Case 1 + the addition of the NE-Extended Area/Domain.	Case 1 + NE Extension	Generic 4+1 Areas/Domains. 5th domain step around beyond Area/Domain 1. 	A step around due to geological anomaly or approval restriction will immediately introduce a step change in logistics strain.
	3	Introduction of variable primary support.	Case 2		Demonstrates "perfect storm" events where all development units primary support is where there is a relatively high productivity combined with high deliveries required per metre. Highlights unique event peaks and troughs of logistics strain whilst also showing the growth of background logistics strain.
	4 - Change of path	Impact of path/sequence change from rehanding across mains to progressing the domain one side of mains then the other.	Case 2		More frequent but less pronounced relief of logistics strain. Steeper logistics strain gradients The risk of all units being at the outer edge of a domain at once is less therefore a slightly lower peak in logistics strain.
	5 and 6a	Installation of additional shafts/portals closer to inbye workings.	5: Case 2 6a: Case 6	 	The introduction of an additional supplies portal closer to workings provides immediate relief to logistics strain upon its commissioning. The strategic positioning of these shafts can suppress logistics breaking strain for the life of mine with a delivery machine cap.
	6	2 single sided domains, same development rates per scheduling block as case 3 onwards. Footprint away from portals is sooner.	N/A	Longwall on single side of 2 domains. Second domain extended with large step around from the first. 	Increases Logistics strain gradient bringing on peaks earlier Highlights the step change in logistics strain of an Area/step around
	7	50% increase in delivery speeds.	Case 6		Logistics strain is reduced proportionally to the distance away from the portals. The closer the operations to the portals the more focus should be made on fixed time tasks in the cycle. Confirms that optimising the loading and unloading tasks should be done up front and concreting and lighting can be deferred until longer travel distances are encountered.
	8	Double payload.	Case 6		If load and unload time remain the same, doubling payload halves logistics strain. However it is critical that loading and unloading time is optimised particularly on short distances hauls or the benefits of additional payload are not realised. Reduces machine movements and overall emission of diesel particulate matter within the ventilation system.
	9	Reducing delivery window times to 13.5hours.	Case 6		Reduction in dedicated delivery times proportionally increases logistics strain.
	11	Increased development rates. Nominally 47% higher than Case 6/Case 3 rates.	Case 6		If all units are required to maintain faster longwall operation: Increases deliveries per day and combined distance from portals meaning logistics strain is proportionally higher. The risk of logistics breaking strain is sooner. Or If longwall production is maintained then faster development rates allow demobilising development units reducing the peaks of logistics strain above.
	12	Capping Logistics Strain.	Case 6		Research provides a fast iterative approach to total production capped by logistics to understand Life of Mine Value. The shortfall in value can therefore justify investment in debottlenecking.

Table 6-3: Summarised tactical findings of FlexSim scenarios and sensitivities.

Case	Comment	Platform	Mine Design	Finding
1	2026 Status 2 loaders.	Case 6		Close to pit bottom in 2026, the increase in delivery machines from two to three creates an increase in delays of 0.8% to 5% for shunting. This directly due to lack of pit room that accompanies shorter mains.
2	**BASE CASE 1** 2026 Status 3 loaders.	Case 6		
3	2059 Status 3 loaders.	Case 6		LOGISTICS BREAKING STRAIN EVENT: Required deliveries for this day is 40, with three delivery machines 15 deliveries would be made, meaning that productivity would be downgraded by 62.5%. ALL PRODUCTIVE UNITS AFFECTED, MAJOR SCHEDULE IMPACTS.
4	2059 Status 7 loaders.	Case 6		MINOR LOGISTICS BREAKING STRAIN EVENT: two loads per day shortfall out of 40 loads, may be able to be managed with early deliveries, or downgrade in lowest priority machine and absorb some longwall float. ONE PRODUCTIVE UNIT LIKELY AFFECTED, ANTICIPATED ZERO SCHEDULE IMPACT IF MANAGED WELL FOR ANY seven delivery machines case because the 12-week rolling average for this peak in 2059 is below seven "loads on road".
4.5	2059 Status 7 loaders + 12kmhr.	Case 6		Confirms an increase in speed of 20% (for example concreting and lighting) along all travel roads will reduce the need for one delivery machine (from eight to seven delivery machines).
5	**BASE CASE 2** 2059 Status 8 loaders.	Case 6		Confirms the XPAC estimate for "Loads on Road" of eight delivery machines for this day in 2059
6	2059 Status (6a inbye shaft) 1 loader.	Case 6a		Confirms and highlights XPAC finding for a typical day, the dramatic reduction in logistics strain from eight delivery machines to two delivery machines if a new inbye shaft is installed at the commencement of Northeast Extension Area/Domain if the licence to operate allows this.
7	2059 Status (6a inbye shaft) 2 loaders.	Case 6a		
8	2059 Status (6a inbye shaft) 3 loaders.	Case 6a		
9	2059 Status 7 loaders - inbye outbye road.	Case 6		Whilst a dedicated inbye and outbye road will certainly assist during heavy traffic times such as shift change, it only contributes to one additional load delivered per day. There is still a significant justification to safety.
10	2059 Status 7 loaders - inbye outbye road + 4 x road train(2 loads).	Case 6		Road trains are beneficial over long haulage routes if load and unload times are optimised. At shorter distances to the time to load and unload the additional loads likely negates any advantage. four / seven delivery machines operating as road trains (double capacity) will match eight single delivery machines on road and is slightly under potential deliveries from a 20% increase in speed.
11	2059 Status 7 loaders - inbye outbye road loader 11kmhr.	Case 6		Increase of speed by 10% adds two loads on top of the 36 loads utilising seven delivery machines on this route but It still falls two loads short of the required 40 loads.
12	2059 Status 7 loaders - inbye outbye road loader 12kmhr.	Case 6		There is no change in deliveries per day between speed only increase and a speed + inbye/outbye travel road FOR THIS CASE. Without considering the safety aspect of singular directional traffic flow it means:- Speed is vital for longer distances There is a need to look very closely in future research at actual machine movements per mine (which is difficult to ascertain reliably) to get a more accurate understanding. In the meantime, a dedicated heavy haulage road and light vehicle/pedestrian road instead of a inbye and outbye travel road would replicate Case five of eight delivery machines and minimise potentially unsafe interactions especially at higher speeds if achieved.
13	2059 Status 8 loaders with 0.5 hour interaction delay.	Case 6		Allows day to day management to understand the sensitivities of delivery machine unutilised time. eight delivery machines are capable of withstanding up to 60 minutes of delay and nine delivery machines are capable of withstanding 120minutes of delay per day in addition to shunting / traffic delays.
14	2059 Status 8 loaders with 1 hour interaction.	Case 6		
14.1	2059 Status 8 loaders with 1.5 hour interaction.	Case 6		
15	2059 Status 9 loaders with 2 hour interaction delay.	Case 6		
15.1	2059 Status 9 loaders with 2.5 hour interaction delay.	Case 6		
15.2	2059 Status 9 loaders with 2.5 hour interaction delay.	Case 6		
16	2059 Status 4 loaders.	Case 6		A four delivery machine cap operating the full 24 hours would deliver 20 loads per day (50% of the required loads) and therefore a write-down in productivity on that day would be the equivalent of 50% loss in productivity. If the four delivery machines only operate for 13.5 hours per day then productivity is written down by 70% on this day. There is no inventory management opportunity because loads on road 12-week rolling average exceeds four units since April 2057 (2.5 years).
17	2059 Status 4 loaders with 13.5 hour operating window triple load road train.	Case 6		
18	2059 Status 20 loaders unlimited supply.	Case 6		20 delivery machines proves that loaders themselves cannot create breaking strain, but they continue to become increasingly inefficient with each additional delivery machine increasing traffic delay. From the eight loader base case traffic delay increase six-fold with 26% of the day being in delay mode due to shunting / traffic delay. However deliveries are well in excess of what is required.

6.3 Further Study

This thesis was undertaken to develop a fast method to identify logistics strain and breaking strain through evaluating the loads on road at any point in time in a life of mine plan and therefore give the mine planning team the best opportunity to proactively address any future perceived bottlenecks. The scope was from pit bottom or portal to the start of a production district. This included: -

- From the surface to the production district where a single haulage method was used. Such as a rubber tyred vehicle access drift, adit or box cut.
- From the bottom of a shaft materials lay down area (pit bottom) to the production district.
- From the bottom of a drift materials lay down area where the drift transport is different to the production district delivery LHD.
- The use of transfer hubs at the commencement of a production panel where larger delivery LHDs could cycle deliveries from pit bottom to this point and transferring the materials delivery over to another usually smaller machine to undertake the rest of the journey to the production district.
- Rubber tyred transport, less commonly but still applicable rail transport or any future pit bottom to production face transport mechanism that could be utilised in the future.

The production district is defined as the start of a production panel where there is a laydown / storage area for materials prior to delivery to the actual face nominally between 100 m and 200 m outside the last line of completed cut throughs in a cut through with sufficient space for storage.

This thesis did not include: -

1. Optimisation of loading and unloading deliveries which was identified as critical using FlexSim particularly for short cycles early within the mine life and if it affected the cycle time of large payloads.
2. The optimisation of delivery from the production district laydown zone to the face operations with minimal interruption to direct operating hours of face machines.
3. Optimisation of the logistics team's shift and the ability to maximise utilisation and the execution of the plan vs actual adherence of the logistics team at mine sites and associated organisational behaviour.
4. The true tracking of delivery packages and actual delay in real time from deputies' production reports and management information systems.
5. The dynamic nature of logistics breaking strain throughout the life of a mine.
6. Technology to increase speed of delivery.
7. The opportunities to use autonomous haulage technologies.

6.3.1 Opportunity 1: Loading and Unloading Optimisation

The reduction in loading and unloading time is critical in an early life cycle or when payloads are increased to reduce loads on road/ logistics strain of movement. In the mine visits undertaken there was a large spectrum between best and worst practice for laydown delivery areas. Some were muddy, poorly lit and inhibiting to optimal traffic flow or speed of transfer to areas that were concreted, others were well lit, all deliveries stored there catalogued.

It is recommended that a comprehensive study of optimal laydown storage areas be undertaken with a view to minimise the loading and unloading component of the delivery cycle time. This would involve collecting data of every movement of machinery and human and the timings of each movement to minimise both. Tracking of delivery packages should also be closely studied to understand how rehandling of these packages may distract the logistics team from their primary role of delivery. It is envisaged that this work can be replicated in FlexSim and would include: -

- Optimal human and machine movement in and around the laydown/storage area. Tracking of this movement in real time to identify opportunities to improve efficiency.
- Optimal storage facilities design to minimise time between arrival and departure of a delivery LHD to the laydown area.
- Approach and departure speeds of delivery LHDs to reduce total cycle time whilst not compromising safety.
- Ensuring sufficient stocks from the store have been delivered to pit bottom and a trigger mechanism for additional stock is developed. If stock has not arrived there should be a real-time dispatching application available to the delivery driver to change priorities on the run. This would reduce the risk of a stoppage during the delivery cycle when the driver would be alternatively required to contact control of what to do next.
- Ensuring there is a fit-for-purpose design and space available for deliveries at the production district to prevent the need for moving storage materials around to make space therefore preventing delay inbye. This is particularly critical as other machines may have to wait due to previously discussed ventilation constraints at the panel start for extended times because of a delay inbye. This could also be app-based in real time and per-shift stocktake can update the priorities of production district delivery prior to loading at pit bottom.

6.3.2 Opportunity 2: Minimising Production Machine Delays Through Optimising Face Delivery

This does not directly affect logistics strain which this thesis is concerned about, but it remains critical that deliveries that interrupt productive activities are minimised. Development of dedicated equipment and optimised movement to aid in this and seeking the best opportunities within the cutting cycle or shift cycle could be studied. At this point loading onto the face delivery LHD is not as critical as unloading, given the level of human and machinery interaction at this location. It is envisaged that this work be replicated in FlexSim and would include: -

- Optimal human and machine movement in and around the production machine, including tracking of this movement in real time to identify opportunities to improve efficiency.
- Establish trigger points in the cutting cycle where deliveries can occur with a focus on maximising direct operating hours.
- A seamless delivery package between the surface warehouse and the production machine to minimise human intervention with repackaging or rehandling.

6.3.3 Opportunity 3: Logistics Plan vs Actual Adherence

More concerned with organisational behaviour, this is a study on the reliability of the logistics team plan when compared to actual outcomes. This may include tracking of actual machines and personnel using PED technology to understand the unique issues that a delivery driver may face. These issues include the distractions that lead to down time such as needing to locate implements required for specific deliveries (QDS to RAS adapters, duck bills, baskets, trailers etc), delays to panel entry due to perceived ventilation constraints at a diesel tag board, or the actual behaviour of the LHD operator. Once an understanding of delays has been reached then optimisation of the delivery routine can be made and cycle times therefore reduced.

As a mine gets larger, the priority of the logistics team should be improved. From an organisational behaviour perspective does the team have the attitude and recruitment processes to fulfill this requirement or has the operation reduced prioritisation of this role and handed logistics to personnel that may simply not be suitable to work within the production district?

6.3.4 Opportunity 4: The True Tracking of Delivery Packages and Actual Delay

Even with machine movements being sufficient, if the wrong materials are taken to the face there is a high risk of stoppages whilst waiting on delayed delivery of the right materials, which is a form of logistics breaking strain. Every effort should be made to avoid errors such as these.

A system should be developed to monitor all relevant inventory, its required destination, and the next highest priority load if priority stock is depleted. Deputies, and management staff should be able to, in real time know where all delivery packages are, for example in transit, in storage at pit bottom, or in storage elsewhere. It is envisaged that an automated delivery dispatch system in real time would significantly reduce the risk of waiting and increase utilisation of delivery LHDs through redeployment. The driver, control officer, management and production deputy would receive real time data on stock levels and priority, and the driver would be able to log delivery times and unplanned delays through a tablet that can communicate using a Wi-Fi system that some mines already employ.

After discussion during mine visits with production supervisors, there was anecdotal evidence that material delays were delaying production but went unrecorded, i.e., logistics breaking strain being masked by “planned process delay”. It was suggested that these events were masked by routine planned delays such as opportune maintenance, ventilation tube installation, or cable extension which may not have been undertaken at the most opportune time in the cutting sequence but were done as an unplanned substitute activity. Research should be undertaken to understand if this issue is true. It is recommended that multiple mines would need to be studied which would be a very difficult task with the variability of tracking delivery packages. One possibility would be to understand how fast a delivery package goes from the outbye laydown storage area (pit bottom) to the face. The slower the delivery turnaround the more likely a delay has occurred.

6.3.5 Opportunity 5: The Dynamic Nature of Logistics Breaking Strain

Logistics breaking strain varies with changes to operations. For example, a small, highly ventilation efficient mine may have capacity to run many delivery vehicles at once. On the other hand, a large complex operation that over time has lost ventilation efficiency may no longer have the ventilation quantities required to maintain the level of deliveries. Logistics breaking strain may occur due to poor loading and unloading practices where haulage distances are low or payloads are large per delivery LHD, or through slow speeds as delivery distances increase over time. Research should therefore be undertaken in finding the crossover point between optimal loading and when there should be a focus on speed (lighting, concreting). Also, further research inter-connecting ventilation capacity with logistics requirements over time is also warranted.

6.3.6 Opportunity 6: New Technology for Speed of Delivery

During visits to operations a consistent future vision was to achieve deliveries above and not on the road surface. For example, a high-speed battery monorail installed from the roof which would not be limited by ventilation constraints and if in a dedicated roadway with no pedestrian access could operate at very high speeds with no wear on roadways and relatively very little rolling resistance. Such a system would be developed with a view to be expandable to autonomous delivery. Such a system would need to operate within the mine's legislative framework, particularly with respect to large batteries employed underground.

6.3.7 Opportunity 7: The Opportunities to Use Autonomous Haulage Technologies

In 2021, Australian Army's Robotic and Autonomous Systems Implementation and Coordination Office (RICO), and Deakin University's Institute for Intelligent Systems Research and Innovation (IISRI) used a single human driven truck at the start of a convoy and the remaining trucks following it as a way to test autonomous haulage technology (Anonymous, 2021b). The system can also use GPS waypoint mode for off-road transport (Smith, 2020) and had recently completed limited road trials (Anonymous' 2021a).

Figure 6-8: Human driven leader truck with unmanned follower trucks. (Source: Australian Defence Magazine, 2021 Anonymous (2021b))

There is an opportunity to adapt leader- follower technology for multiple delivery LHDs in underground mining, particularly when delivery distances are long and utilising waypoint navigation combined with outbye delivery hubs. A human operator would participate in the loading and unloading of these vehicles. Autonomous technology would be another step which would likely deliver directly to the production district laydown area. A completely autonomous delivery system could be installed from loading, transport, and delivery to the production district and even directly to the production face with a view to place human operators on more value adding tasks.

6.4 Final Remarks

The research undertaken in this thesis successfully highlighted logistics strain at a strategic level and confirmed this at a daily level. Using algorithms developed within this thesis calculating the cumulative distance from a portal that a vehicle would travel, the deliveries required per development metre for varying geotechnical trigger action response plans (TARP) and a life of mine schedule combines to form “loads on road” also known as logistics strain. Logistics strain trends were studies for both generic models and for an actual operation and were found to easily insert into an existing mine schedule.

As the licence to operate coal mines into the future becomes more difficult, the age-old solution to logistics strain has been to sink a shaft which this thesis has proven provides immediate relief. Now such a solution is becoming less and less palatable, particularly within an Australian context. This thesis enables proactive early intervention to address bottlenecks using shaft alternative solutions and paves the way for isolating and addressing more efficient logistics mechanisms into the future. At the very worst if a solution cannot be found, it provides the mine planner with a way to forecast production that is capped to logistics breaking strain that will be a more realistic value for the life of mine and give more certainty of profitability, or lack of, into the future.

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