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Case Study: Refrigeration Requirements During Mineshaft Excavation as a Function of Heat Stress Index

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Agenda

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- Background
- Objectives

Methodology

- Cooling Power Surplus (CPS)
- Natural wet bulb globe temperature ($WBGT_n$)

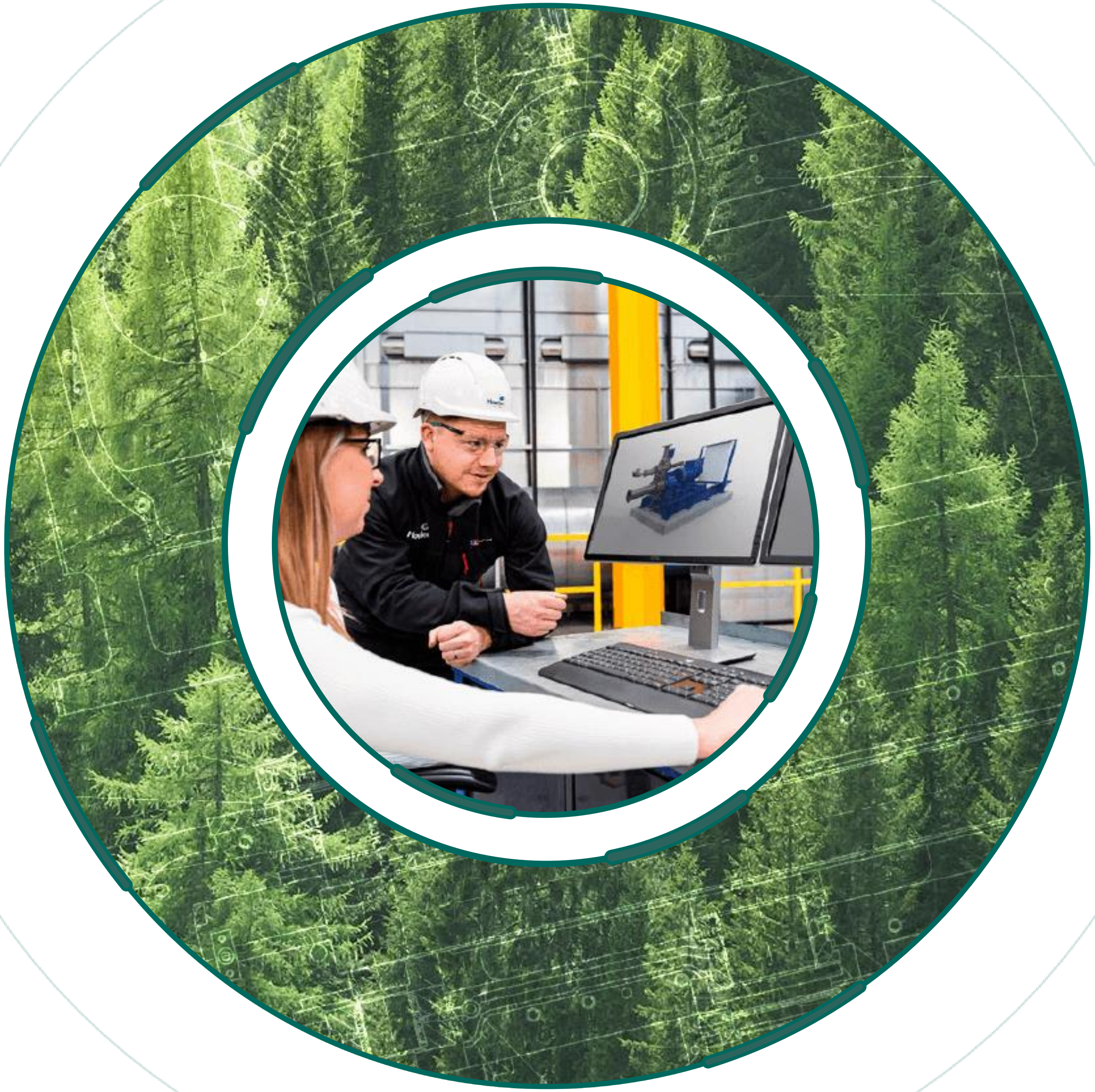
Problem Overview

- Schematic
- Design criteria and simulation inputs

Results

- Baseline, $WBGT_n$ informed scenarios, energy balance

Conclusion



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Introduction: background and objectives

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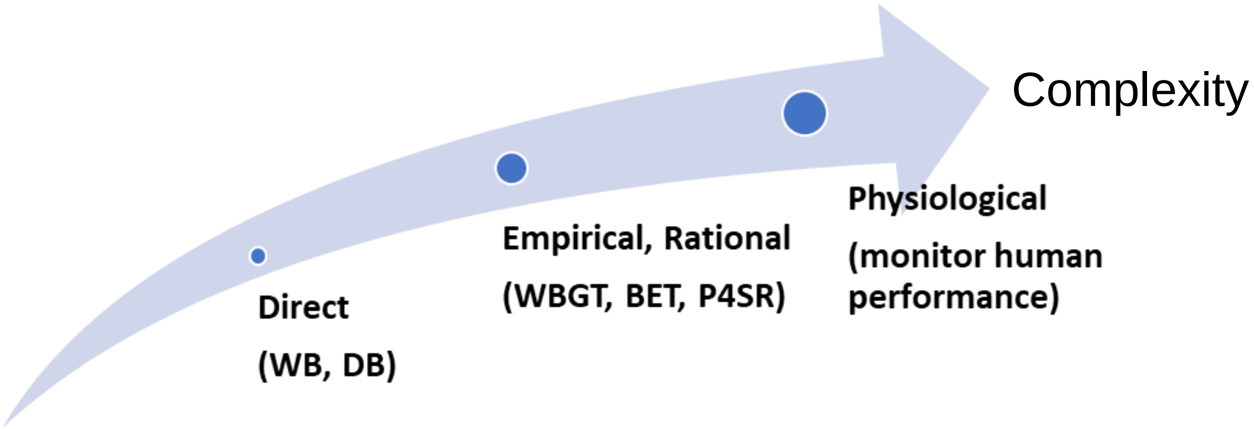
Introduction - background

- Two inherent factors workers contend with at great work depths are autocompression and strata heat.
- Mines continue to develop and extract ore at increasing depths, which subjects miners to potentially dangerous levels of heat stress.
- Heat stress: heat load a person is exposed to from a combination of environmental and physiological factors, resulting in a net increase in heat storage in the body (NIOSH, 2016).
- Heat stress index: a single number that predicts the level of heat stress in a hot environment in order to assess compliance with local legislations on heat. There are 3 broad categories,



Complexity

Direct

(WB, DB)

Empirical, Rational

(WBGT, BET, P4SR)

Physiological

(monitor human performance)

Introduction - background

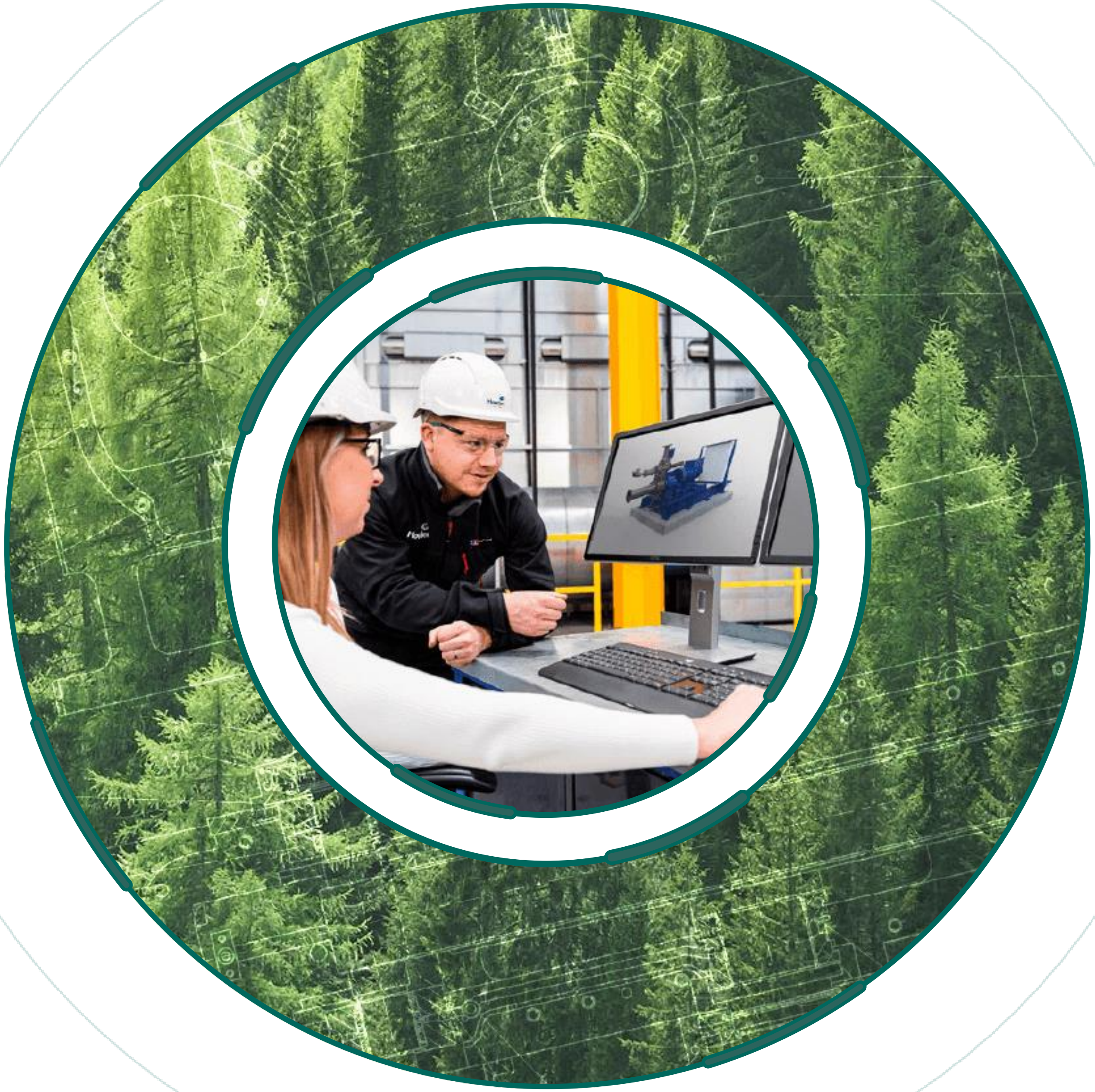
- No universal agreement on a "one-size-fits-all" heat stress index that satisfies[+],
  - Be accurate and feasible,
  - Account for both environmental and physiological indicators of heat stress,
  - Calculations or measurements that are easy to perform,
  - Exposure limits that function under a wide range of metabolic and environmental conditions.

- Previous works do not address practical consequences on the choice of heat stress index category on engineering controls.

[+] (Epstein and Moran, 2006; NIOSH, 2016)

Introduction - objectives

- Analyze the refrigeration and airflow requirements during shaft excavation using Ventsim^{TM} DESIGN.
- Investigate the concept of cooling power surplus (CPS) when working with WB.
- Explore how an empirical heat stress index, the $WBGT_n$, influences the ventilation and cooling design initially conducted with the more basic WB.



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Methodology: CPS and WBGT_n

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Methodology - CPS

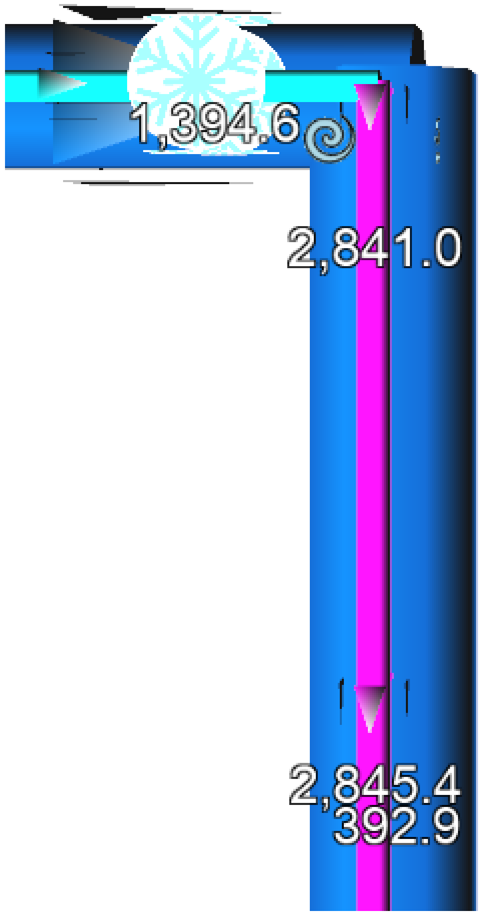
$$CPS = \dot{m}(\sigma_{reject} - \sigma_{in})$$

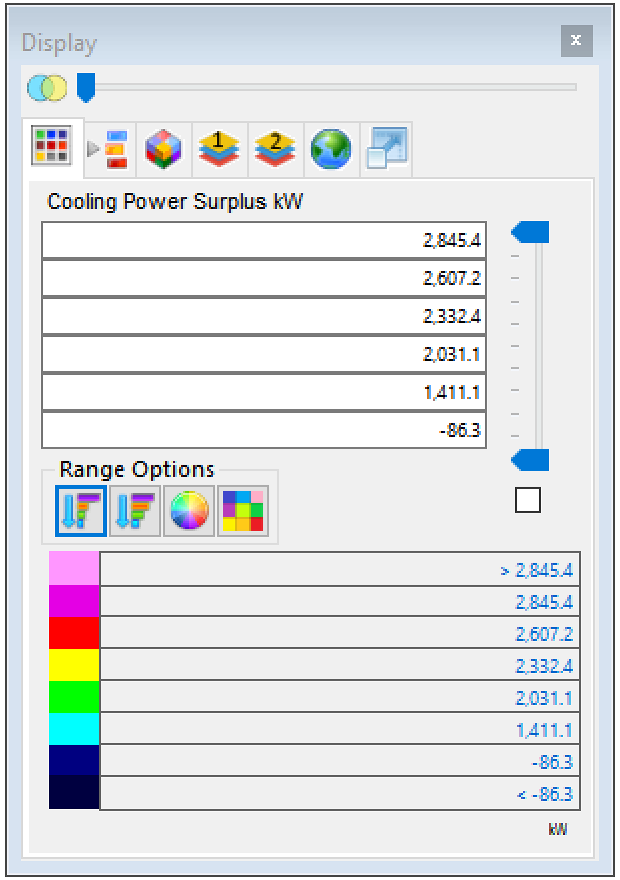
Where,

$$\sigma = 1.005 \times WB + \omega(2502.5 - 2.386 \times WB)$$

CPS	Cooling power surplus (kW)
$\dot{m}$	Mass flow rate of air (kg/s)
σ	Sigma heat (kJ/kg$_{\text{dry-air}}$)
ω	Absolute humidity

DEF: *Quantifies the air's remaining capacity to absorb heat before equaling target WB.*





Cooling Power Surplus kW

2,845.4
2,607.2
2,332.4
2,031.1
1,411.1
-86.3

> 2,845.4
2,845.4
2,607.2
2,332.4
2,031.1
1,411.1
-86.3
< -86.3
kW

Methodology - WBGT_n

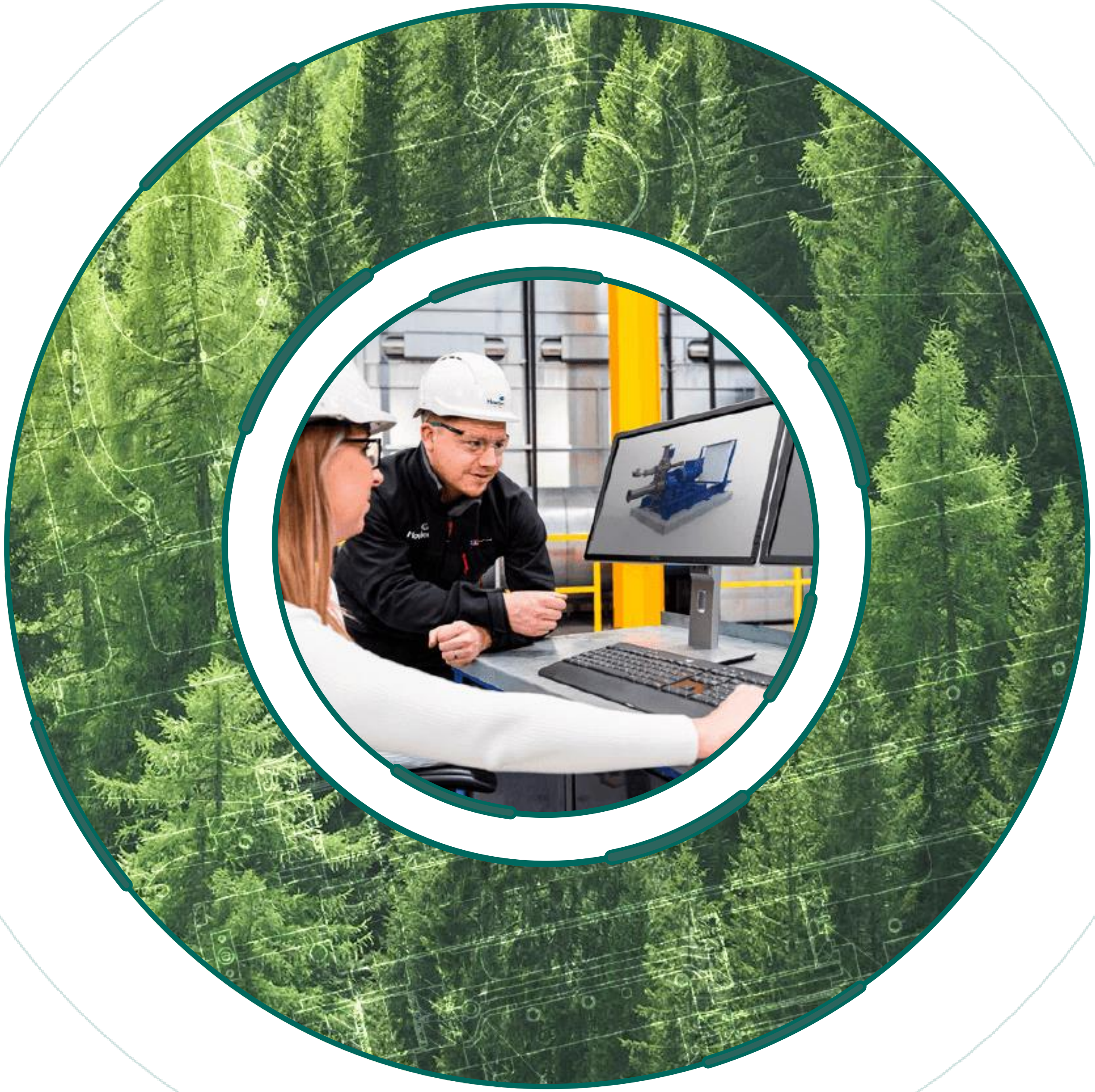
- One critique of the WBGT: it is insensitive to air velocity.
- To partially address the problem, modify WBGT equation,

1. $\text{WBGT}_\text{n} = 0.7 \times \text{WB}_\text{n} + 0.3 \times \text{DB}$
2. $\text{WB}_\text{n} = \text{DB} - \text{C}(\text{DB} - \text{WB})$

Where *C* is given by,

$$C = \begin{cases} 0.85 & V < 0.03\ m/s \\ 0.96 + 0.069 \log_{10} V & 0.03\ m/s \leq V \leq 3\ m/s \\ 1 & V > 3\ m/s \end{cases}$$

* n denotes natural
non-subscript abbreviations denote psychrometric



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Problem Overview: schematic, design criteria, simulation inputs

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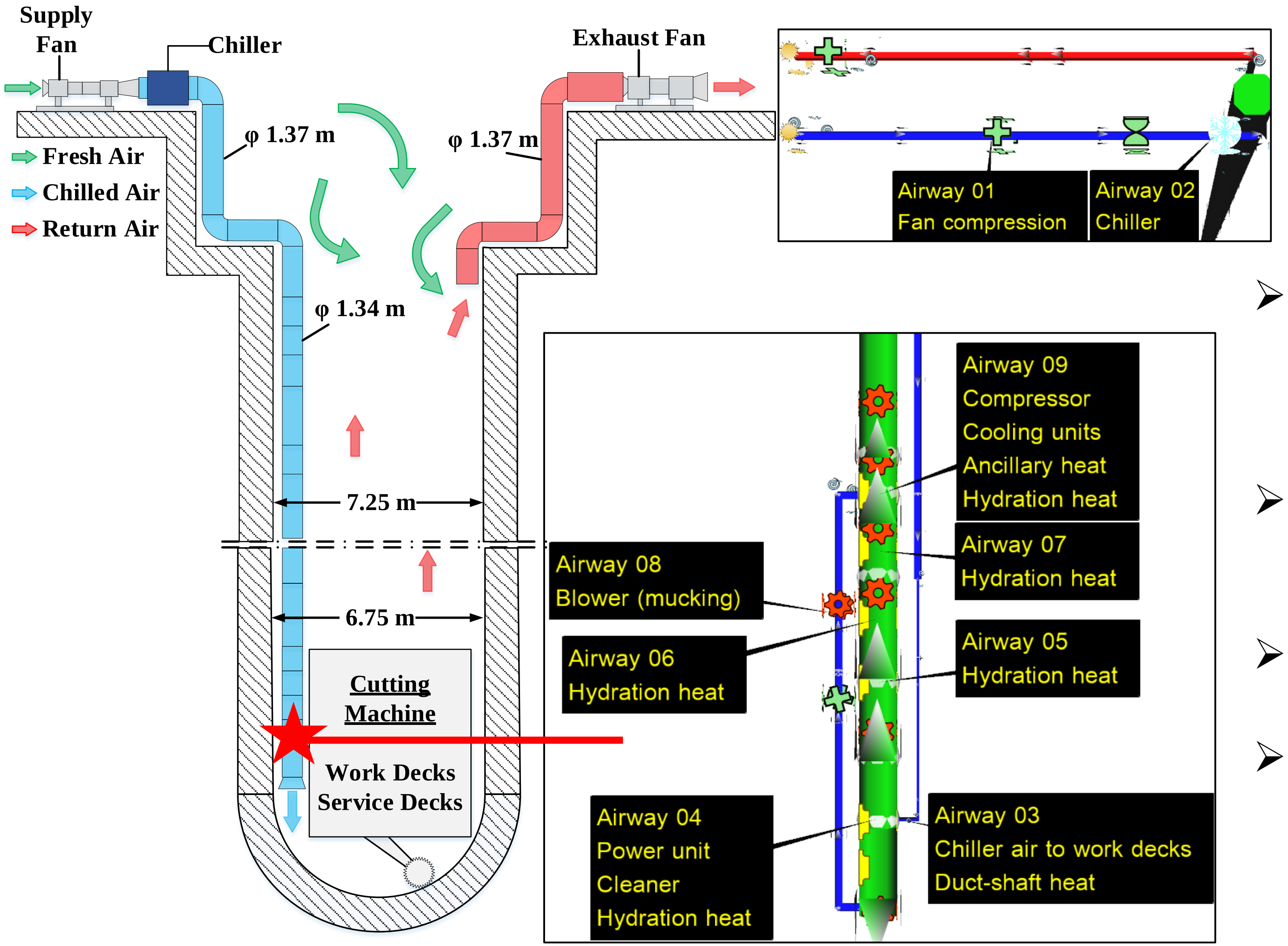
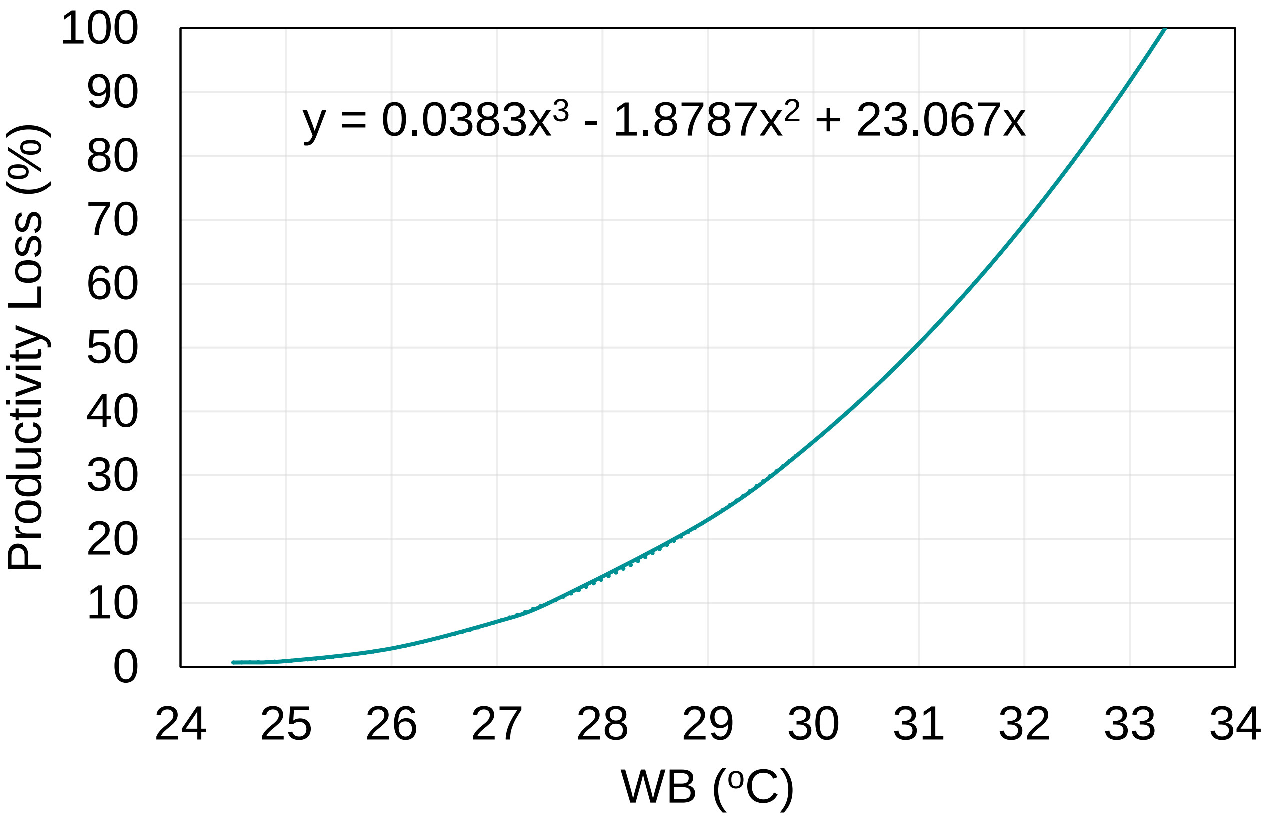
Problem Overview - schematic



- Dual-stage intake fan supplies chilled fresh air to the service and work decks on the “cutting machine”.
- 1.37 m ϕ ducting transitions to 1.34 m ϕ, due to space restrictions.
- Uninsulated duct.
- Single-stage exhaust fan discharges a mixture of fresh and return air to environment.

Problem Overview – wet bulb and productivity

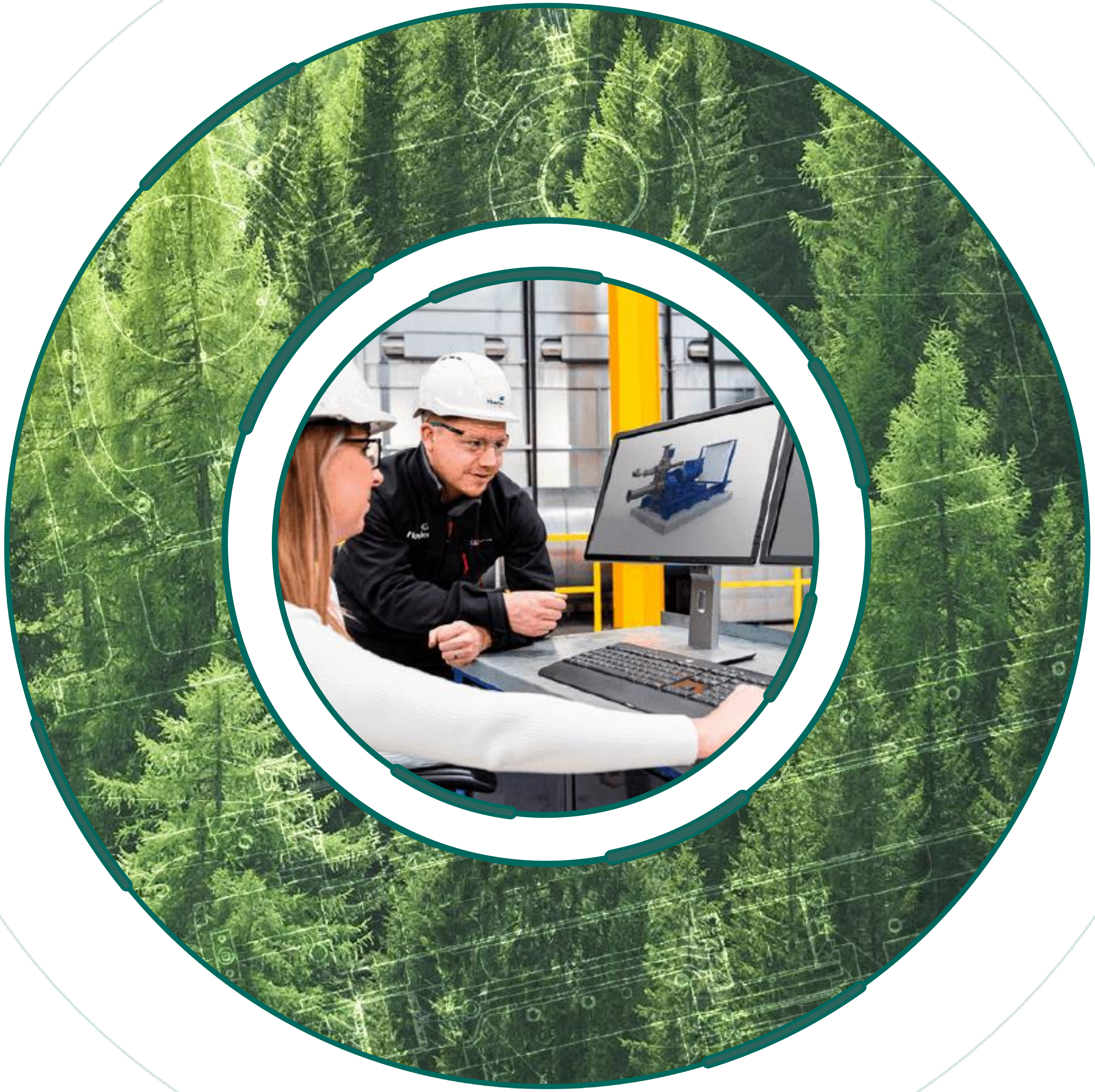


- ➢ Graph representative of productivity loss in Australian coal mines,
  - 27.8°C WB permits 87.5 % productivity (i.e. 7h in 8h shift)

Problem Overview – design criteria & simulation inputs

Parameter	Units	Value
95th percentile WB/DB	°C/°C	15.1/19.7
Minimum velocity	m/s	0.5
Collar WB	°C	6
Geothermal gradient	°C/km	Considered
Rock density	kg/m³	Considered
Rock specific heat	kJ/(kg°C)	Considered
Rock thermal conductivity	W/(mK)	Considered
Shaft wetness	%	30 – 80
Duct friction factor	kg/m³	0.0013
Leakage porosity	mm²/m²	25
Duct thickness	mm	3
Duct thermal conductivity	W/(mK)	0.48
$WBGT_n$ activity level	-	Moderate

Parameter	Units	Value
Limiting WB/DB	°C/°C	28/37
Limiting $WBGT_n$	°C	27.8, if $V < 1.5$ m/s 30.6, if $V \geq 1.5$ m/s



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Results

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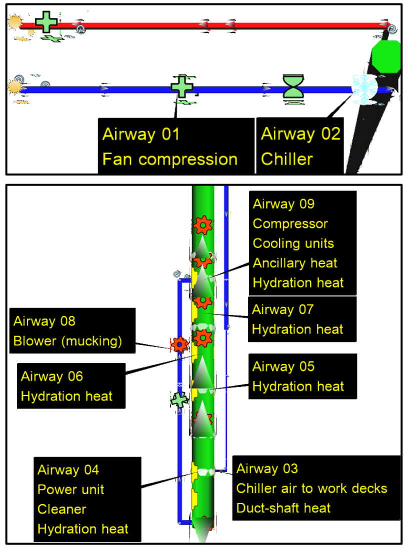
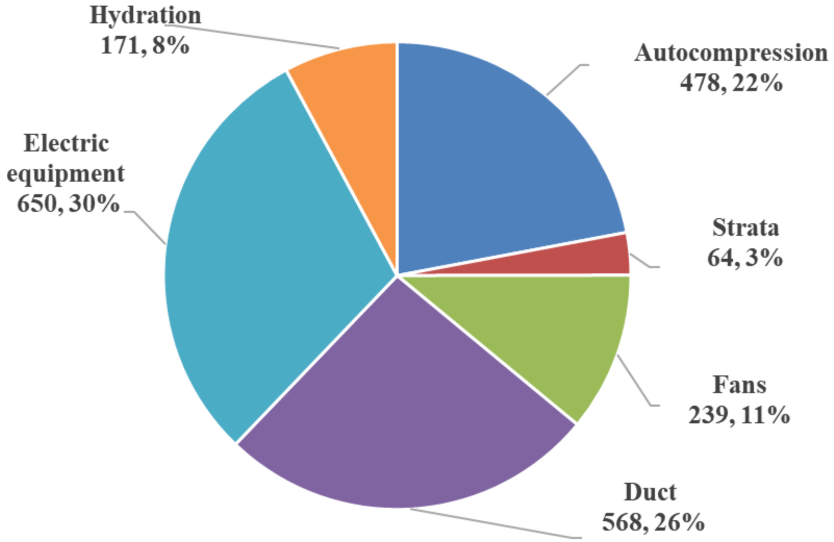
Results - baseline



Airway	Density (kg/m³)	Flow (m^3/s)	V (m/s)	WB_{in}/DB_{in} (℃/℃)	WB_{out}/DB_{out} (℃/℃)	CPS (kW)	$WBGT_{n,in}$ (℃)	$WBGT_{n,out}$ (℃)
1	1.19	29.5	20.0	15.1 / 19.7	18.1 / 26.5	1600	16.5	20.6
2	1.21	28.9	19.6	17.9 / 26.5	6.0 / 6.0	1272	20.5	6.0
3	1.3	21.3	32.3	21.6 / 41.1	21.5 / 41.1	620	27.5	27.4
4	1.28	16.4	2.1	21.6 / 41.2	24.0 / 47.6	469	27.7	31.4
5	1.27	16.4	1.6	24.0 / 47.5	24.5 / 48.1	309	**31.5**	32.0
6	1.27	16.7	1.4	24.5 / 48.0	25.0 / 48.0	277	**32.0**	32.4
7	1.27	16.7	1.6	25.0 / 48.1	25.1 / 47.0	238	**32.3**	32.1
8	1.18	5.8	4.1	22.3 / 41.4	34.8 / 92.2	137	28.0	52.0
9	1.21	23.4	3.0	**27.8 / 57.9**	**29.7 / 64.6**	24	**37.0**	40.3



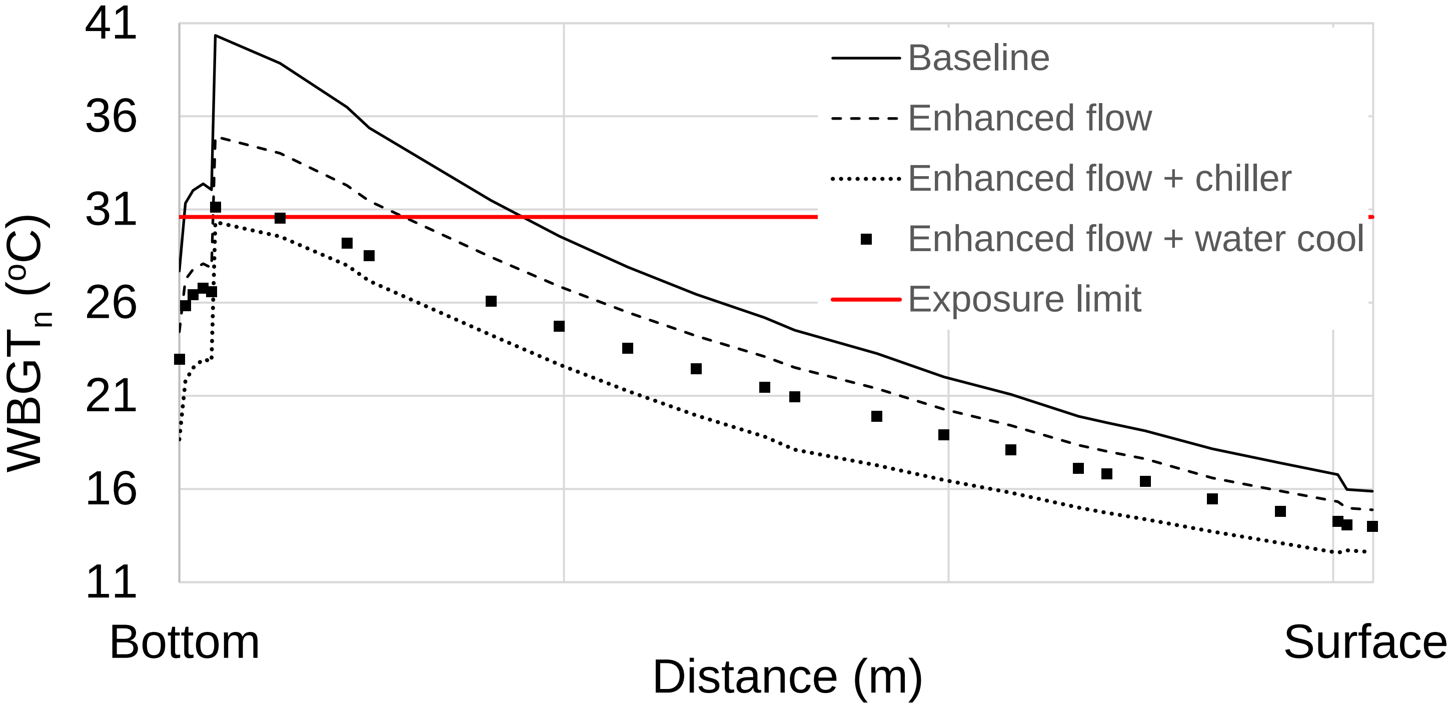
- Climatic conditions are mostly favorable w.r.t WB.
- Predominantly dry heat → large wet-bulb depression.
- CPS decreases monotonically.
- Options to de-escalate heat stress risk limited to increased ventilation and additional cooling.

Results – WBGT$_n$ informed scenarios

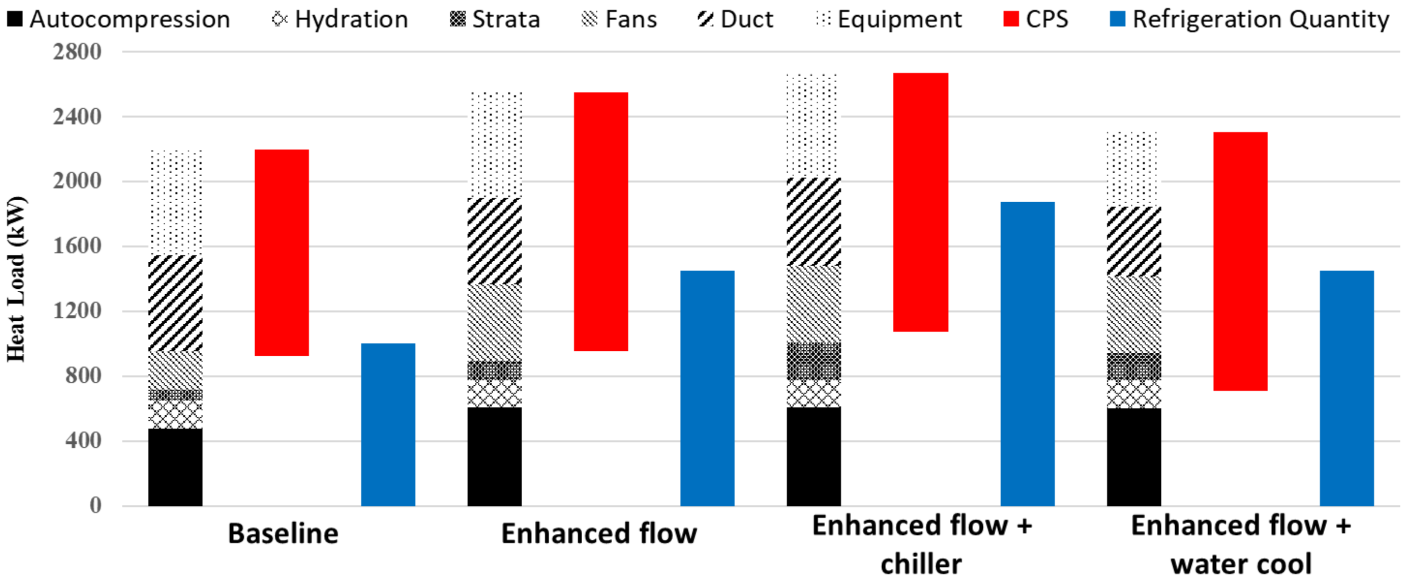
3 additional scenarios to check WBGT$_n$ compliance,

1. Increase fresh air intake from 30 m^3/s to 38 m^3/s.
2. Enhanced flow with additional mid-shaft chiller.
3. Enhanced flow with water cooling on cutter.

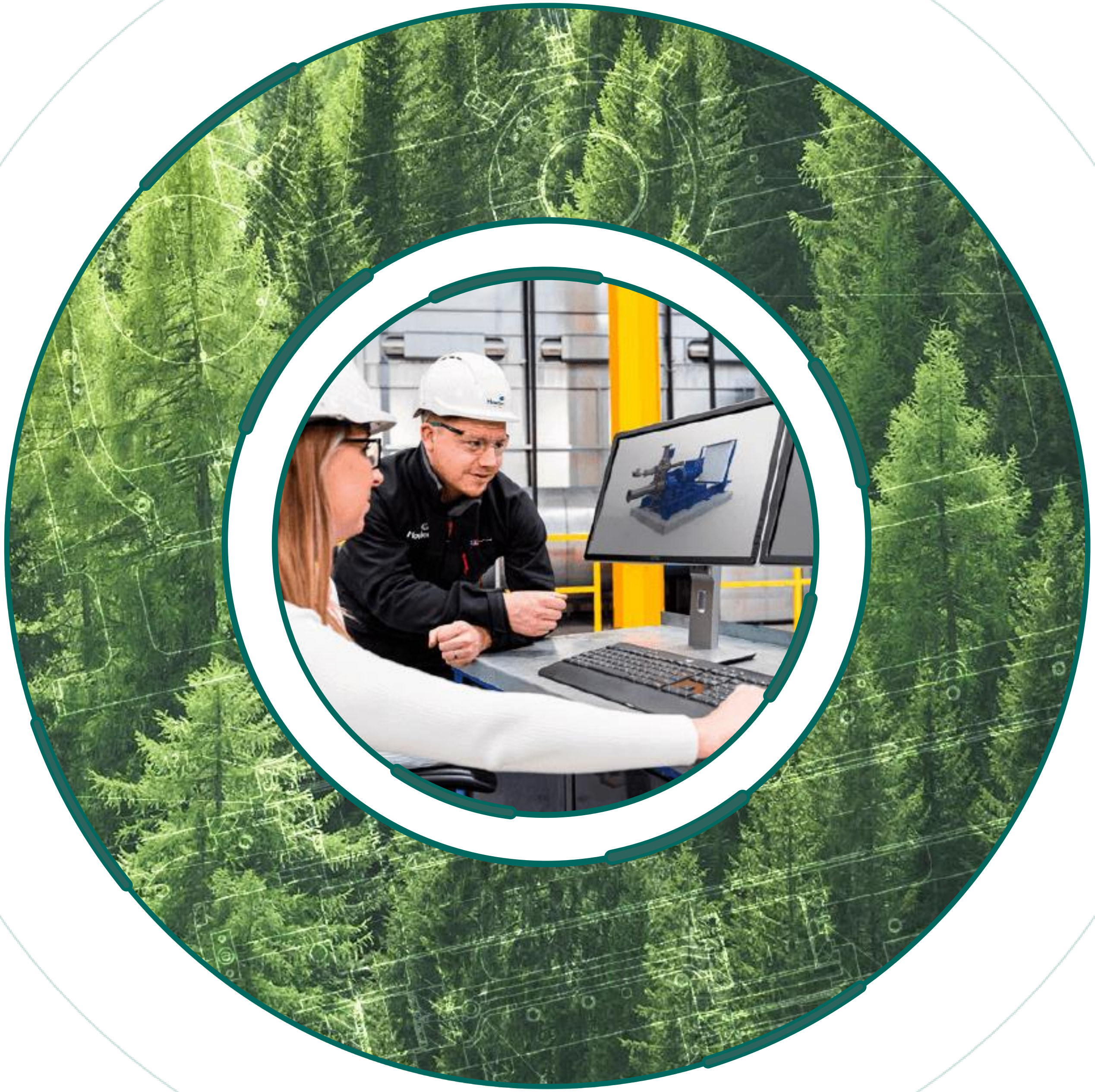
- ➢ Peak in graph is the outlet to airway 9 (above the cutter)
- ➢ Options 2 & 3 (majority) satisfies WBGT$_n$ constraint.



Results – energy balance



- CPS evaluated on surface, but adjusted for leakage.
- Ideally, the refrigeration quantity based on WB should be $\sum Heat - CPS$. Duct and strata heat makes the energy balance accounting non-trivial.
- Larger overlap between CPS and refrigeration: lower WBGT_n.



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Conclusions

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Conclusions

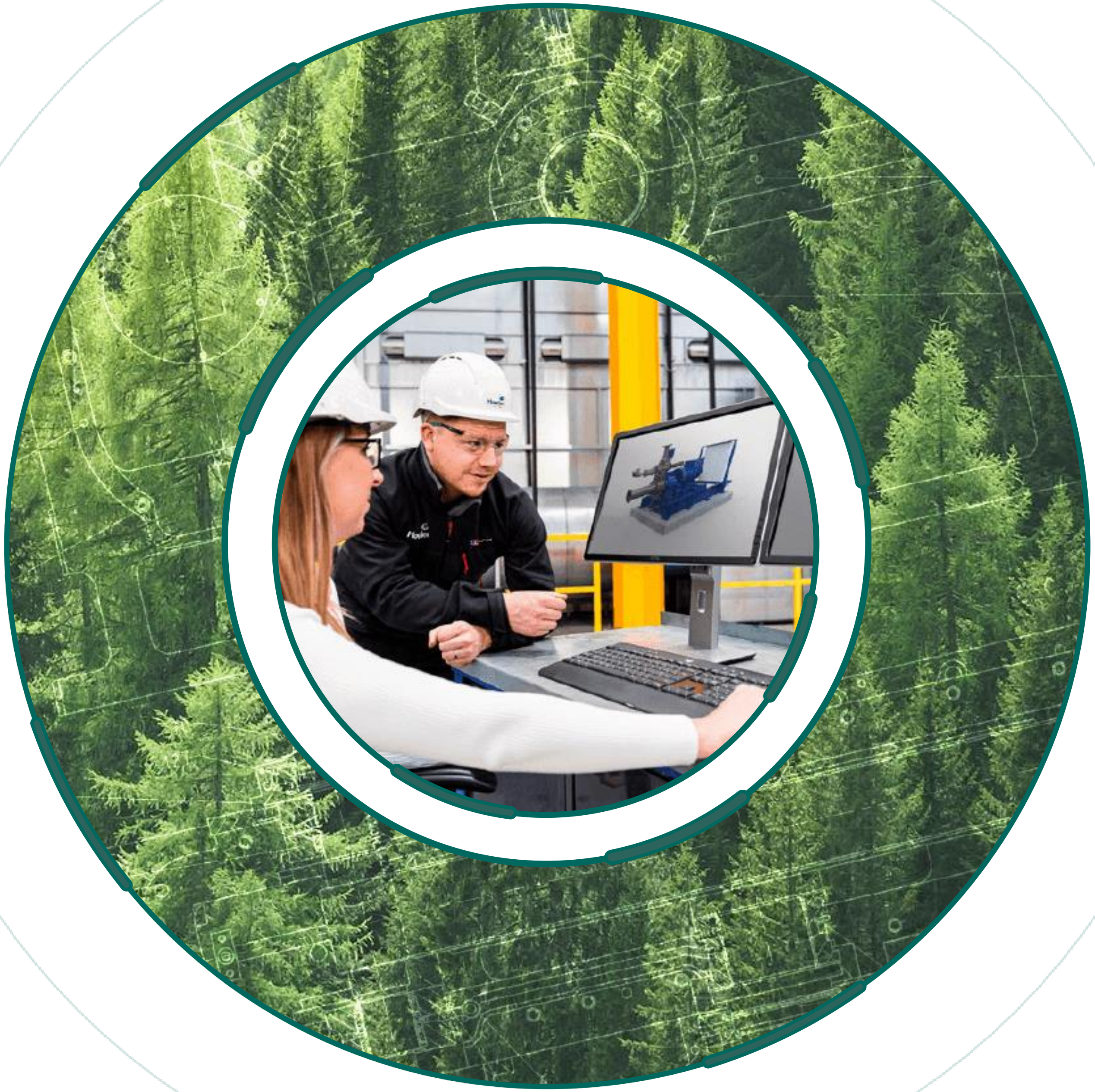
For this specific case, the work reported the following,

1. Baseline results informed by the WB index predicted a mostly favorable thermal environment.

2. The advantage of the WB is that it facilitates the energy balance calculation through CPS. Consequently, the predicted refrigeration quantity is derived by subtracting CPS from the known heat sources.

3. Solutions driven by WBGT_n compliance required enhanced ventilation (26%) and cooling (100% more), or increased ventilation plus reduction in equipment heat through retrofits.

4. Mines with a similar heat source profile (sensible >> latent) may be confronted with a choice between WB and WBGT_n,
    - During design phase, utilize WBGT_n
    - For monitoring and managing heat stress, utilize WB



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Questions

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