PPSDM Jakarta, October 31st, 2017

Company decision-making for geothermal projects

(GEOCAP course 1.07)

Topic: investment decision-support tool for high enthalpy geothermal projects *(GEOCAP WP2.01)*

Integrating physics, technical installations, operations, planning, economics & uncertainty

Tool developers - Christian Bos, Logan Brunner (TNO)

Public document (GEOCAP-2016-REP-TNO-2.01-xx)

Background of XL tool

- Currently, no easy / comprehensive / integrated tool available in Indonesia.
- Developed by TNO as part of GEOCAP work package 2.01 (R&D on DA), based on ideas ITB (Ali Ashat) and TNO (Christian Bos)
  - Prototype tool coded in XL with limited functionality, could be start for more comprehensive tool. To be distributed in WP1.07 course to participants.
- Free for all, including source code. However:
  - Tool still being tested, you can take part in the testing and send your comments to christian.bos@tno.nl. Tool not yet fully validated.
  - If there's interest in further developing the tool, contact ITB or TNO.
  - If Indonesian parties want to use it, it would be much better to coordinate / centralize the testing, maintenance and further development of the tool. Better to prevent all kinds of versions to co-exist! Better to avoid confusion.
- Use tool at own risk, no liability accepted. Feedback appreciated.

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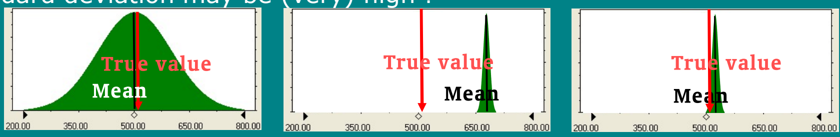
Fundamental to the tool’s philosophy

- *Precise*
  - = distribution with a (very) low or negligible standard deviation, or just a deterministic spike
  - Mean of distribution (spike) may be far away from the true value !
- *Accurate*
  - = distribution with a mean equal to or close to the true value
  - standard deviation may be (very) high !



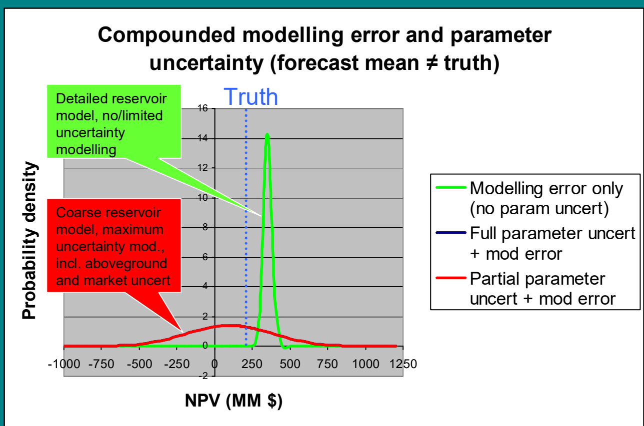
Imprecise & Accurate | Precise & Inaccurate | Precise & Accurate

- **Can we accept, at least initially, large modelling errors, provided that the mean is close to the true value?**
  - Later in SA, study Δprecision / ΔKPI-pdf + impact on decision-making

Limited vs. full uncertainty modelling

”I’d rather be approximately right than precisely wrong” – John Maynard Keynes

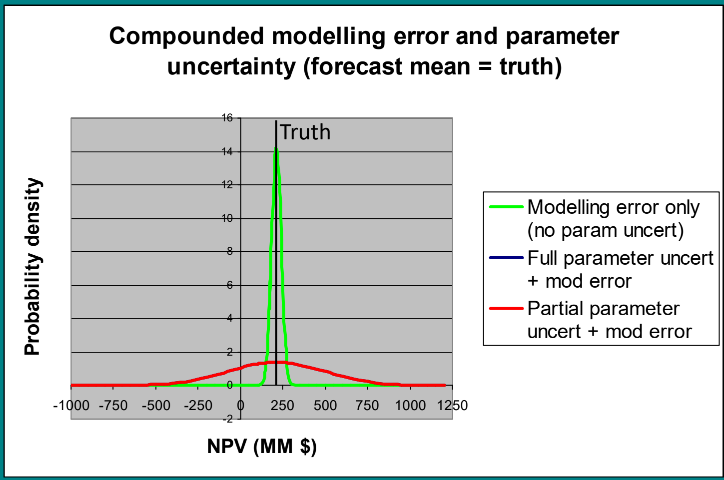
- Philosophy: trade-off between
  - Precision
  - Accuracy
- *Precision*: uncertainty range of a KPI is small (e.g. res. simulator)
- *Accuracy*: mean of the KPI output distribution ≈ Truth
- Using simple models, but over the full value chain and life-cycle *may be* better than ‘precise’ models that cover only part of the chain and operations: averaging can be OK!
  - Compare pressure transient testing



- Precise full-physics model only caused a false impression of engineering accuracy, illustrating the subsurface industry’s quite typical problem of “inflated expectations” and “under-estimated risk”

Compounding modelling error and parameter uncertainty in KPI-pdf: increasing steps of modelling parameter uncertainty (mean = truth)

- In figure various degrees of full chain / full life-cycle uncertainty modelling are depicted.
- The point however is that in many cases the precise models can only do a rather limited uncertainty modelling, and that as a result, their computed mean and risk are biased.



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Main purposes of tool

- Investment decision support (technical/economic feasibility) to geothermal operators who wish to evaluate high enthalpy geothermal assets in their *early planning phase* (preliminary survey – exploration – appraisal – initial development phases, i.e. when uncertainties on volume, productivity, planning, costs and revenue are relatively large):
  - Following an *initial qualitative / semi-quantitative screening* of geothermal prospects by the geothermal developer / company, this tool allows to conduct a preliminary fully quantitative analysis of the asset's full life-cycle techno-economical performance under uncertainty and under a number of fundamental assumptions and possible development scenarios.
- Discussion platform for Government & Geothermal operator
  - Understanding and appreciating investment risk vs. expected reward, problem solving
- Education
  - Helping students to understand the (relationships between) physics, technical installations, economics, planning & uncertainty related to immature (not yet developed, or under-developed) geothermal assets.

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Disclaimer, conditions of using current version

- The **authors** of this Geothermal asset life-cycle valuation XL-model are Christian Bos (email: christian.bos@tno.nl) and Logan Brunner (logan.brunner@tno.nl , TNO Applied Geosciences, POBox 80015, 3508TA-Utrecht, Netherlands.
- The XL-model has been developed as part of Work Package 2.01 of the **GEOCAP program** (https://www.geocap.nl/, see also https://www.geocap.nl/index.php/workpackages/research/wp-2-01). The GEOCAP program is being financed by the Netherlands Ministry of Foreign Affairs and runs from 2014 - 2018.
- The model has been prepared for the **sole purpose of teaching students** of author Christian Bos, who is also the lecturer of GEOCAP course 1.07 (see https://www.geocap.nl/index.php/workpackages/training/wp-1-07). The model should not be used for any other purpose. Note that the model has only been tested / validated in a limited way.
- The reasons for choosing XL as the programming language are: 1) almost all pc's and laptops have XL installed; 2) economists and managers / decision-makers often use XL only; 3) XL has good graphical display options; 4) **for teaching uncertainty analysis / decision analysis**, XL can be easily combined with commercially available statistical Monte Carlo XL plug-ins such as Crystal Ball (™ Oracle) or @Risk (™ Palisade Corporation). This opens up a whole realm of further analytical capabilities that would otherwise have to be programmed by the geothermal tool developer.
- When using (any idea contained in) this model for any other purpose than for (self-)education, and/or when changing any of the software code, the user does this at his/her **own risk**.
- The model is **not to be distributed or copied** to any other person than the direct recipients of the model who have been given the model as part of the lectures by the author.
- The holder of this model automatically **accepts the above conditions**.
- The user of this model is kindly requested to **report** any inaccuracies, suggestions for improvement etc. to the author(s).
- Should users of the model wish to further **disseminate the model and/or to maintain** the model, then please contact christian.bos@tno.nl or logan.brunner@tno.nl or secretariaat-aarde@tno.nl .

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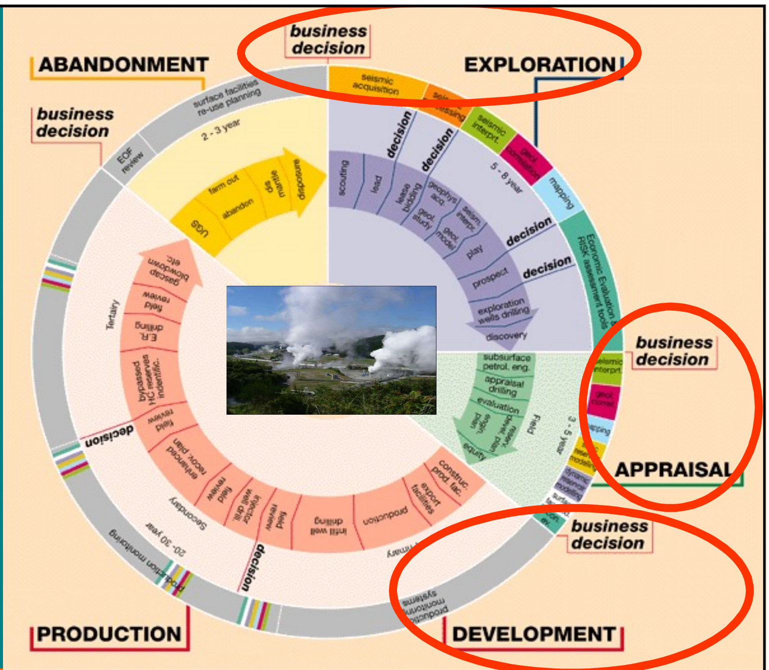
Geothermal Asset Lifecycle

- **5 main phases**
  - **+ 6th: Monitoring**
- **Many major decisions:**
  - **Inter-phase**
- **And minor decisions:**
  - **Intra-phase**

GT Asset is depletable in economic terms , i.e. non-renewable. ABD-decision based on 1) FTHT < T_{min} and/or 2) Opex > declining revenues, i.e. NCF < 0 over > *n* consecutive yrs.



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Geothermal asset life-cycle phases

'Preliminary survey' (pre-phase): *Govt site selection + inviting exploration bids*, leading to
- Operator DG '***Exploration license application***', followed by *Operator/Govt negotiations* + if successful:
- Govt DG '***Exploration license granting***'

1. Exploration, if promising leading to
   - Operator DG '***Appraisal work programme***' (or directly to DG '*Conceptual engineering*').
2. Appraisal, leading to
   - Operator DG '***Conceptual engineering***' (or FEED: Front-End Engineering & Design),
   - Operator DG '***Concept selection***' and
   - Operator DG '***Production license application***' + Govt DG '***PDO sanction***'
     - Leading to Operator DG '***FID***' (***Final Investment Decision***)
3. Development
   a) *EPC activity* (Detailed Engineering – Procurement – Contracting)
   b) *Construction activity* (leading to DG '***Commissioning***' and '***COD***')
4. Operation (production operations & maintenance / exploitation)
   - Direct or indirect utilization (condition of license)
   - Including Operator DG's for '***Incremental development(s)***'
5. Decommissioning (joint Operator and Govt decision)
   - Dismantling surface installations + abandoning wells (+ prepare for mandatory monitoring)

- Tool targeted for early phase decision support.
- All phases simulated (until decommissioning)

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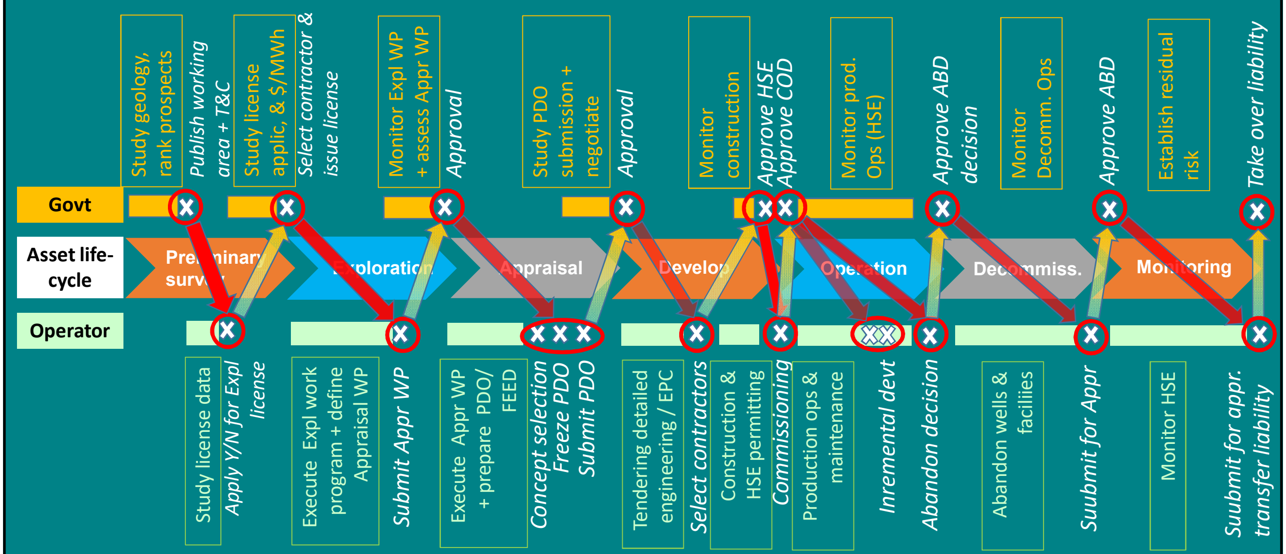
Asset life-cycle Decisions: Govt. vs. Operator



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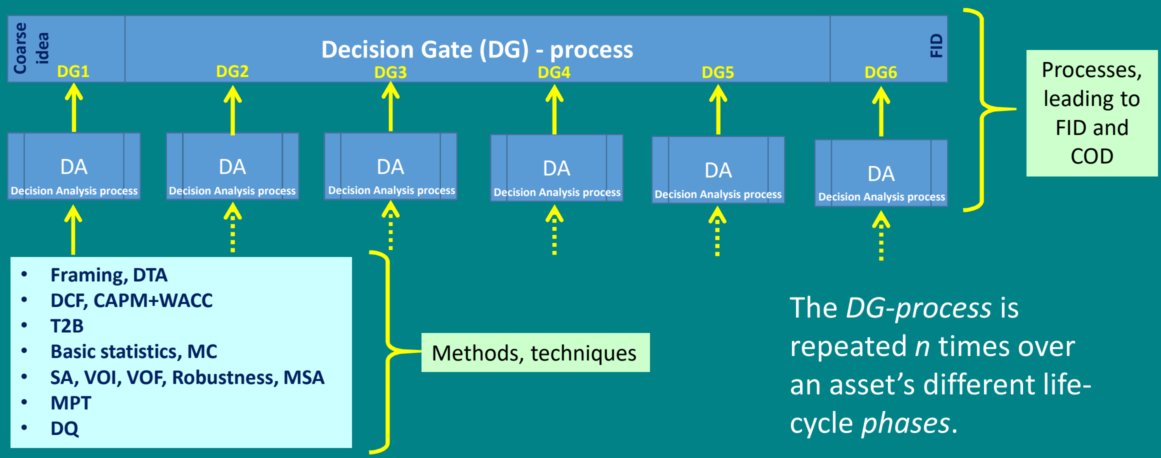
Company decision-support processes & methods



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Main assumptions of tool

- Technical / economic:
  - Physics / technical: homogeneous primary porosity reservoir, steady-state reservoir *liquid* flow into well (→no pressure depletion: injection = production; no reservoir steam directly entering the well), dynamic skin-build-up around all wells, simplified well VFP, temperature depletion due to cold water breakthrough, thermodynamics of turbine, lowest throughput constraint determines total-chain performance (reservoir → well → surface facilities → turbine → reinjection into well → into reservoir), high enthalpy / power generation only.
  - Economics: DCF analysis, pre- and post-tax cash flows operator, Government Take.
  - Planning: decision-gate process, asset maturation process, drilling/workover rig planning including well success rate and (re-)stimulation of wells, maintenance, turbine replacement, incremental field development and field abandonment / transfer of liability after mandatory monitoring period.
- I / O:
  - All input variables can be assigned an uncertainty range (pdf).
  - Output can be displayed as histograms of Key Performance Indicators (including all statistics), or as probabilistic time-series (p_{90}-p_{50}-p_{10} etc.).
  - Output includes a series of diagnostic graphics, sensitivity analysis and I/O automatic reporting.
- Software: XL and Crystal Ball (Oracle™).

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Input

Geological and flow variables		Units
Total area of reservoir (km2)	2.75E+01	km2
Formation thickness (m)	1251.51607	
Reservoir rock porosity (%)	10%	
Rock density (kg/m3)	3060.49239	
Rock specific heat (kJ/kg*C)	0.80134812	
Permeability (mD)	23.7694459	mD
Reservoir temperature (°C)	296.318239	
Reservoir pressure (Pa)	2.66E+07	Pa
Flowing bottomhole pressure, production well (Pa)	1.92E+07	Pa
ΔP from bottomhole to tubing head, prod. well (Pa)	1.34E+07	Pa
ΔP from flashing chamber, if not vapor at tubing head (Pa)	1.00E+06	Pa
Pressure after turbine (Pa)	5.00E+05	Pa
Reinjection pressure (at injector wellhead) (Pa)	5.00E+07	Pa
Wellbore diameter (m)	0.4	m
Tubing inner diameter (m)	0.25	m
Tubing surface roughness (mm)	0.0457	
Initial and post-workover **prod.** well skin factor	3.57140785	
Initial and post-workover **inj.** well skin factor	1.24788092	
Yearly skin growth factor for **prod.** wells (positive number)	1.00	
Yearly skin growth factor for **inj.** wells (positive number)	2	
ΔT of produced fluids from reservoir to tubing head (°C)	14.3912753	
Minimum allowable temperature at tubing head (°C)	210	
Average ambient temp (°C)	10	

Production variables	
Select units for the loadtime per year:	Fraction
Loadtime per year, as a fraction	0.87
Select if appraisal and explor. wells are reused for inj.	Yes
Producer / Injector ratio	1.00
Completion interval of well ('h' in kh/μ-factor) (m)	547.8180467
Pump e-consumption (kW)	1000
Select conversion efficiency (MWth to MWe) source:	Sarmiento
If van Wees, enter relative efficiency -->	0.6
User-defined conversion efficiency -->	10%
Conversion efficiency value used -->	14%
Breakthrough volume before temperature decline (m3)	1.33E+08
Linear decline rate for temperature (°C/year)	2.0
Isentropic turbine efficiency	86%

Well success rate	
Select eqn. for well success learning curve	y=m*ln(x)+b
Initial well success rate (b factor)	54%
Slope of well success rate curve (m factor)	0.051142076
Select realization of the random number generator	Variable

Phasing variables	
First year of evaluation	2017
COD (First year of production)	2024.0
# yrs from end of prod to abd (monitoring)	10
Workover rig capacity - max # wells/yr	12
Workover duration (days)	30
Avg **prod.** well W/O frequency (every *n* yrs)	7
Avg **inj.** well W/O frequency (every *n* yrs)	6

Well-related costs	
Along hole depth of single well (m)	3000
True vertical depth of well (m)	1847.296571
Drill & compl. cost per **explor.** well ($ MM)	9.81
Drill & compl. cost per **appraisal** well ($ MM)	10.55
Drill & compl. cost per **dev.** well ($ MM)	8.64
Drill & compl. cost per **injection** well ($ MM)	5.21
Well stimulation cost ($ MM)	1.75
Workover cost per well ($ MM)	1.48
Well opex ($ MM/well/yr)	0.29

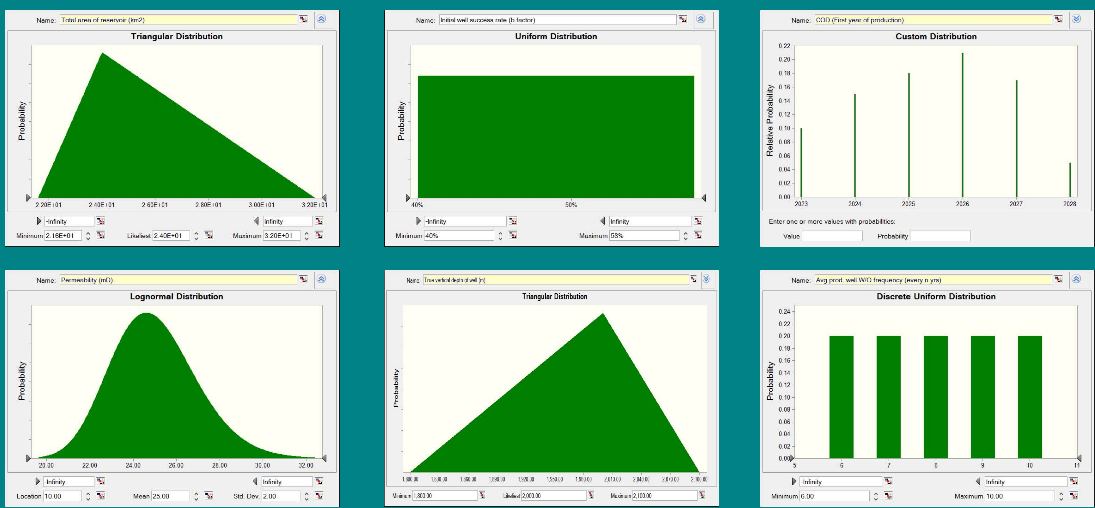
Economic variables	
Variable water opex ($/m3 water)	0.127068664
Royalty (% of electricity sales)	2.5%
Is royalty tax deductible?	No
Corporate tax (% taxable income)	25%
Select type of depreciation scheme:	DDB
Years to depreciate	10
Salvage value of depreciated asset (%)	10%
Capex multiplier	1.00
Fixed opex multiplier	1.00
Select O&M costs calculation method:	Fraction
O&M yearly costs (fraction of capex)	0.01
Discount rate (%)	13%
Discounting reference year	2017
Select who pays for connection to grid:	TSO
Targeted economic life (years)	50
Select electricity sales per MWh tariff:	Fixed
Fixed e-sales/MWh tariff ($/MWh)	90.00

Economic variables (cont'd)	
# Max well-slots per cluster	5
New well cluster capex if # well-slots exceeded ($ MM)	7
Field shut-in: max. allowable # years in row @ NCF<0	4
Select field abandonment cost calculation:	Percent
Field abandonment cost ($ MM)	200
Field abandonment cost (% cum capex)	12%

Surface facility variables	
Max flow through surface facility (m3/s)	10
Select turbine O&M cost method:	Constant
Cost of replacement turbine ($ MM) -->	50
Hrs until turbine needs replacement -->	100000

- Many comments to help user complete input sheet and interpret output

Input of uncertain variables (some pdf examples)



Geothermal field - geological, technical, planning and economic input variables

Time-series input:

B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
Cash-in items	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Define electricity sales per MWh tariff above	60.00	60.00	60.00	60.00	60.00	60.00	70.00	70.00	70.00	70.00	70.00	70.00	70.00	70.00
Other tariffs received ($ MM)									40.00	40.00	40.00	40.00	40.00	40.00
Other cash-in ($ MM)									50.00	40.00	20.00	10.00	5.00	
Cash-out items ($ MM)	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
CAPEX (read comment!)														
Scoping phase ($ MM)	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Consultancy costs														
Survey costs	(30.00)	(10.00)	(5.00)											
Transactions to government	(0.50)	(1.00)												
Other costs														
Exploration phase ($ MM)	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Survey costs				(30.00)										
Nr. of exploration wells to attempt				2										
Exploration drillex				(19.6)										
Transactions to government														
Other costs														
Appraisal phase ($ MM)	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Survey costs				(30.00)										
Nr. of appraisal wells to attempt					2									
Appraisal drillex					(21.1)									
Transactions to government														
Other costs														
Initial development phase ($ MM)	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
FEED (Front-End Engineering & Design)					(20.00)									
Detailed engineering					(50.00)									
Nr. of initial development wells to attempt							1	2						
Initial devt. drillex							(8.6)	(17.3)						
Transactions to government														
EPC - initial surface facilities costs					(100.00)	(75.00)	(50.00)	(20.00)	(10.00)					
Grid connection capex														
Other costs					(30.00)	(25.00)								
Incremental devt phase ($ MM)	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
FEED (Front-End Engineering & Design)														
Detailed engineering														
Nr. of incremental development wells to attempt									2	2	2	2		
Incremental devt. drillex									(17.3)	(17.3)	(17.3)	(17.3)		
Transactions to government														
Surface facilities														
EPC - incremental facility costs etc.														
Other costs														
Total capex, excluding multiplier ($ MM)	(30.5)	(11.0)	(5.0)	(79.6)	(221.1)	(100.0)	(58.6)	(37.3)	(27.3)	(17.3)	(17.3)	(17.3)		
OPEX ($ MM)	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Fixed opex (not related to prod, # wells)	(5.00)	(5.00)	(5.00)	(5.00)	(5.00)	(5.00)	(5.00)	(5.00)	(5.00)	(5.00)	(5.00)	(5.00)	(5.00)	(5.00)
Fixed O&M costs														

- Time-series input
- Per life-cycle phase

Output KPIs

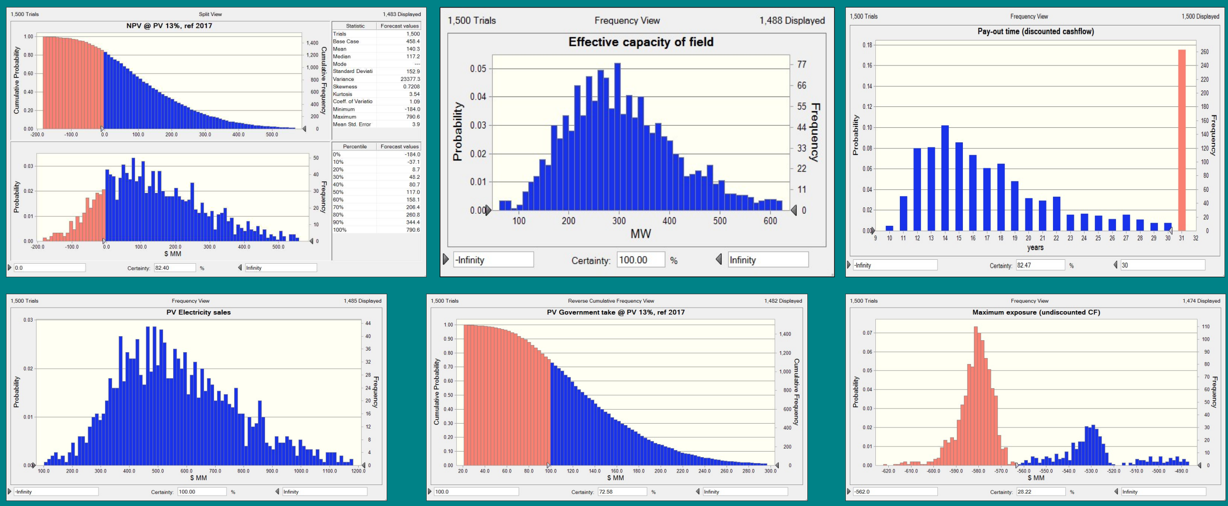
Project Key Performance Indicators Hotrock

Discount rate = 13%; Average flow = 1565.30 L/s; 5 wells/platform; Prod : Inj ratio = 1.00

Royalty = 2.5% & not tax-deductible; Tax = 25%; Depreciation period = 10 yrs

KPI	Value	Unit	Comment
Cumulative electricity produced over evaluation period	64.6	TWh	
PV Electricity sales @ PV 13%, ref 2017	797.9	$ MM	
PV Government take @ PV 13%, ref 2017	193.1	$ MM	Note: no Loss Carry Back implemented / Govt may use different discount rate
NPV @ PV 13%, ref 2017	303.8	$ MM	
IRR	20.9%		
Maximum exposure (undiscounted CF)	-536.2	$ MM	Max. undiscounted exposure in year 2024
Maximum exposure (discounted CF)	-335.3	$ MM	Max. discounted exposure in year 2024
PIR undiscounted	5.43	ratio	
PIR discounted	0.82	ratio	
PV Capex / MW	0.72	$ MM/MW	For power plants, a rule of thumb is $2 million/MW installed capacity
Unit Technical Cost (undiscounted cost/MWhe)	19.20	$/MWhe	
Unit Technical Cost (PV cost/MWhe)	7.18	$/MWhe	[PV(capex+opex) / cumulative MWh produced over life-time]
Unit Technical Cost (PV cost/PV MWhe)	51.50	$/MWhe	[PV(capex+opex) / PV(MWh produced over life-time)]
Levelized Cost of Electricity (PV break even price)	55.05	$/MWhe	Use Data-What If Analysis-Goal Seek" (set NPV=0); see comment cell A16
Pay-out time (undiscounted cashflow)	10	years	
Pay-out time (discounted cashflow)	13	years	
Nr of add'l well clusters constructed	2	well clusters	1st add'l well cluster operational in year 2026
Nr of production + injection wells drilled	15	wells	@ avg. gross liquid rate per prod well = 1565.3 L/s
W/O rig availability: max. # wells / yr exceeded?	No	year	
Productive life of asset	23	years	Still producing at end of evaluation period
Effective capacity of field	403	MW	
Upside potential	0	MW	Effective MW of field > max theor. power capacity ref. Sarmiento

Output KPI histograms (+ many more)



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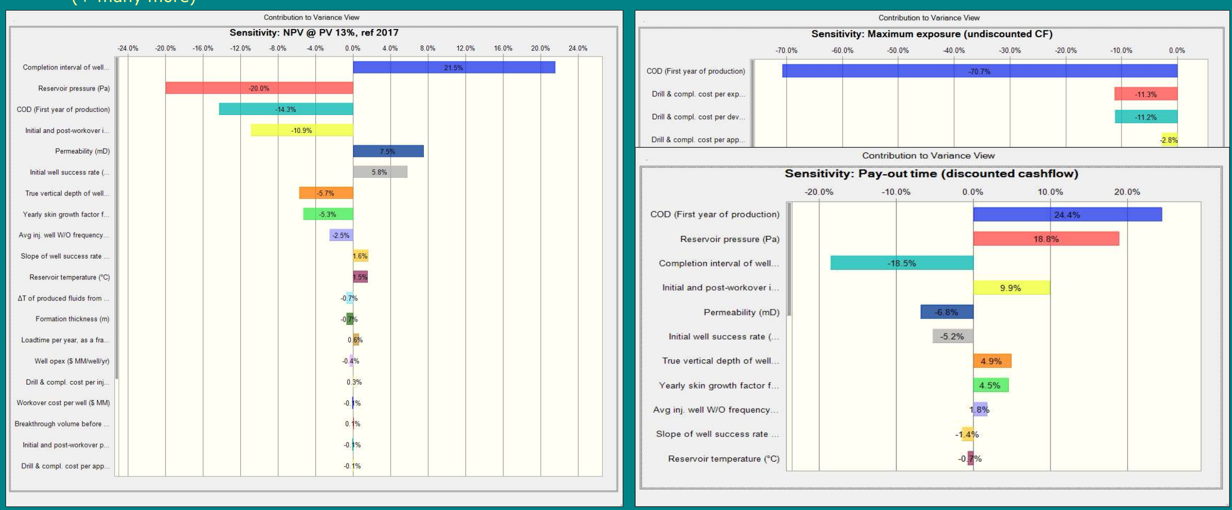
Output KPI multivariate sensitivity analysis
(+ many more)



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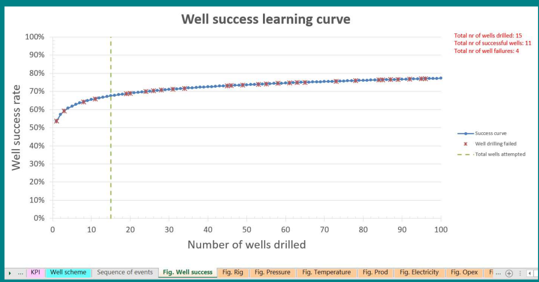
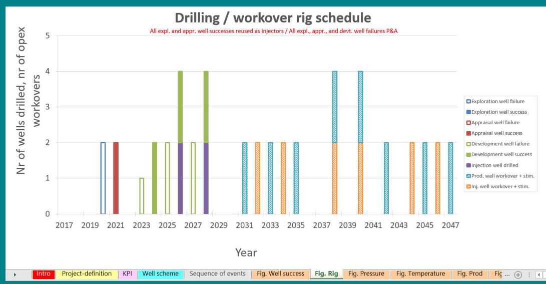
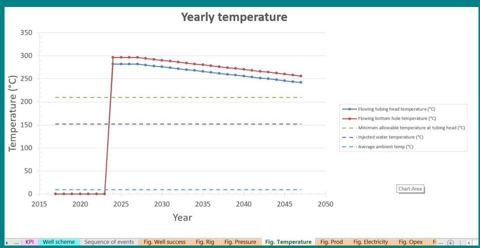
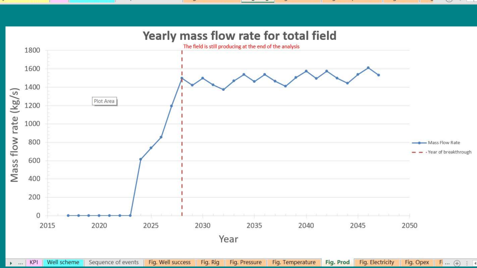
Output diagnostic plots – 1 (per realization)









Short demonstration of tool

- Test case: dummy values filled in for input parameters
- No real Indonesian case yet
- Run through main worksheets
- Run tool using Crystal Ball
- Do multi-variate sensitivity analysis

- Go to demo

- Further detail on input/output in next slides

Main features of XL tool

- Life-cycle technical-economic tool, covering exploration-appraisal-development-production-incremental development-decommissioning phases of asset.
- Yearly time-steps
- Heat-In-Place volumetric analysis
- Drilling success rate and learning per phase (WB correlations)
- Darcy steady-state *liquid* flow equation for production + injection in multi-wells
- Vertical Flow Performance in wells (better VFP under development)
- Conversion efficiency modelling of heat to electricity in surface facilities
- Heat depletion / cold-water breakthrough in production wells
- Cash flow projections and decision metrics (KPIs)
- Graphical displays
- When Crystal Ball installed, full probabilistic and sensitivity analysis

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Further features of XL tool

- Introductory worksheet to explain main modelling principles.
- Many operational features, such as drilling sequence, workover frequency due to skin build-up, effect of stimulation job, downtime penalty of non-producing wells, dynamic injection well constraint (e.g. due to skin / scale build-up), etc.
- Many comments to explain variables, suggest ideas on how to use model, references with Indonesian information etc.
- KPI worksheet giving a wide range of decision metrics. When used with Crystal Ball, KPI-histograms can be computed, allowing a wide range of further analyses. Also, probabilistic time-series can be computed.

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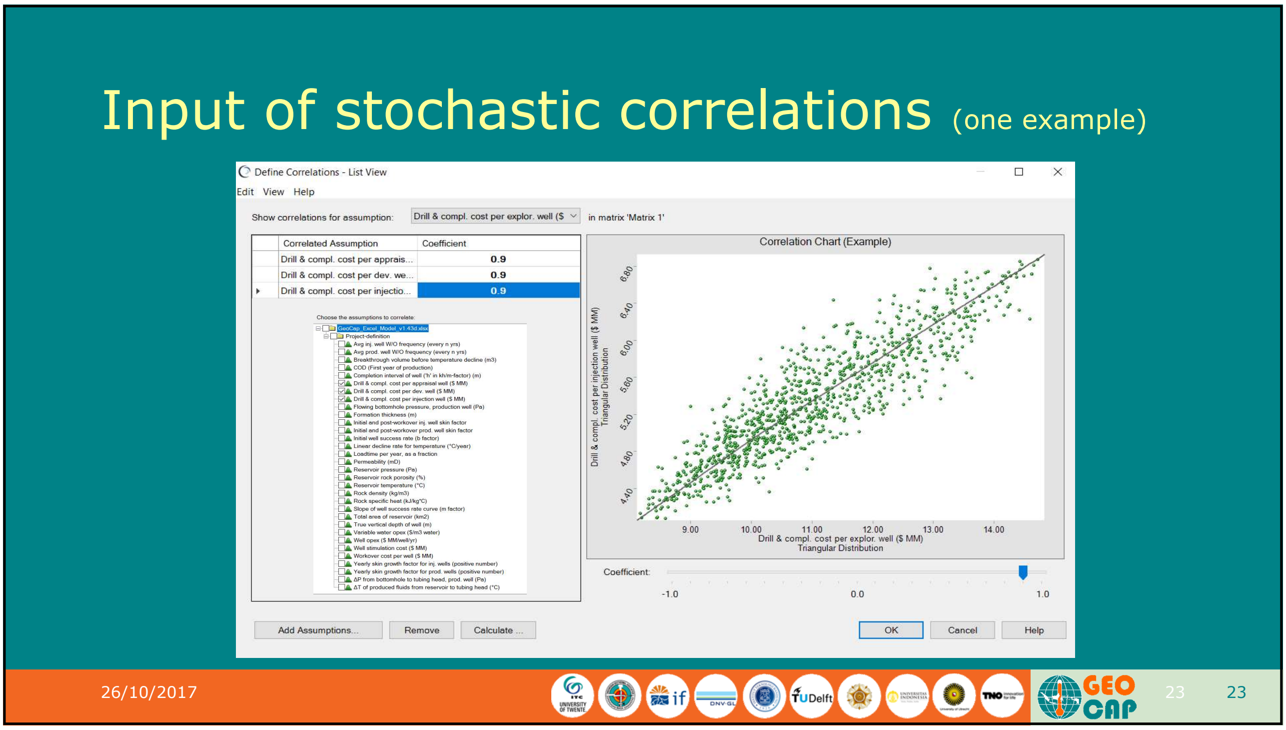
Input of stochastic correlations (one example)
Define Correlations - List View
Show correlations for assumption:
Correlated Assumption
Coefficient
Correlation Chart (Example)
Add Assumptions...
Remove
Calculate ...
OK
Cancel
Help
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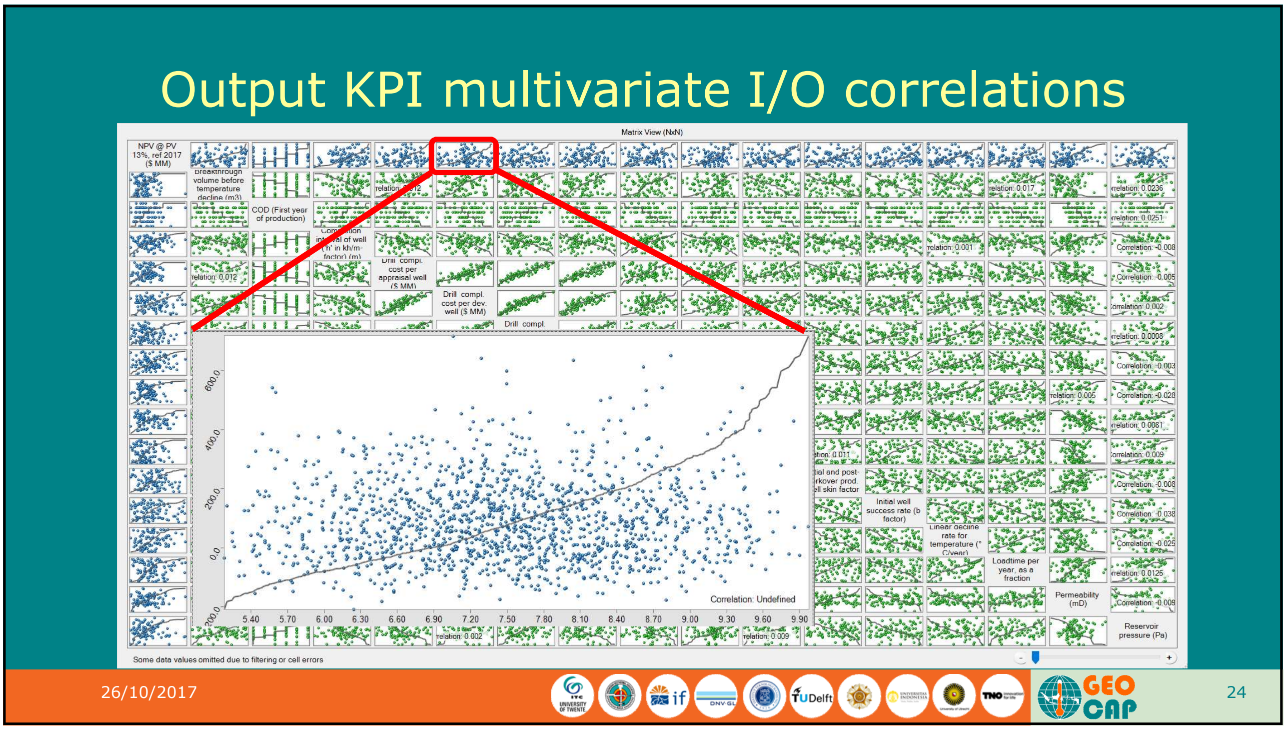
Output KPI multivariate I/O correlations
Matrix View (NxN)
Correlation: Undefined
Some data values omitted due to filtering or cell errors
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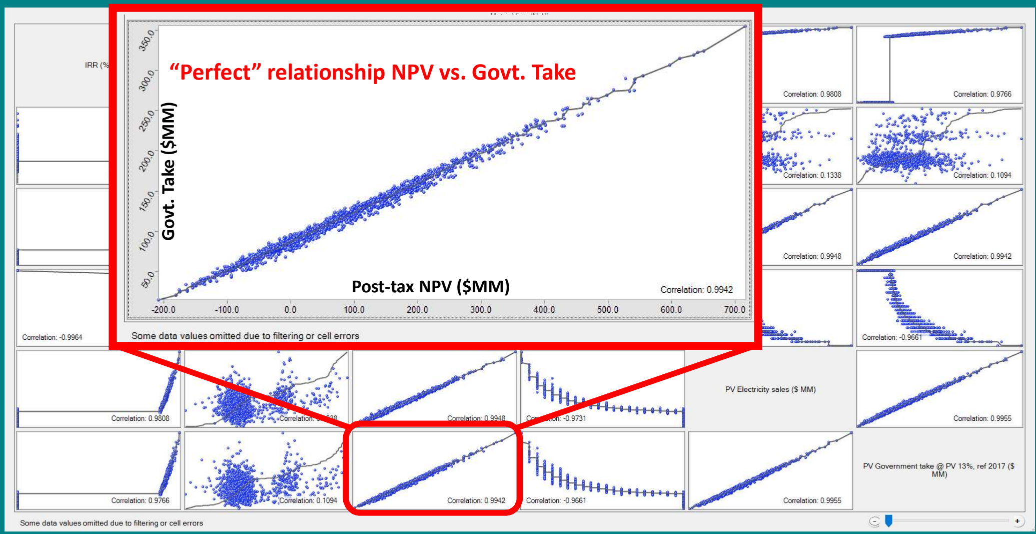
Output KPI multivariate O/O correlations



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Output diagnostic plots - 2 (per realization)

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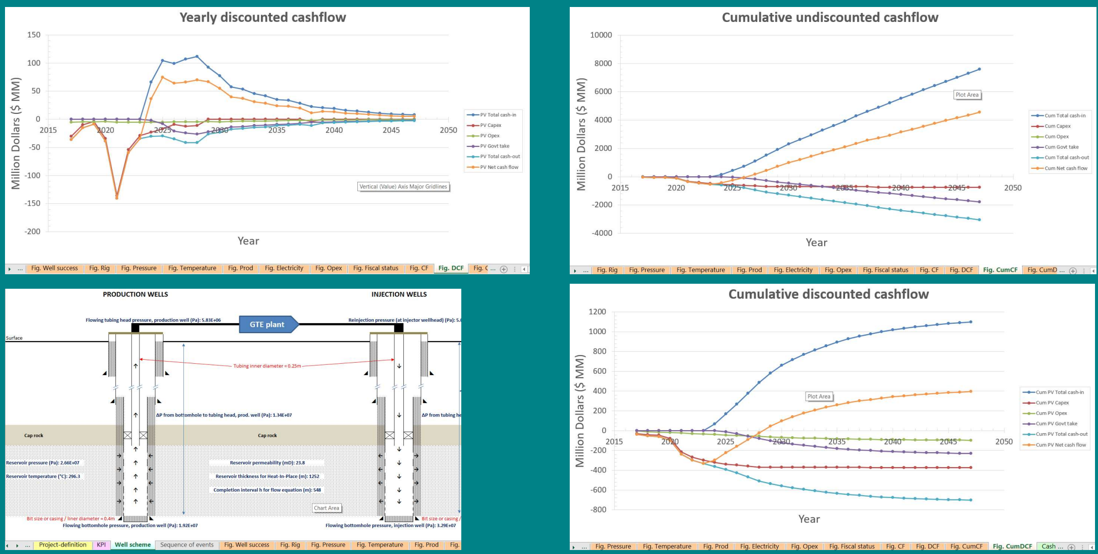
Output diagnostic plots – 3 (per realization)



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Further plans

- Validate tool + suggest improvements (ITB)
- Develop realistic case study (IF Technology + ITB)
- Use tool in WP1.07 course
- Depending on feedback Indonesian GEOCAP partners, decide whether and how to maintain tool

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Discussion (1)

- The tool has a *time resolution of one year*. All production wells are assumed to be identical and to be worked-over (stimulated) in a fixed user-defined frequency. Ditto for injectors. This causes the production and cashflow profiles to be rather *noisy*.
  - In practice, the operator would smoothen the profiles by shifting operations in time, and by exploiting differences between wells. The tool is therefore not fit for detailed operational / capacity planning, however for coarse planning and for long-term economics the tool should be reasonably adequate.
- Obviously, the tool has many limiting assumptions. But again, the tool's main purpose is *education*.

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Discussion (2)

- The current model is only a prototype aimed at triggering a discussion on what precise functionality would be required for an easily accessible & applicable, open-source XL tool.
- Discussions should be held in a language that is sufficiently precise for software developers, building on the functionality / concepts of the tool that are already there. Wishes must be translated into workable solutions, these must then be translated into (improved) code. One must understand the inner workings and principles/assumptions of the current version to suggest workable improvements.
- One should understand the *trade-off between precision and accuracy*. XL will not give a very precise model, however it may be *accurate* in the sense that the *mean of the output distribution is close to reality*, and that the *range of the output distribution reflects the uncertainties one might expect*. A precise simulation tool (e.g. finite difference or finite element, with many iterative matrix computations) will not be able to do the uncertainty analysis comprehensively (too CPU intensive). Moreover, such tools are highly demanding in terms of required skills to run the tool. An XL tool is much more accessible and may give a valid first impression of a project subject to large uncertainties. And: *open source*!
- No more GEOCAP budget left for further extending the tool. Finances would have to come from elsewhere.

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