Decision analytics for infrastructure project design under uncertainty – case study

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Embodied carbon is the overall CO_2 emitted in the construction phase of an asset life cycle, including emissions from the production of materials used in construction (e.g. CO_2 emitted by earthworks, manufacturing concrete and steel used in the structure of a bridge). Use phase carbon refers to CO_2 emissions associated with the use of an asset (e.g. emissions of vehicles crossing the bridge every day over the bridge lifetime).

We consider the problem of determining the optimal trade-off between embodied and use phase carbon emitted in relation to a major infrastructure asset, more specifically a railway tunnel (Jackson & Brander, 2019). Jackson & Brander (2019) showed that approximately 91% of total embodied carbon emissions associated with the construction of a railway tunnel come from concrete, steel rebars and earthworks. By utilising emission factors from existing libraries and by modelling two possible scenarios (tunnel diameter of 8.8m and 9.9m), they were able to estimate average embodied carbon emissions for each scenario.

However, it is recognised in the literature that carbon emissions are subject to uncertainty (Kang et al., 2015). For instance, concrete emissions in kg per m^3 can be expressed as a lognormal random variable with parameters mu=5.43 and sigma2=1.22. As it is possible to observe in Figure 1, the variability of these emissions is substantial.

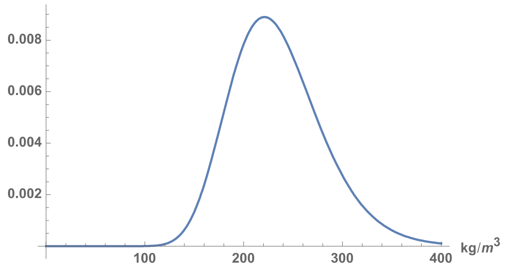


Figure 1: lognormal emissions (kg/m^3) associated with concrete production (Kang et al., 2015)

Ignoring uncertainty associated with concrete and steel production, or earthworks may lead to considerable underestimation of **embodied** as well as **use phase** carbon emissions for an asset. For instance, in the case of the (smaller) tunnel with diameter of 8.8m, a Monte Carlo analysis reveals substantial fluctuations about the average emissions reported by Jackson & Brander (2019), see Figure 2 and Figure 3.

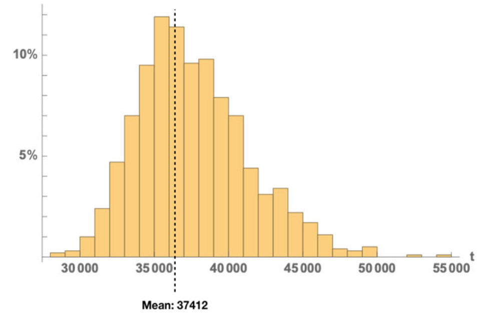


Figure 2: concrete emissions for the "small tunnel" scenario

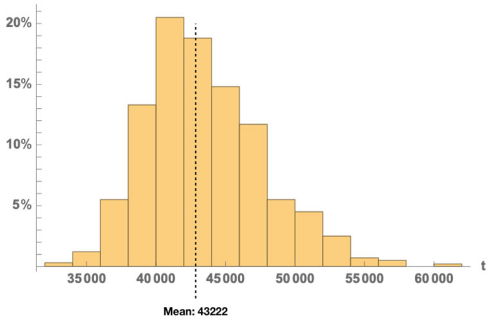


Figure 3: concrete emissions for the "large tunnel" scenario

A similar analysis can be carried out in relation to use phase carbon emissions. Trains are propelled by electricity, to model emissions associated with electricity production, we built upon the analysis in Jackson & Brander (2019), which is based on the Department for Business, Energy & Industrial Strategy (BEIS) CO_2 emission forecast from 2026 onwards (kg/kWh), see Figure 4.

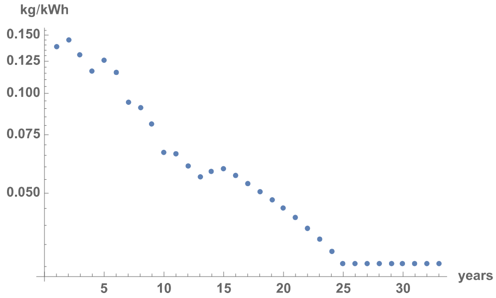
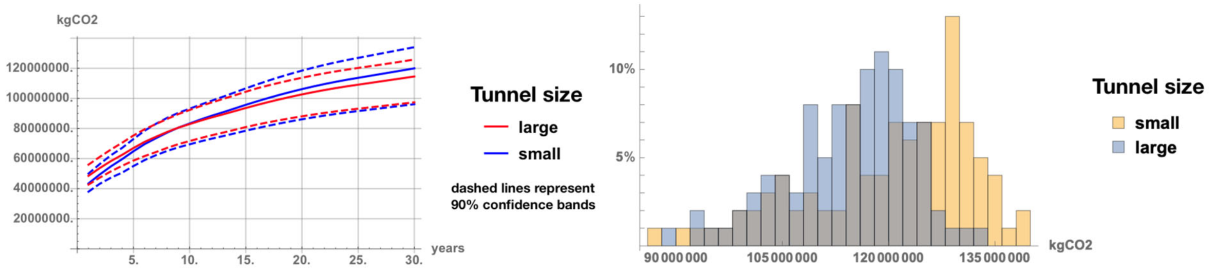


Figure 4: Department for Business, Energy & Industrial Strategy (BEIS) CO_2 emission forecast from 2026 onwards (kg/kWh)

In the case of use phase carbon emissions, random variables to be factored in our analysis may include the number of trains passing through the tunnel every day, the speed of these trains etc.

More specifically, we extended the trade-off analysis in Jackson & Brander (2019) between embodied and use phase carbon emissions by building a decision-support model based on the techniques illustrated in Rossi et al. (2017). The model considers lognormal distributed concrete emissions – instead of a constant average emission factor; and train speed in tunnel uniformly distributed between 50km/h and 300km/h – instead of constant average speed of 250km/h. The resulting analysis revealed that a larger tunnel leads not only to 5% average emission reduction over 30 years of service, but also to 44% reduction in uncertainty (i.e. variance) associated with lifetime emissions, see Figure 5. This result is surprising. In contrast to other settings (e.g. Markovitz's portfolio management) in which an improvement in, say, expected return on investment, generally leads to higher variance associated with these returns; we here observe that the decision which leads to lower expected emission (i.e. larger tunnel) has also the advantage of reducing uncertainty (i.e. variability) on future emissions.



Overall emissions during asset lifetime

Overall emissions after 30 years of service

Figure 5: integrated (embodied + operational) analysis

Acknowledgements

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References

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Kang, G., Kim, T., Kim, Y.-W., Cho, H., Kang, K.-I., 2015. Statistical analysis of embodied carbon emission for building construction. Energy and Buildings 105, 326–333. https://doi.org/10.1016/j.enbuild.2015.07.058

Rossi et al (2017). Declarative statistics. https://arxiv.org/pdf/1708.01829.pdf

Work Package 5 – Research Outputs

Research articles

Rossi et al (2017). Declarative statistics. http://arxiv.org/abs/1708.01829

Software

Syat: a Declarative Statistics library.
Open source, available at: https://gwr3n.github.io/syat-choco/