DESIGN OPTIMISATION FOR CARBON SAVINGS ON THE NEW LINES OF THE COPENHAGEN METRO

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ABSTRACT:

The Copenhagen metro, Metroselskabet, has an ambition to reduce the carbon footprint of new constructions by 50%. The baseline is set as the as-built design of the newest sections of the existing system, constructed with current materials and their emission factors. The most recent line opened in June 2024. To achieve this, Metroselskabet is applying a process of active carbon management.

Carbon management must be seen in a holistic sense. This process must run from the very start of a project through to its conclusion. If any part of this process is omitted or weakened, there is a risk that the desired carbon reductions will not be achieved.

Innovation is essential if we are to build better metros in the future. A dedicated innovation team is exploring all parts of our system and ways to improve them, including reducing embodied or operational carbon. This paper will present examples of innovations and design optimisations which have made significant carbon savings.

The carbon accounting is driven by BIM data from an early stage of planning (i.e. the concept design for the Environmental Impact Assessment). The granularity and extent of this data naturally increase as the design progresses. The carbon account is aligned with the cost estimate so that the impacts of each one on the other is transparent. During construction, the plan is to continue this by monitoring the carbon “spend” via normal progress monitoring which is based on the Bill of Quantities and As-Built BIM data.

While this paper focuses on the benefits of design optimisation on the carbon footprint, the process of critically re-examining the design has also led to improvements in many other areas such as operations, passenger experience, construction cost and sustainability more broadly, despite the fact that the current metro is already regarded as very successful.

1. INTRODUCTION

Metroselskabet operates the Copenhagen Metro which consists of 44 stations and 43 km of track. Driverless trains run on all 4 lines. The lines are mainly underground but there are significant lengths running on elevated structures. About 126 million passengers used the system in 2024, rising to 135 million in 2025 and this is growing each year. We have ambitions to extend this network with an extension of M4, further into Nordhavn, and a new M5 line from the main central station through new development areas in the east of the city such as Lynetteholm.

The M4 extension will encompass 2 new elevated stations and 1.6 km of twin track, mainly on viaducts in the brownfield area of the “North harbour”. An Early Contractor Involvement contract was signed in October 2025. The concept design is well underway.

The M5 project comprises of up to 9 stations and 16 km of twin track. The Environmental Impact Assessment for Stage 1 was approved in 2025. This comprises 5 underground stations and 1 overground one, along with the Control and Maintenance Centre. Tendering for the construction contracts will begin in 2026.

In 2016, Metroselskabet signed the UN Global Compact and develop the Corporate Social Responsibility (CSR) policy on the basis of the UN Sustainable Development Goals (UN SDGs). Amongst other things, this has led to an ambition, enshrined in the business strategy, to reduce the carbon footprint of new constructions by 50%. This has been accompanied by a cultural shift within our organisation so that sustainability plays a much greater role in decision making now. While the rest of this paper will focus on detailed aspects of carbon management, it is important to recognise that the success of that relies on fostering that supportive culture.

Sustainability is a broad subject which traditionally is seen as encompassing 3 areas: financial; social and environmental. This paper will focus on one of aspect of environmental sustainability: the carbon footprint. The other aspects are equally important and Metroselskabet works actively in all fields of sustainability.

2. KEY STEPS IN CARBON MANAGEMENT

2.1 INNOVATION

The definition of insanity is sometimes described as doing the same action repeatedly and expecting a different outcome. The construction industry is in many ways one which has been highly optimised from a financial perspective. One might even argue that the short-term focus on money has distorted the industry, leading in fact to higher risks and higher outturn costs. The common debate over how much money to spend on the geotechnical investigation for a tunnel is a good example of this.

In this context, it is unrealistic to expect that the "business as usual" approach will be able to meet all the usual demands and also deliver a lower carbon footprint. Innovation is essential. Metroselskabet has set up an innovation department to drive improvement in all aspects of our business – from safety to passenger experience and, of course, carbon. Many organizations aspire to embed innovation into their business. The formation of a dedicated innovation department in Metroselskabet added focus to the subject and arguably extended its impact, compared to other approaches.

A wide range of topics have been studied by the Innovation Department independently of individual projects, ranging from timber viaducts to geopolymer concrete, from GRFP reinforcement for tunnel segments to energy recovery via regenerative braking. At the end of the studies, the suitability of the innovation is evaluated against a number of criteria, ranging from carbon to passenger experience, from risk to cost. Upon project commencement, a series of recommendations are made for implementation.

2.2 CARBON MANAGEMENT

Carbon management must start in the earliest stages of planning. Metroselskabet has developed its own high level carbon calculator for the planning phase. Based on generic elements (such as deep or shallow stations, viaducts and tunnels), a simple model of project can be built in a GIS platform. From this a wealth of data can be extracted, from journey times to construction cost estimates and an estimate of the baseline carbon footprint. This sort of tool has an inherently high level of uncertainty despite the fact that each element has been based on as-built information. 25% to 50% is the typical contingency that is added to the carbon estimates in concept design and feasibility study stages respectively. Currently we assess the A and B phases (construction and operation) over the lifetime of the project which is typically 100 years.

As soon as possible – for example, during the Environmental Impact Assessment (EIA) – the main source of data shifts to BIM. Figure 1 shows an example of part of the output from the EIA for the proposed M5. The initial BIM model has a low level of detail so it is supplemented with data from other sources such as the planning tool. By the time that the design has reached Concept level, the bulk of quantities are obtained from BIM. From that point onwards, the carbon footprint is tracked in a much more detailed spreadsheet, known as the Carbon Estimate.

One subtle but crucial step in this process is the alignment of the structure of the carbon estimate with the cost estimate. This greatly simplifies the process of evaluating options for design changes. When a change is examined, both the cost and carbon impacts can be determined easily because the basis of the elements affected is the same in both estimates. This also opens the door to the evaluation of scenarios in which a number of design changes can be combined and the impact of them on the carbon (and cost) estimate visualized.

The design teams for major projects must now have a Carbon manager to lead this field. Having a dedicated person creates a focal point – for example, for knowledge sharing and inspiration. This has led to faster and better progress in carbon reduction. The Carbon manager ensures that all parts of the design team are evaluating the carbon footprint in a consistent manner, generating their share of reductions and providing the required data for the carbon estimate of the whole project.

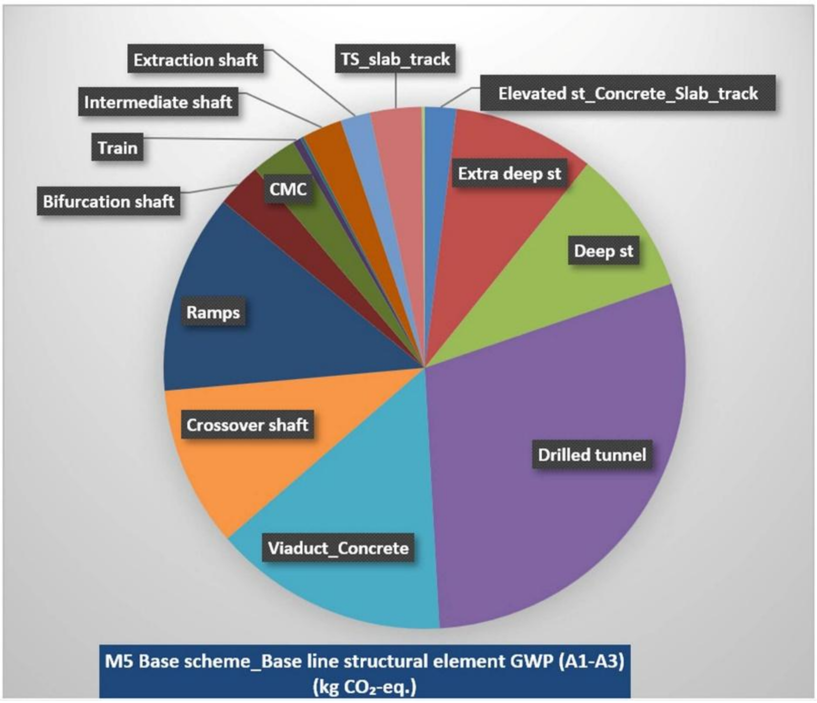

Figure 1: Breakdown of carbon footprint estimate from M5 EIA submission for the Base case alignment (for life cycle phases A1-3 – construction materials)

On the projects, the whole team has access to a live version of the carbon estimate in a Power Bi dashboard format. By clicking on individual items, anyone can drill down and interrogate the estimate. This helps inform the team about the current hot spots. The visual nature of a dashboard also helps checking as anomalies are clearly more visible. This provides a visual indication of the relative importance in terms of carbon of each element. The estimate can be examined from various perspectives, such as by structural element – down to the level of slabs and walls in a station – or by materials. Figure 2 shows one snapshot of the work in progress to illustrate the structure of the dashboard and the data presented in it.

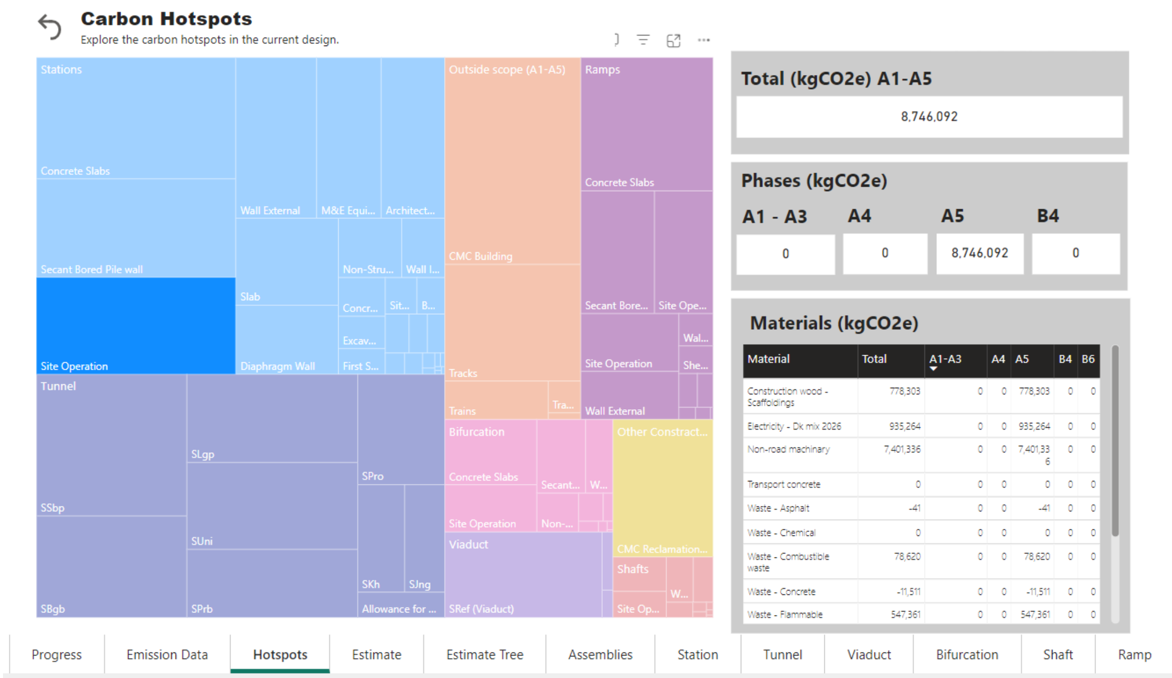

Figure 2: A screenshot of one page in the Carbon dashboard.

2.3 DEVELOPING DESIGN WITH A FOCUS ON LOW CARBON SOLUTIONS

As the design develops, the focus shifts into more and more detailed areas, from station layout to major design concepts, then to major design elements such as retaining walls and slabs and finally secondary structures such as intermediate slabs and internal walls. Similarly, one starts with the concrete strategy, the structural and durability requirements and then moves into the calculations of section dimensions and reinforcement ratios. The methodology for reducing carbon is very simple and mirrors the familiar approach in value engineering: focus on the big items first and then systematically work through the other elements. There is a hierarchy of actions:

1. Build nothing – avoid and minimize elements wherever possible
2. Build smarter – i.e. optimize the geometry and arrangement
3. Build greener – either by using materials which have a lower embodied carbon or by using low emission / emission-free equipment

In practice this is more complicated in the case of a metro because of the complex interrelationship between elements. The implications of changes in one element on other aspects – e.g. in construction or operations – must be considered carefully. On the other hand, one could say that this part of normal design work. The only difference is that carbon has now been added as a parameter in decision making.

Naturally the opportunities to reduce carbon shrink and become more difficult as the design develops – see Figure 3. For this reason, it is vital to incorporate carbon management from the earliest stages of design.

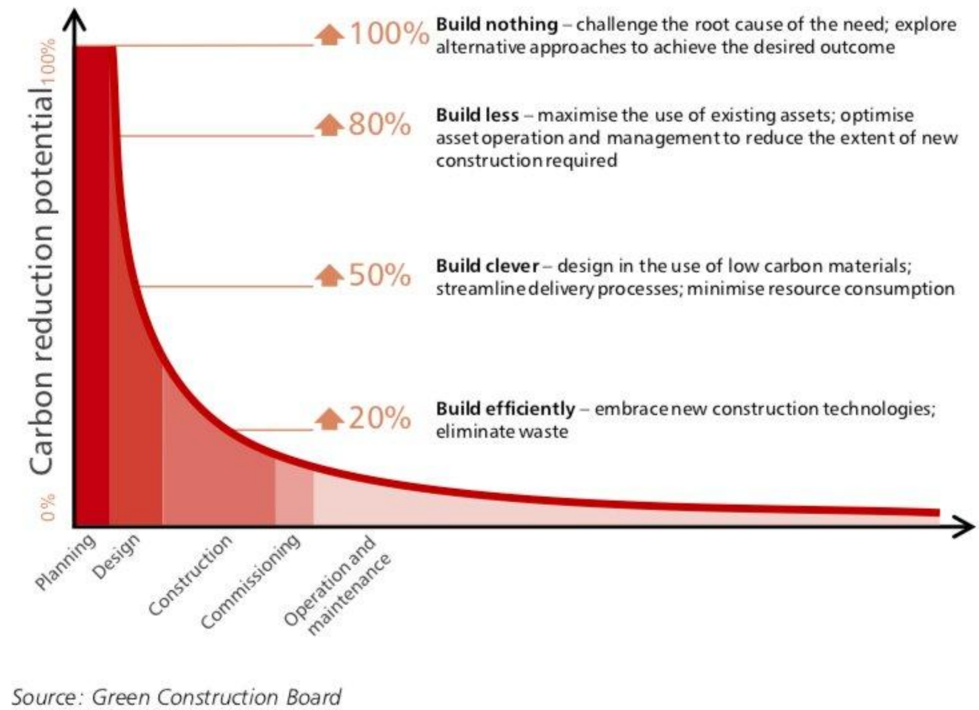

Figure 3: Carbon reduction potential vs project stage (HM Treasury 2013)

Currently the projects are making excellent progress towards the target of 50% carbon savings. Taking the M5 project as an example, the following sections will describe some of the key changes that have reduced the footprint.

2.3.1 Track layout between platforms & switches

To ensure flexibility during operations, there are a number of switches where trains can change from one track to another along the alignment. M5 has 6 of these along its 16 km alignment. Firstly, for this project, it has been decided to locate these crossovers at the stations. For the 4 underground cases, this creates an enlarged station box but it saves the construction of a separate shaft.

Previously there was a guideline which set a distance of 29 m from the end of the platform to the start of a switch. By re-examining the actual speed of trains in this configuration and a dialogue with possible suppliers, it was possible to revise this down to 16m. This reduces the length of the box by 13 m which has a large saving in concrete and therefore carbon.

This is good example of the multidisciplinary nature of metro design and how a simple requirement in one discipline can have a big impact on the rest of the project.

2.3.2 Intermediate emergency intervention shafts

According to the safety concept of the existing M3 line, if the distance between stations is greater than 1250 m, an intervention shaft is required. In fact, the system is designed so that in the event of an incident, the trains would continue to the next station and decant the passengers there. After a review of the safety case and dialogue with key stakeholders, such as the local fire brigade, it was decided that these shafts could be replaced by a cross-passage between the running tunnels.

2.3.3 Design optimization of structural elements

This is simply good engineering. However, all too often the pressures on time and budget during the design phase, coupled with a tendency to rely on simplistic design methods or conservative approaches, lead to designs which are significantly more conservative that ones that have been successfully built in the past. Much of this happens subconsciously so we must take conscious steps to counter this. Our experience has shown that by re-examining our design through the prism of carbon reduction, we have discovered many opportunities to optimize. Obviously, the reductions in quantities of concrete and steel have the dual benefits of saving cost as well as carbon. The improvements to the M5 viaduct sections and tunnel lining are good examples of this.

2.4 PROCUREMENT

Except where items have been deleted from a project, the carbon savings made during the design phase remain theoretical. The real test comes with construction. Then there is a creative tension between the desire to gain from the contractors' experience and optimise the design – for example, via a design and build contract – and the need to protect the carbon savings.

Traditionally the Copenhagen Metro has used design & build contracts. Considering design & build contracts, the client produces a reference design which contractors bid to develop into a detailed design and then build it. Our strategy is to develop a reference design which includes significant reductions in carbon, in comparison to the baseline, and to set up a contractual framework which incentivizes (and facilitates) the contractor to make further reductions in carbon.

One way to achieve this is to set a target for carbon reduction at the project level – with associated incentives and penalties – and permit the contractor the freedom to determine where best to achieve the reductions. We have successfully used carbon caps for intensive components like concrete and steel to avoid "carbon creep" – i.e. in the early phase of construction, "high carbon" solutions are adopted to satisfy other demands such as the construction programme, resulting in an increasing proportion of the savings required being pushed towards the end of the project where they are harder to realise. Regular, rigorous carbon monitoring also guards against this "carbon creep".

On the extension of the M4 line at Nordhavn, we have adopted an Early Contractor Involvement form of contract. We are jointly developing the reference design with a contractor and his designer before agreeing a more conventional "design and build" contract to construct the works. The form of contract aims to maximise collaboration between the parties – in this case, to reduce carbon.

2.5 MONITORING

Monitoring carbon during construction remains a challenging topic. Without an effective, regular check on the as-built carbon account, there is a clear risk that the reductions foreseen in the design phases may not be achieved. We are developing an automated process which will be centred on the as-built BIM data, including the actual EPDs, and driven by the normal monthly progress monitoring for payments – see Figure 4.

Monthly progress is monitored by reviewing the ongoing works and assigning a percentage complete to the items in a Work Breakdown Structure (WBS). This list of quantities mirrors the list in the carbon estimate. By aligning the WBS of the cost estimate and the carbon estimate, the progress monitoring process can produce simultaneously the information on financial spend and carbon spend.

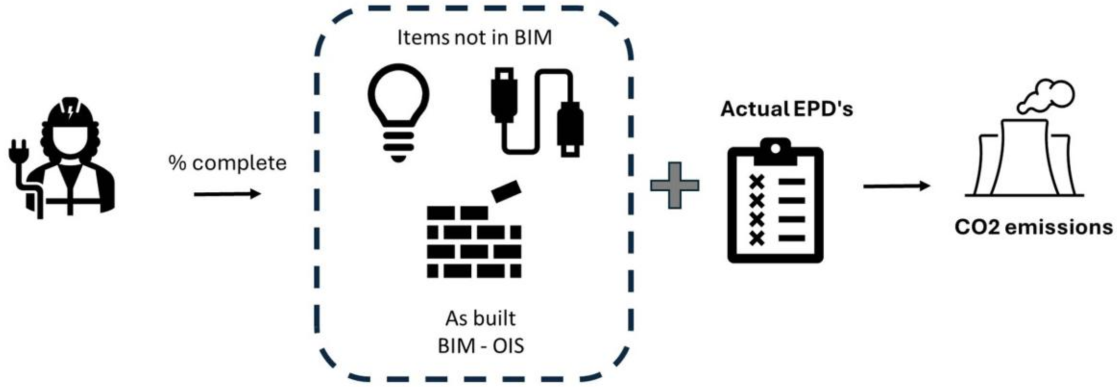

Figure 4: Proposed data flow for carbon monitoring during construction

By reducing the manual effort where possible, this will increase both the quality of the data and extent covered. While this should cover the phases A1-4 well, a significant pool of data remains to be tapped, namely the carbon expended during the construction process and waste. Fortunately, the fuel and energy consumed on each site can be recorded simply. As a first approximation, the associated carbon can be apportioned to the major elements in proportion to their fraction of the total A1-3 carbon footprint. Regarding waste, it is important that the impact of producing the material is included in the phase A1-3 along any benefit (i.e. a credit in phase A5). Waste can be a significant component of the footprint, especially for certain types of tunnelling such as sprayed concrete linings.

Another lesson from our early work on carbon monitoring during construction is that the process works much better when there is a single person responsible for reporting in the contractor's team. A Carbon Manager or Coordinator is now a requirement on these contracts.

3. CONCLUSIONS

Carbon management a journey in which we are all learning. There are many topics where we have yet to develop the optimal tools. In that spirit, we would like to share our experiences and stimulate the discussion in this area of sustainability. Metroselskabet has an ambition to reduce the carbon footprint of the construction of new metro lines by 50%, compared to a baseline of the metro lines (M3 & M4) which we have just opened. This clear goal has helped to focus attention on the carbon footprint and to inspire all parts of the project team. The previous work of the Innovation Department has also been instrumental in delivering the cultural shift required to make significant reductions in the carbon footprint. This has continued, for example, with the contractor and his designer in the Early Contractor Involvement contract for the extension of M4 at Nordhavn.

The carbon footprint for new metro lines is estimated from the earliest stages of planning. As the design progresses, the source of data shifts from generic elements which are based on historical data to quantities taken from BIM.

Progress so far on our projects in the design stages indicates that we can make significant reductions in the carbon footprint of new metros vs our baseline. A hierarchy of measures has been applied during the design, starting with not building objects, then optimising quantities and finally adopting low carbon materials. The introduction of a defined role of a Carbon Manager for each project has facilitated this process greatly. The current reference design for one project has shown that savings of 40 to 50% are possible, provided that there is sufficient time for the design to be optimised.

The next task is to ensure that this can be delivered in reality during the construction. How the contract handles carbon emissions and how the as-built carbon footprint is monitored are pivotal in order to achieve the goal on substantial carbon reductions.

4. ACKNOWLEDGEMENTS

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LITERATURE

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