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ASSESSING THE CARBON COST OF UTILITY INSTALLATION VIA MULTI-UTILITY TUNNELS (MUTs)

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Abstract: Progressive urbanization and the concomitant requirement to develop new cities fuels the need for more sub-surface utility infrastructure. Conventional methods of utility placement, i.e. open-cut trenching techniques, are expensive in terms of their many social, environmental, and indirect economic costs. This necessitates consideration of alternative construction methods such as Multi-Utility Tunnels (MUTs). However, a lack of quantification of their short-term and long-term costs and impacts (i.e. a comprehensive understanding of all the consequences of moving to MUTs) inhibits uptake. Carbon accounting, a globally important consideration, is increasingly adopted within the construction industry and could be used as a convincing argument for why alternatives such as MUTs might be a preferred method of utility placement in cities that are advancing global sustainability agendas. This paper compares carbon cost estimations of open-cut excavations with flush-fitting MUTs. The results show that although flush-fitting MUTs have much greater carbon footprints in the short-term compared to open-cut installation methods, they would save a considerable amount of carbon in the long-term (over their lifetime) by eliminating the need for numerous excavation and reinstatement (E&R) procedures, which are inevitable for repair and maintenance of buried utility services. The research reveals the tipping points in favour of flush-fitting MUTs, in terms of carbon saved, when repetitive E&R works are eradicated, to support their adoption.

1 INTRODUCTION

Global population growth, increasing urbanisation, sprawl and the emergence of new cities and towns are fuelling need for far more buried utility infrastructure. Although there are alternatives to traditional open-cut methods of utility installation, their short- and long-term cost estimation(s) are lacking. Many authors state that they should not be limited to economic costs, but broadened to include social and environmental impacts (Rogers and Hunt, 2006; Hunt et al. 2012, 2014; Hojjati et al., 2016, 2017, 2018). In contrast to economic and social costs, carbon emissions for utility works have been under-reported, primarily because they are relevant to long-term, whole-life considerations (Hunt et al., 2014), yet carbon costing is increasingly viewed as justification for changes to construction practices to account for environmental consequences of works. This research aims to justify the use of Multi-Utility Tunnels (MUTs) for utility installation as an aid to sustainable development. This is achieved by comparing the short-term (MUT construction) and long-term (i.e. maintenance, upgrading, renewal) carbon costs for utility installation via traditional open-cut methods and a newly-constructed MUT. Building on the work of Hunt et al. (2014), the carbon cost comparisons were determined for undeveloped (greenfield) and urban (high density) locations, i.e. the carbon embodied within the MUT's structure and that due to the construction process, and where the tipping point occurs such that MUTs become a preferred option in terms of carbon saved.

2 MUTs AND CARBON ACCOUNTING

MUTs can accommodate many types of utility (water, wastewater, gas, electricity, telecommunications) and represent a 'smart' and 'open-ended' approach (Rogers and Hunt, 2006). They can be constructed as flush-fitting shallow (visible), (searchable) conduits, and deep (compartmentalized) tunnels, and offer significant advantages over traditional installation methods in terms of: assured utility placement, leak detection, ease-of-access for maintenance, replacement and utilities upgrading. However, the short-term economic costs are likely to be significantly greater (Hunt et al., 2014) and there are other barriers to their adoption. Table 1 lists advantages, barriers, and possible enablers to the implementation of MUTs, showing the strongest enablers being related to locations where the utility infrastructure is independently owned and operated.

Table 1 - Advantages, barriers, and possible enablers of Implementation of MUTs (after Hunt et al., 2012)

Advantages	Barriers	Enablers
Long-term financial benefits (such as ease of maintenance, upgrading, leakage detection)	High short-term capital cost	Site owners (e.g. universities, hospitals) are able to exploit long-term benefits
Long service life of MUTs	Lack of long-term planning for utility installation	Increased flexibility for future utility installation / upgrade
Assured utility placement / avoidance of damage	Lack of funding and bodies willing to own / operate	Sustainable (social, economic, environmental) costing models
Ease of location	Poor company coordination	Change governance policies
Minimal surface disruptions at the time of maintenance	Lack of practical experience, knowledge, and case studies	Increased awareness of whole system benefits

One of the most important considerations in today's construction industry is the issue of carbon accounting; this will form an essential part of the environmental costing of MUTs. It is therefore essential to calculate and compare the carbon embodied within an MUT with that associated with traditional utility installation, maintenance, and refurbishment. According to UK Government policies, crafted to meet the Kyoto Protocol of 1997 objective of reducing CO_2 emissions by at least 80 per cent by 2050 from a 1990 baseline (Clarke, 2010), the construction industry was identified as a major contributor to the carbon emissions: it requires huge quantities of materials to be extracted, processed and transported to site, while 'operational carbon' includes emissions arising from the use and maintenance of vehicles, machines and ancillaries such as lighting and cooling equipment. Additionally, emissions like CO_2 may be 'embodied' within materials: in the Inventory of Carbon and Energy (ICE, Hammond and Jones, 2008) *"Embodied energy (carbon) is defined as the total primary energy consumed (carbon released) from direct and indirect processes associated with a product or service and within the boundaries of cradle-to-gate. This includes all activities from material extraction (quarrying/mining), manufacturing, transportation and right through to fabrication processes until the product is ready to leave the final factory gate."*

Carbon calculation methods and databases of the amount of embodied carbon of construction materials are available for different types of projects and should be considered for the carbon calculation of MUTs. However, although there are many tools and calculators for the carbon footprints in the construction industry, not all are likely to be widely applicable for construction works. This is because of the differences in energy generation methods, combined with material production and transportation procedures, in different countries, leading to different patterns of carbon emissions (Knight and Addis, 2011). In addition, several countries have no publicly available databases of carbon emissions and impacts of construction materials and activities (AlMulhim, Hunt and Rogers, 2020). Helpfully, in the UK, the Carbon Trust (2011) and the Inventory of Carbon and Energy (ICE) have published updated databases, while the Swiss database Ecoinvent (2011) is used in Switzerland, Germany and the Netherlands, the Athena Institute (2011) database is available in Canada and in the USA, there is the US Life Cycle Inventory (2011). Moreover, different industry sectors have developed their own assessment tools appropriate to their needs; for example, in the UK, the Environment Agency (2011) and the National House Building Council have developed their own tools based on the UK Carbon Trust and the Inventory of Carbon and Energy (ICE) databases. Bespoke tools for the utilities and trenchless technology industries could, therefore, be created.

2.1 Inventory of Carbon and Energy (ICE)

The University of Bath's Inventory of Carbon and Energy was developed as an open-access and reliable database of both embodied energy and carbon for construction materials, particularly in the UK construction industry (Hammond and Jones, 2011). It lists data for almost 200 construction materials extracted from reliable literature sources: peer-reviewed journal papers, technical reports and monographs based on a precise methodology; for example, Chartered Institution of Building Services Engineers (CIBSE, 2006) and Boustead and Hancock's handbook (1979). All of the literature drawn on for the ICE was consistent with Life Cycle Assessment (LCA), as recommended by the International Organisation for Standardisation (ISO). A particular feature of the ICE model is that it incorporates a simple sub-model that estimates the embodied energy and carbon for cements, mortars, and concretes according to their constitutions, thus enabling the ICE to be more flexible and accurate when using the database for real world case studies.

2.2 Environment Agency (EA) Carbon Calculator Tool

This online Carbon Calculator Tool (CCT) was created in an Excel spreadsheet format by the Environment Agency (EA) in collaboration with Jacobs Consultants. It measures the environmental impact of construction materials by calculating the embodied CO_2 of construction materials and the amount of CO_2 emitted due to their transportation, using calculations and databases taken from the ICE. The tool offers the opportunity to reveal carbon savings strategies in the planning and design stages of a project and estimate the overall carbon footprint of a finished project. The spreadsheet allows the user to enter the quantities of material used in the project, the transport distance and mode of transport (rail, road, and water). For some materials it is possible to enter more detail (e.g. the type of cement and percentage of aggregates used in a concrete mix), while the project size is used to estimate the emissions from staff personal travel. The EA tool essentially multiplies the tonnage of materials (plus unit of distance travelled) by the emissions factor associated with that particular material, to give the CO_2e or 'equivalent carbon footprint' associated with it. While the EA calculator is a generally well accepted, if far from intuitive, approach to carbon accounting, providing comprehensive results for different materials and considering impacts of both construction and other related activities, further investigation regarding its performance and applicability to MUTs is needed. Nevertheless, it can be considered an appropriate tool for benchmarking of MUT's carbon costs. Figure 1 shows an overview of the EA tool. The orange cells representing data that need to be entered into the tool by the user, and green cells indicate data which already exist as the background information of the calculator.

3 ESTIMATING THE CARBON FOOTPRINT OF UTILITY INSTALLATION METHODS

3.1 Methodology

The foundation of this research involved calculation and comparison of carbon emissions due to open-cut methods and flush-fitting MUTs using the EA CCT. A simple model for the utility tunnel was defined to enable material quantities (by weight) to be calculated, along with assumed distances from material supply source to the site and from the site to landfill. The material quantities were input into the CCT, which contains the embodied carbon for all materials considered. The figures presented in the following sections of this paper represent the embodied carbon of materials used in each utility placement method together with the transportation carbon due to material supply and waste taken to the nearest landfill, to provide generic cost comparisons. Carbon footprints of plant and equipment, staff personal travel and staff accommodation in a project were not considered in the calculations; these will be site- and project-specific and should be determined for specific case studies.

Short-term calculations (for the construction stage of utility installation) were carried out for both open-cut method and flush-fitting MUTs. Open-cut construction operations involved excavation, pipe placement and surface reinstatement, while for flush-fitting MUTs they were excavation, culvert placement and utility pipe placement. It was assumed that one 200mm diameter steel pipe (UK/EU average recycled content) was installed in the open-cut trench and the flush-fitting MUT in order to calculate the basic carbon footprint of material used in two different locations: undeveloped (greenfield) and urban areas. Calculations were then carried out for an increasing number of pipes and Excavation and Reinstatement (E&R) operations in each location to reveal the carbon production trends and to perform a sensitivity analysis of the results.

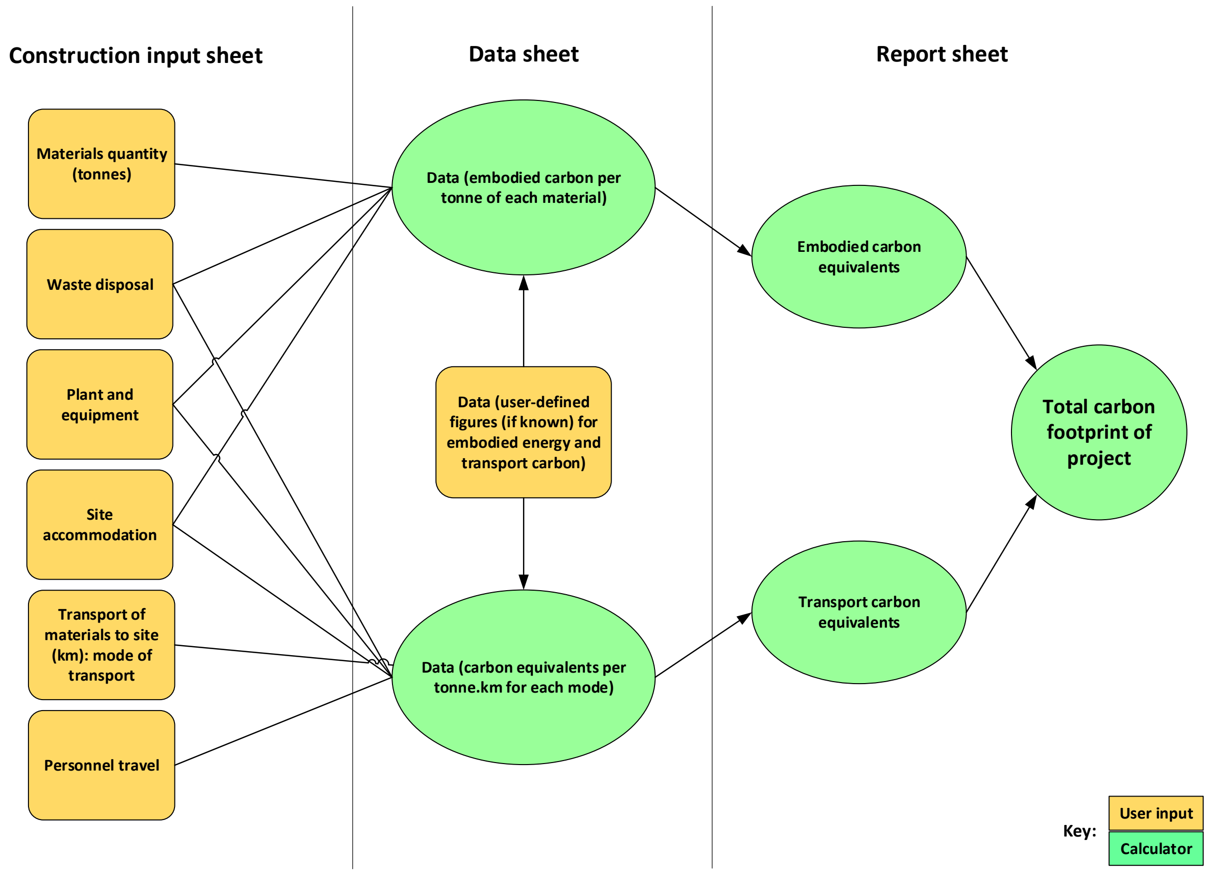

Figure 1 - Overview of the EA CCT (adapted from EA (2011))

The long-term carbon costs concerned carbon emissions due to the post-construction works involved in routine maintenance and renewal of utilities. These costs were based on the number of E&R operations typically encountered in the UK for the open-cut method compared to those involved for MUTs.

3.2 Carbon Measurements in Open-Cut Installation

In order to quantify the amount of material in an open-cut utility installation, a 1.0m x 1.0m x 1.0m trench was considered in each location (undeveloped and urban). One 200mm steel utility pipe is placed at shallow depth via open-cut trench on asphalt-covered road or footway. Soft materials were backfilled according to the location of the placement and any excess soft materials (i.e. volumes equivalent to that of the pipes) sent to landfill. Preparations of all surfaces were assumed based on the location of the work.

Distances for material transportation to and from site, which is an important factor in the CCT calculations, vary for each area. This is because the distance between construction sites and the material supply source or landfill in an urban area was assumed to be greater (25km) than the distances for an undeveloped, greenfield site (15km, see WREN, 2012). These distances were checked by Google Maps for Birmingham area as an example and found to be representative. Materials were assumed to be locally sourced to have the least environmental impact. The mode of transportation was considered to be by road in all cases.

3.2.1 Undeveloped Areas

A 1.0m x 1.0m x1.0m trench in soft soil was assumed to be excavated, and subsequently backfilled with the same soft soil, in an undeveloped, or greenfield, location (Hunt et al., 2014). A total of 1m^3 of soft soil with a density of 1.7 tonnes/m^3 was excavated (yielding 1.7 tonnes of soil). The weight of a 200mm steel pipe with outside diameter of 219mm, inside diameter of 203mm and a wall thickness of t = 8.2mm was taken to be 43kg/m length (FT Pipeline Systems, 2012). The volume occupied by the pipe was calculated to be 0.038m^3, meaning soft soil equal to this volume and weighing 0.065 tonnes was transported to landfill and 0.962m³ of soil weighing 1.635 tonnes was backfilled in the trench (Table 2).

Table 2 - Material quantities and associated carbon footprints (per metre length of installation, using the CCT) of an open-cut utility installation using one 200mm steel pipe in undeveloped areas

Material	Density (tonnes/m³)	Volume (m³)	Weight (tonnes)	Distance (km)	Mode of Transport	Carbon (tonnes/m)
Soil (waste to landfill) = volume of one pipe	1.70	0.038	0.065	15	Road	0.001
Soil (backfilled soft soil)	1.70	0.962	1.635	0	-	0.039
Pipe Material (steel)	7.80	0.038	0.043	15	Road	0.062
Total Carbon Footprint						0.102

Using inward and outward transportation distances by road of 15km, the carbon footprint figures for each material have been calculated by the CTT according to their respective weights in Table 2, yielding 0.102 tonnes, or 102 kg, of CO_2 per metre length of utility installed – the carbon footprint for open-cut installation.

3.2.2 Urban Areas

The same basic calculations were done for urban areas assuming that a 500mm (0.5m) depth of made ground surfaced by bitumen macadam, considered as mixed commercial and industrial waste with a density of 2.4 tonnes/m³ in the CCT, was removed and sent to landfill (Hunt et al., 2014). The weight of this 0.5m³ (i.e. 0.5m wide x 1m deep x 1m length) of surface material excavated was 1.2 tonnes. The underlying 500mm of soft soil was excavated and subsequently reinstated as backfill. Surface reinstatement was assumed to be carried out using a 200mm hardcore sub-base, overlain by a 300mm dense bitumen base, binder, and surface course (Hunt et al., 2014). The volume, weight and associated carbon footprints of these layers are shown in Table 3, while the pipe material and dimensions are the same as those used for undeveloped areas. Material transportation distances were assumed to be 25km for urban locations, based on average historical distances to landfill sites in the UK (Brand et al., 2017). This yielded a total carbon footprint of 0.399 tonnes, or 399 kg, of CO_2 per metre length of utility installed.

Table 3 - Material quantities and associated carbon footprints (per metre length of installation, using the CCT) of an open-cut utility installation using one 200mm steel pipe in urban areas

Material	Density (tonnes/m³)	Volume (m³)	Weight (tonnes)	Distance (km)	Mode of Transport	Carbon (tonnes/m)
Soil (waste to landfill)	2.40	0.500	1.200	25	Road	0.242
Soil (waste to landfill) = volume of one pipe	1.70	0.038	0.065	25	Road	0.001
Soil (backfilled soft soil)	1.70	0.562	0.955	0	-	0.023
Pipe Material (steel)	7.80	0.038	0.043	25	Road	0.062
Hardcore Sub-base	2.00	0.200	0.400	25	Road	0.033
Dense Bitumen base course	1.70	0.300	0.510	25	Road	0.038
Total Carbon Footprint						0.399

Comparing the findings for the two locations (undeveloped and urban), it is evident that carbon emissions increase by almost 300% due to the change in material type and quantity (materials removed to landfill and reinstatement materials supplied to site). Interestingly, the difference in material transportation distances was found to have only a small impact on the overall carbon footprint.

3.3 Carbon Measurements in MUTs

Flush-fitting MUTs, consisting of rectangular pre-cast concrete culverts with flush-fitting lids, have been used widely, such as for the 1992 Olympics in Spain and on the University of Birmingham campus (see Hunt et al., 2012). These surface access MUTs typically have external dimensions of 1.0m x 1.0m x

1.0m, and are categorised as Class 1 (pedestrian areas such as footways, walkways and cycle tracks) or Class 2 (low traffic private driveways and grassed areas). The weight of such a culvert (1,224 kg) and its flush-fitting lid (262 kg) gives a total of 1,486 kg (1.486 tonnes; Aggregate Industries, 2012), as shown in Table 4. For this research, flush-fitting MUTs were modelled as a 1.0m x 1.0m x 1.0m precast concrete culvert with a lid flush to the surface in an asphalt-covered road or footway. Excavation for flush-fitting MUTs was assumed to require 45 degree slopes on both sides for stability and to provide working space (Hunt et al., 2014). The volume of soft soil and made ground taken to landfill was consequently considerably greater than open-cut method, because of the size of excavation required and the size of the flush-fitting conduit being installed. As before, excavated material equal to the size of the flush-fitting conduit were taken to the landfill with transportation distances of 15km, and 25km for undeveloped and urban areas, respectively. However, the volumes of slope material (excavated for stability and working space) were backfilled once the culvert was in place. The pipe material and dimensions were the same as for the open-cut construction.

3.3.1 Undeveloped Areas

The volume of materials initially excavated for the 1.0m x 1.0m x 1.0m MUT with side slopes of 45 degrees was calculated to be 2m³ (3.4 tonnes), with half of this material (1m³, 1.7 tonnes, equivalent to the volume of the culvert) removed as waste and transported to landfill and the remaining 1.7 tonnes used to backfill around the MUT. The pre-cast concrete culvert with lid accounts for the largest amount of embodied carbon (0.161 tonnes of CO_2 per metre placed), while that of the pipe material remains the same as for the open-cut installation. Calculations performed using the CCT and presented in Table 4 gave 0.301 tonnes (301 kg) for the total carbon footprint of installing a 1.0m x 1.0m x 1.0m flush-fitting MUT containing one 200mm steel pipe in an undeveloped area. [It should be noted that the carbon cost of the concrete could be significantly decreased by using replacement materials (e.g. Fly Ash and Ground Granulated Blast Furnace slag) for a proportion of the cement used within the concrete mix (e.g. AlMulhim, Hunt and Rogers, 2020).]

Table 4 - Material quantities and associated carbon footprints (per metre length of installation, using the CCT) of a flush-fitting MUT housing one 200mm steel pipe in undeveloped areas

Material	Density (tonnes/m³)	Volume (m³)	Weight (tonnes)	Distance (km)	Mode of Transport	Carbon (tonnes/m)
Soil (waste to landfill)	1.70	1.000	1.700	15	Road	0.041
Soil (backfilled soft soil)	1.70	1.000	1.700	0	-	0.037
Pipe Material (steel)	7.80	0.038	0.043	15	Road	0.062
Pre-cast concrete culvert with lid	1.35	-	1.486	15	Road	0.161
Total Carbon Footprint						0.301

3.3.2 Urban Areas

The equivalent calculation for urban areas, as expected, differs only in terms of material types and quantities. The main difference in terms of material quantities is that the subsurface material in urban areas is not soft soil. In urban areas subsurface material is assumed to be made ground with a greater density (2.40 tonnes/m³) and consequently weight (EA, 2011). The 1m³ of waste material which should be sent to landfill has a weight of 2.4 tonnes. With a 45 degree slope to the excavations, this means that 1m³ of made ground needs to be excavated and removed to landfill, while 1m³ of soft soil is excavated and is used as backfill. Table 5 presents the breakdowns of material types, quantities and their carbon emissions for this case, from where it can be seen that the total carbon cost is 0.750 tonnes (750 kg) per metre length of utility installed: far more than the value obtained for a flush-fitting MUT installed in undeveloped (greenfield) conditions.

Table 5 - Material quantities and associated carbon footprints (per metre length of installation, using the CCT) of a flush-fitting MUT using one 200mm steel pipe in urban areas

Material	Density (tonnes/m³)	Volume (m³)	Weight (tonnes)	Distance (km)	Mode of Transport	Carbon (tonnes/m)
Soil (waste to landfill)	2.40	1.000	2.400	25	Road	0.484
Soil (backfilled soft soil)	1.70	1.000	1.700	0	-	0.041
Pipe Material (steel)	7.80	0.038	0.043	25	Road	0.062
Pre-cast concrete culvert with lid	1.35	-	1.486	25	Road	0.163
Total Carbon Footprint						0.750

4 EVALUATION OF RESULTS

As discussed above, total carbon footprint figures have been calculated using only one pipe (a 200mm steel pipe) as the baseline installation requirement. It can be seen from the tables that the contribution towards the overall carbon footprint of materials transportation is substantially less than the embodied carbon of materials themselves, provided that the locations of material supply and landfill for waste deposition is in close proximity (i.e. as in the UK, <25km). More importantly, it can be seen that the carbon costs of utility placement in the short-term (i.e. immediately after construction) for MUT construction is considerably greater than that of open-cut construction in both undeveloped, or greenfield locations (0.301 versus 0.102 tonnes of CO_2 per metre length of pipeline) and urban locations 0.750 versus 0.399 tonnes of CO_2). This is mainly because construction of MUTs requires considerably larger quantities of materials to be excavated then transported from site to landfill and likewise materials transported onto site (i.e. pre-cast concrete culverts, and where necessary reinstatement materials). When considering the short term, therefore, trenching is the less carbon intensive approach to utility placement.

4.1 Sensitivity Analysis

What has been presented so far was the quantification of basic carbon footprints for the installation of a single pipe via traditional open-cut and flush-fitting MUTs. However, for a more realistic assessment (i.e. throughout the lifetime of the utility pipelines) the long-term carbon costs of maintenance and renewal of utility systems should be included and combined with the installation costs of a larger number of utility pipelines since an MUT has considerable capacity. In order to investigate these long-term carbon footprints for the two types of utility installation methods, the costs E&R procedures for repair, replacement or upgrading have been considered for the open-cut case, these costs not being relevant for MUTs. This has been done on the form of a sensitivity analysis (a study of the influence of the frequency of a parameter on the model's output) based on increasing number of yearly E&Rs in both locations. The number of pipes has been increased from one to 15 for both open-cut installation and flush-fitting MUTs, with the calculations reflecting the initial carbon footprint figures using one 200mm steel pipe for the open-cut case and simply delivery of the pipe to site for the MUTs. It should be noted that whilst the size and material type for pipes (e.g. polypropylene vs clay vs cast iron vs concrete vs electrical cables) are beyond the scope of this paper, they would have an impact on the resulting calculations.

In order to study the long-term effect of maintenance, renewal and upgrading of utility pipes on the size of their carbon footprints, material and carbon calculations, determined using the CCT, for 1, 3, 6, 9 and 12 yearly E&R procedures have been carried out for undeveloped (Figure 2), and urban (Figure 3) areas.

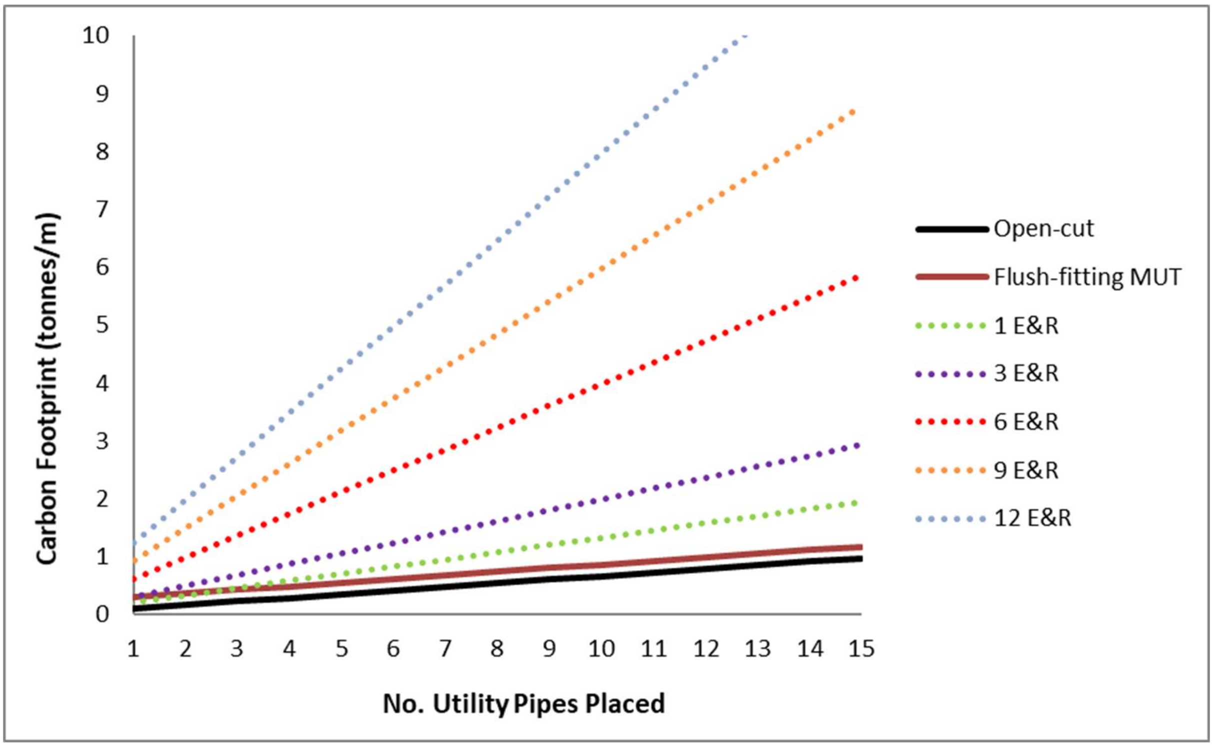

Figure 2 – Carbon costs for flush-fitting MUTs vs. open-cut with and without yearly E&Rs (undeveloped areas)

Figure 2 for undeveloped areas shows the lines for a single 200mm steel pipe installed via open-cut or in an MUT are offset and the two lines do not cross. However, when we add in the carbon costs for repeated yearly E&R required for the routine maintenance, renewal or emergency repairs with respect to open-cut the lines cross and then lie above that for the MUT option, indicating that carbon is being saved due to placement of utility pipes via the MUT option. This saving increases considerably as both the number of utilities placed and number of E&Rs rises, as might be expected. Moreover, Figure 2 shows that the tipping point(s) in favour of MUTs occur when installing 3 pipes with one E&R operation. After this threshold, the carbon savings are very much in favour of the MUT option: the greater the number of pipes installed and the greater the number of E&Rs, the greater the carbon savings. Thus, streets with high occurrences of both would benefit, in terms of carbon savings, through the adoption of MUTs. This would be in addition to the economic costs that could be saved (see Hunt et al., 2014). The same analysis was conducted using the carbon footprints for urban areas (Figure 3), with similar general observations, yet the tipping point occurs with only one annual E&R procedure for a single 200mm steel pipe. Moreover, the savings made as the number of pipes and E&Rs increases is much higher than in undeveloped areas.

5 CONCLUDING DISCUSSION

The aim of this research was to estimate the carbon costs of utility placement via MUTs compared with those for traditional open-cut excavation methods for different construction contexts: undeveloped (greenfield) and urban areas. Carbon cost comparisons have been presented for each option and location when considering both the short-term (i.e. construction stage) and long-term (i.e. post-construction stage). The data were analysed through a sensitivity analysis with an increasing number of pipes (1 to 15) and number of E&R procedures (1 to 12). The results showed that the carbon costs for construction of flush-fitting MUTs are significantly higher than those for open-cut installation in both locations when considering installation of a single 200mm diameter pipe (i.e. 750 kg carbon per metre length of flush-fitting MUTs compared to 399 kg carbon per metre length of open-cut installation in urban areas).

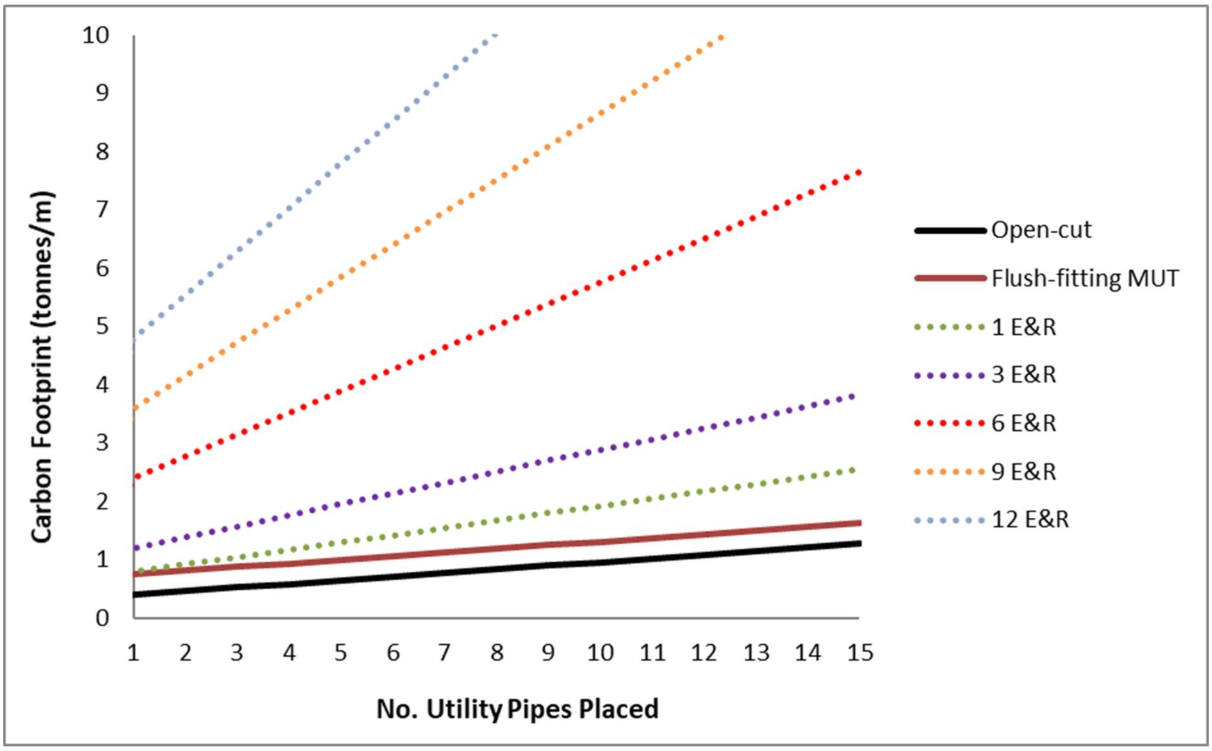

Figure 3 - Carbon costs for flush-fitting MUTs vs. open-cut with and without yearly E&Rs (urban areas)

However, in urban locations this conclusion changed when considering only 1 subsequent E&R operation even with only 1 utility present; for undeveloped areas the carbon savings were in favour of MUTs when the number of utilities increased to 3 with 1 subsequent E&R operation. Beyond these tipping points, the greater the number of pipes installed and/or number of E&R operations occurring the greater the carbon savings that can be made. In other words, a flush-fitting MUT, in the long-term, can be considered to provide an environmentally sustainable solution from a carbon costing point of view for subsurface utility placement, and the case for MUTs becomes most compelling for streets where many pipes need to be installed and/or the occurrences of E&R operations are high. This would be in addition to the significant economic costs that could be saved.

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