Optimization of Cable Routing During Construction

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Abstract

One important component of large industrial electrical projects is the placement of cables that are routed between various pieces of equipment. Many large contractors are still determining routes manually through informal walkthroughs and visual assessment of possible paths. Thus, there is significant room for automation and improvement in this process. This paper describes the general problem, relating it to established problems such as the Multi-Agent Pathfinding Problem (MAPF). We cover some of the practical complications of the real-world problem, describe several abstractions of the problem, and then discuss possible algorithms and approaches for solutions that could be deployed in the real world.

Introduction

This paper studies the *construction cable routing* (CCR) problem. There are many industrial variants of this problem that appear when handling logistics for constructing industrial facilities. A substantial portion of the effort in constructing modern industrial infrastructure lies in the electrical scope. This consists of many tasks. Two major ones are the placement of electrical cables, and the tray to support those cables; every cable must be supported by tray, and a single tray can hold many cables. However, different type of cables (e.g. high power and communication) may not be placed in the same tray.

In a CCR problem instance there are a given set of source and destination pairs in a supplied graph. The goal is to define both paths and tray for each cable, such that all cable is supported by tray, and that the total dollar cost is minimized, while ensuring safety, professionalism, and adherence to electrical code. The total cost of these industrial plants can run into multi-billion dollar budgets, and electrical scopes generally constitute 30-40% of this cost.

Cable routing solutions are typically still being solve by hand with 2D layout drawings by on-site electricians. This requires teams of highly paid professionals walking the site to identify appropriate structural elements to install tray on, installing a tray of an estimated size, laying the cable in that tray, sharing tray when opportunities are manually identified. Manually defining routes is time-consuming, which pushes back a construction timeline. Defining ad-hoc routes on-site can be wasteful for many reasons. Sometimes the size of the tray put down initially was too small to accommodate all the cables, and additional trays need to be installed to fit all of the cables. Sometimes a tray between two cable routes could have been shared so additional tray is needlessly installed. This process can be inefficient, slow, inconsistent, and hard to evaluate.

The optimization problem described in this paper shares many similarities with Multi-Agent Pathfinding (MAPF) problems. At the most abstract level, the input and output to both problems are the same - a set of start and goal locations, with output as a set of paths between these locations. However, in MAPF collisions must be avoided while in the CCR problem shared paths are preferred. The CCR problem also has a more complex cost structure.

This paper describes the real world constraints involved with the CCR problem, outlines one particular instance of the problem, and compares some early results in leveraging several multi-agent and Steiner Tree approximations to produce cable routes and supporting tray. Future challenges and steps are outlined.

Related Work

There are a range of similar problems have been studied, which we briefly cover here.

Routing Problems for Cables

Many routing problems arise when considering power distribution in electrical networks.

Power Optimization in Wind farms In wind farms, problem formulations have focused on minimizing power loss over time in addition to installation cost while minimizing cable crossings (Fischetti and Pisinger 2018). In this work Mixed Integer Linear Programming (MIPS) was used for the solver. The CCR problem differs from this in that it does not consider constraints such as voltage drop and requires routing through a more complex 3D space.

Routing Area Minimization in Circuit Boards On circuit boards, designs have focused on shortest path between terminals while minimizing the overall routing area for fabrication efficiency (Martin and Weismantel 1993). The solvers used here were geometric approximations to Steiner

Minimal Tree of the circuit board. In the circuit board setting the focus is on fabrication costs, while the CCR problem focuses primarily on the tradeoff between the cost of cable, and the tray to physically support that cable.

Robotic Cable Routing Construction Other work has considered how robots can physically install electrical cables, some of these are physical, termed the Robotic Cable Routing Problem (Jin et al. 2022). The focus here was on using robots to plan and manipulate cables into target configurations. The CCR problem is not designed for robotic installation, but for human installers and the structural elements available for routing.

Pipe Routing Planning piping in 3D is closely related to the construction cable routing problem. (Belov et al. 2021) This work involved using Multi-Agent search search approaches to minimize piping material required to connect sources and destinations. This is very similar to the CCR problem however pipes may not share routes, whereas in the CCR problem shared routes are preferred.

Previously studied variations of the CCR problem Initial variants of the CCR problem have been considered in the past (Alsakka et al. 2020), using simplified models, and independent path planning solvers to produce routes. Support for routes was not considered in the costing of these routes.

Multi-Agent-Pathfinding

The single agent shortest path problem is the problem of finding a path between two nodes in a graph, its a key problem in AI and has been extensively studied (Sturtevant et al. 2015). Multi-agent pathfinding (MAPF) (Stern et al. 2019) is a generalization of this problem where a number of agents a_k which must find paths sharing some graph G with unique start and destination nodes. There has been a flurry of work exploring multi-agent search problems (Zhang et al. 2025; Jiang et al. 2025; Bardugo, Koyfman, and Atzmon 2025; Lam and Stuckey 2025; Koyfman et al. 2025), motivated by applications in warehouses and dispatch systems. Conflict-based formulations of the problem are of interest. In robot routing physical space prevents two agents from occupying the same space. Consequently a great deal of effort has been placed into deciding routes to work around agent collision.

Conflict based search (CBS) (Sharon et al. 2015) forms the foundation of many optimal and bounded suboptimal MAPF solvers. CBS is based on a high-level tree of possible solution paths. Conflicts in that tree are resolved via single agent searches that gradually resolve these conflicts.

Prioritized planning (Belov et al. 2021) and PIBT (Okumura and Nagai 2025) are effective algorithms when bounded solution quality constraints are not needed. Prioritized planning greedily plans for agents sequentially, while PIBT searches over configurations of agents.

Steiner Trees

The process of minimally connecting a subset of nodes in a graph is associated with a problem called the *Steiner Minimal Tree Problem in Graphs*. Given a set of terminals to connect S and a graph with weighted edges G, find a tree

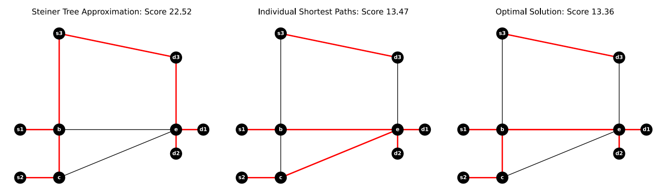

Figure 1: Different answers to a mock cable routing problem. When score is measured as the sum of distance of edges used + sum of path distances.

which connects these terminals with minimal edge weight. This problem was first formally proposed by Gauss in 1836 and was one of the 21 first problems to be shown to be NP complete in 1975 (Karp 1975), as it was an extension of the exact cover problem. Approximations of Steiner Minimal Trees have been used in problems including electrical circuit design, networking, and bio-informatics (Ljubić 2021).

Approximation algorithms often use a set of single agent searches as an approximation. Kou, Markowsky, and Berman (1981) compute the minimum spanning tree of a complete graph defined by the shortest paths between each terminal node. This has a runtime of $O(|S||V|^2)$. The Mehlorn (Mehlhorn 1988) approximation algorithm improves on this by finding the closest terminal node for each non-terminal node, which is then used to create a complete graph containing only the terminal nodes where edges are the shortest path between each terminal, and achieves $O(|E| + |V|log|V|)$. This is bound to be at linearly sub-optimal.

Finding the minimal tray utility to connect all source and destinations in the CCR problem is similar to the Steiner Minimal Tree Problem. But, solutions to the CCR problem do not need to be a tree. Acceptable solutions would also include a forest of disconnected trees, or graphs with connectivity cycles. But the problems are similar in that we are trying to minimize the number of edges that are used to connect sources and destinations, and that performant approximation methods use a composition of single agent search algorithms.

Applying either a Steiner tree approach or many of the multi-agent shortest path formulation would yields non-optimal results for the CCR problem, although the CCR problem is related to both.

Problem Formulation

In the construction cable routing problem, two categories of information are used to determine cable routes. The first is a set of specifications describing the structural layout upon which cables can be routed. The second is a set of specifications concerning the cables themselves, which includes a list of sources/destinations pairs to connect, and the types of cables to connect those source destination pairs. These must be used to satisfy a number of constraints which are detailed below. The goal is to minimize the cost of constructing these routes and any necessary supports.

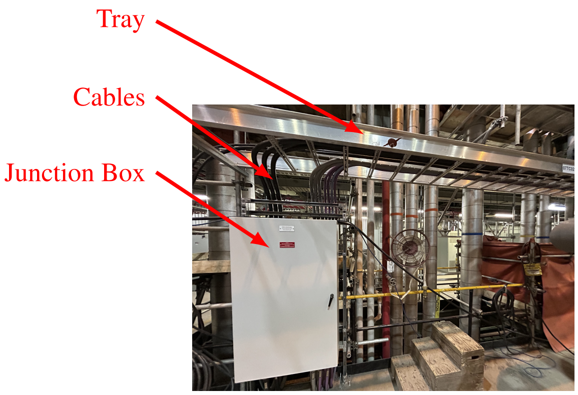

Figure 2: An example of a number of cable trays, a example source (junction box) and cable tray an industrial setting.

Overview of Real World Problem

The following outlines a brief overview of the details of the real world construction cable routing problem, including input, output, and evaluation.

Structural Specifications The layout of a plant is generally received as a set of 2D schematics which a contract is agreed upon to construct adhering to these 2D schematics. However, as building information modeling (BIM) is modernizing engineering, more and more often constructors are provided with a 3D model of the plant. With this smart model, it now possible to use computational methods to assist with tasks like cable routing. Once all the potential structural elements upon which cable or tray can be placed, this can then be modeled as a graph, with the nodes and edges representing the various paths cables may take. This graph includes pre-existing tray described by engineering called *engineered tray*. Engineered tray is never complete; it is always necessary to install additional tray known as *field tray* to route all the necessary cables.

Cable Specifications The CCR problem is made challenging by the number of constraints which restrict routes. Cables come in several different major voltage categories, High Voltage (HV), Medium Voltage (MV), Low Voltage (LV), Instrument (IC), and Fibre Optic (FO). Some cables cannot be run together with other voltage categories, for instance IC cable often must be run by itself, because if it shares a tray with MV cable, then the electromagnetic field generated by the adjacent cable will interfere with the signal of the IC cable. Which cables can or cannot be run with each other varies from project to project. Different cable types have different diameters, which must be considered when sizing the supporting tray. Some cables cost significantly more than others, which is discussed below in the following evaluation section.

Problem Size Hundreds of kilometers of cables are installed to connect thousands of source/destination pairs. These graphs are generally of the order of tens of millions of edges, and millions of nodes. These graphs include a set of cable tray along which cables may be routed, they also include structural elements upon which tray and cable can be installed.

Engineered Tray Voltage Categories To make sure a cable is not run in the same tray with an incompatible cable, it is typical to label engineered tray as belonging to only a specific voltage category HV, MV, LV, IC, or FO, such that only cables of that voltage category are to run in that engineered tray. It is possible to run other cable types on that location, but this requires installing additional field tray on top of the existing tray.

Tray Fill Rate Cable tray, required to support cables, has certain physical capacity to contain cables as they have finite volume, and may only be installed on structural building elements. As cables are installed and fill up the physical space of the tray, there are often cases where there is an opportunity to run a cable a longer distance to make use of some alternate tray which is not yet full. Additional tray on top of existing tray can also be installed to increase the capacity. Any problem of fill rate or voltage category mismatch can be solved by paying to install another tray atop of the existing tray.

Project Specific Constraints There are other constraints, which further complicate the real world CCR problem. For instance, on some projects, some cables, can be run along bare steel by being pinned directly to it, as long as no more than one or two cables are run together. This generally applies to low voltage or signal cable, and is inconsistent between different engineering firms and contracts. Electrical code allows for some cables to be pinned to steel, but some engineering requirements require that all cables needs a tray. There are other restrictions, which are defined in the *Canadian Electrical Code (Canadian Standards Association 2024)*.

Online and Dynamic Setting Engineered schematics are not typically delivered all at once, as designing an entire plant which typically consists of many buildings with interconnecting systems is time intensive, so often as soon as the electrical design of one area is complete construction starts on it. This means that specifications for sets of cables arrive in *revisions* which may contain batches of hundreds/thousands cables, generally months apart. This results in construction crews being able to start some areas while the specifications for other areas are still being designed. The extent to which design is done up front or incrementally changes from project to project, and complicates the real world CCR problem. The graph representing different ways you may run cable, could change, as details in the specifications for that building may be slightly adjusted between revisions. Additional cables may come in future revisions, which exceed the tray already installed in the last revision when knowledge that there would be more cables in this area was not available. In this way, the real world CCR problem is similar to lifelong MAPF problems (Jiang et al. 2024), similar to algorithms used in amazon warehouses or dispatch systems. While this is not ideal, having months between revisions, and having only minor adjustments to the underlying network allows more lengthy planning strategies to be employed.

Evaluation The cost of determining cable layouts consists of the cost to install tray, and the cost to install cable. The cost of cable and tray are comparable, with the per meter cost of tray being about six times as much as the per meter cost of cable. However some specialty cables are as much as twenty-five times as expensive as the average cable, and are of significant priority.

This results in some cases where it is better to pay the additional cost to lay a tray to reduce the total run length of the cables in that tray, but other cases where it would be better to re-route cables to use some other existing tray. If there are more than about six cables sharing a route, the cost of the cables dominates, otherwise the cost of minimizing the tray starts to dominate.

Respecting voltage category and tray fill rate are the major restrictions which impact routing. Either of these restrictions can be resolved by either placing a tray, or by re-routing cables to use some other path, and the cost of which is the correct course of action is determined by the cost of the tray, and the quality of other available paths as impacted by other cable routes.

A CCR Problem Instance

What follows is a particular instance of the CCR problem. We outline the challenges with the instance, simplifications and assumptions, inputs, outputs, evaluation method, and some initial results with a few algorithms.

Challenges Modeling the complete cable routing problem, has some logistical challenges. For example, how much a specific type of cable costs is not something that is knowable at the time of determining routing. This might seem counter-intuitive, but when you are ordering cables at such a massive scale the quantity that you are ordering begins to significantly impact the cost of the cable due to economies of scale. Therefore, the exact per meter costs of cable will not be known until the quantities are known so that a bidding process can be performed and a quote obtained. Consequently, the exact prices of cable cannot be leveraged to determine ideal routes, because the quantity of cable must be known before the cost of the cable can be determined. Current practice is to estimate the distance using the manhattan distance between a cables source and destination, then use those quantities to obtain a quote from a cable supplier.

One issues that has been discovered, was the availability of free air jumps. Current electrical code allows for cables to be unsupported for up to 1.5 meters. Free air jumps require no tray to be installed, and because they are direct, the path of least distance will almost always utilize a free air jump. Free air jumps are legal maneuvers, however extensive use of free air jumps in constructing an electrical network are both unsafe, and unprofessional. The quantifiable cost of professionalism in this context is a factor that is difficult to quantify. Our early approaches have used custom penalties for free air jumps. Without this any too many routes consisting of frequent free air jumps, zig-zagging between trays.

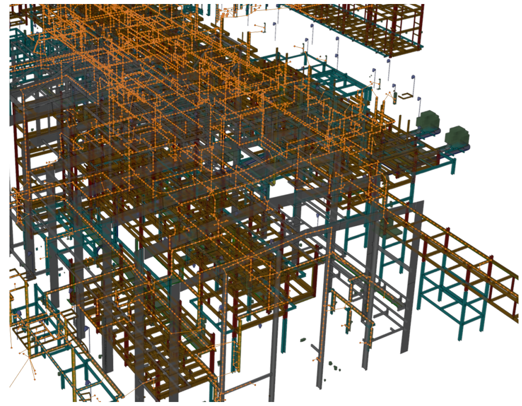

Figure 3: An example showing cables in orange routed in a large industrial project a relatively simple implementation of Dijkstra to find routes.

The current state of the art approach in industry is to manually plan cable routes by walking the work site and inspecting structural elements, and referring to the 2D engineering schematics. The amount of manual time this takes is considerable. In light of this, even an incomplete abstraction of the problem, with a slow solution (Dijkstra) is of great value. Also, due to the relatively slow arrival of cables the quality of the solution is much more important than the speed of the solution, compared to other path-planning use cases which can require very quick computation times.

Simplifications and Assumptions Our initial solution to the problem considers the following:

- Voltage category conflicts within tray.
- Every cable requires a tray.
- Tray can only be installed on structural elements.
- Engineered Tray marked with only one voltage category, shall be respected.
- Relative costs of cable and tray are considered.

The following proposed formulation is a simplified abstraction the cable routing problem, and makes the following concessions:

- The graph is static.
- All cables arrive at once.
- The physical capacity of tray is not handled.
- All trays are of the same cost per meter.
- All cables are of the same cost per meter.

Input Input to this formulation of the cable routing problem, consists of the following.

- $G = (V, E)$ is a graph representing all paths by which cables can be run. Nodes represent physical building elements (existing tray, structural steel, conduit), and edges define legal jumps between elements. Edges have the following attributes: an allowed voltages set (for engineered tray marked to only allow certain voltage categories), an isJumper flag to show if an edge is within one structural element or if its an edge jumping between two structural

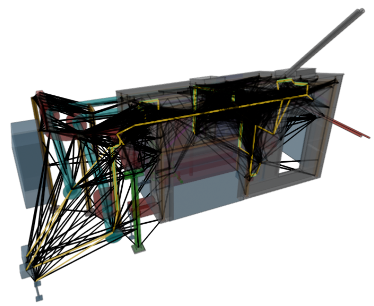

Figure 4: A prioritized planning solution for a small sample project, cables stay within trays due to free air jump penalty, required field tray to support cables colored in green. This provided reasonable routes.

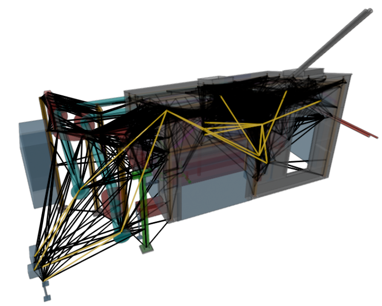

Figure 5: The same sample project with prioritized routing, without the free air jumps penalty applied, cables take zig zag free air jumps so that no tray cost is incurred.

elements, a capacity field representing the area of cables that could fit in that tray in mm^2.

- C, an array of unique identifiers, one for each cable.
- S, an array of nodes representing the start of each cable.
- D, an array of nodes, representing each cables destination.
- V_t, an array of strings, representing the voltage category of each cable, being either (HV, MV, LV, FO, or IC).
- A, an array of floats, representing the cross sectional area of each cable in mm^2.

Output A solution to the cable routing problem, is a set of paths, one for each cable, and a set of edges indicated tray needed to support those cables. The paths are a set of nodes connecting the start and destination nodes.

Evaluation For evaluation, there is a cost for each linear meter of cable, and a different cost for each linear meter of tray. The manual of labor rates (National Electrical Contractors Association 2024) was used in conjunction with a historical data analysis on several industrial projects in collaboration with PCL Construction to produce an average cable cost and an average tray cost. These costs include material and hour costs for the major tasks in installing cables and tray, and are averaged across all cables used in several large industrial projects.

Initial Exploration and Challenges

Initial exploration has been to establish the problem, set some baselines, and explore potential approaches.

The baseline algorithm used is *Independent Dijkstra*. Independent Dijkstra plans all paths separately, with any structural edges assigned tray after planning was complete. The next algorithm considered is *prioritized routing*, where cable paths are planned in order, and later paths can use the tray that is needed for previous cables. A final approach was to try and minimize the tray cost by restricting a Dijkstra search to only run on states in an approximate steiner tree, as computed using the Mehlhorn algorithm (Mehlhorn 1988).

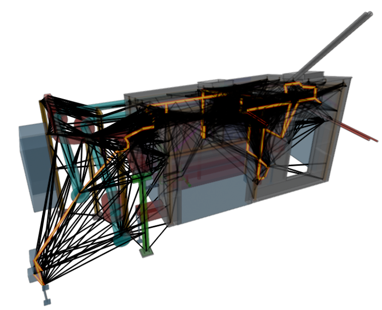

Figure 6: Restricting the single agents to search along an approximation of a Steiner Tree (Mehlhorn Algorithm) connecting the sources/destinations (shown in Red)

We implemented each of these approaches an evaluated them on a small authentic subset of a large industrial facility produced in collaboration with PCL construction.

The results for all algorithms are found in Figure 4-6 and in Table 1. These results show that restricting routes to the Steiner tree significantly increase both the tray and cable cost. Thus, despite the similarities to the Steiner Tree problem, there currently is not an advantage for basing the solution on Steiner Trees. The results from independent Dijkstra searches are better than the Steiner trees, but are not as a strong as Prioritized Planning, which significantly reduces the tray cost while slightly increasing cable cost, in comparison to the independent searches.

It should be noted that the baseline algorithms studied here are producing simple results on a small problem. Further work is needed on larger problems to expand our understanding of this problem.

Future work

In addition to practical concerns, such as properly modeling actual construction costs, there are a number of theoretical foundations for the problem which need to be estab-

Algorithm	Tray Cost	Cable Cost	Total Cost
Ind. Dijkstra	2969	3485	6455
Prioritized	2378	3520	5899
Dijkstra on ST	4069	4604	8673

Table 1: Overall costing of several different answers to a sample instance of the cable routing problem with 13 cables

lished. These include the overall complexity of the problem as well as baseline algorithms which guarantee optimal performance.

Because there is substantial time between engineered revisions, and the size of the graph is relatively small, it is likely worthwhile to spend more time computing solutions that are closer to optimal. There are many additional algorithms that could be evaluated, including random restarts, and variants of conflict-based search (CBS) (Sharon et al. 2015).

Estimating cable costs

While, at the time of routing, knowing the exact costs of the cables is not logistically possible, estimating the cost is. The cables voltage category, the number of conductors (wires within the cable), and the presence of shielding (protective layering around the cable) can be used to estimate the relative cost, it is not yet clear how consistent this approach is. Exploring this would open up more accurate evaluation metrics, and enable leveraging the exact cost of the cable for routing instead of the average cost of the cable. This would enable better planning the rare expensive cables.

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