A New Look at Designing Electrical Construction Processes

A Case Study of Cable Pulling and Termination Process

on Data Center Construction Sites

by

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A Thesis Presented in Partial Fulfillment
of the Requirements for the Degree
Master of Science

Approved April 2020 by the
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ARIZONA STATE UNIVERSITY

May 2020

ABSTRACT

At least 30 datacenters either broke ground or hit the planning stages around the United States over the past two years. On such technically complex projects, Mechanical, Electrical and Plumbing (MEP) systems make up a huge portion of the construction work which makes data center market very promising for MEP subcontractors in the next years. However, specialized subcontractors such as electrical subcontractors are struggling to keep crews motivated. Due to the hard work involved in the construction industry, it is not appealing for young workers. According to The Center for Construction Research and Training, the percentages of workers aged between 16 to 19 years decreased by 67%, 20 to 24 years decreased by 49% and 25 to 34 age decreased by 32% from 1985 to 2015. Furthermore, the construction industry has been lagging other industries in combatting its decline in productivity. Electrical activities, especially cable pulling, are some of the most physically unsafe, tedious, and labor-intensive electrical process on data center projects. The motivation of this research is the need to take a closer look at how this process is being done and find improvement opportunities. This thesis focuses on one potential restructuring of the cable pulling and termination process; the goal of this restructuring is optimization for automation. Through process mapping, this thesis presents a proposed cable pulling and termination process that utilizes automation to make use of the best abilities of human and robots/machines. It will also provide a methodology for process improvement that is applicable to the electrical scope of work as well as that of other construction trades.

This thesis is dedicated to my parents;
who never failed to believe in me and push me to become the individual I am today
To my siblings, Aya and Mohamed;
and my fiancé, Mohamed ElDesouky;
without your enormous sacrifice and unconditional love, I would have never been here

I had promised to make you all proud by the achievement of this goal and I hope that I have fulfilled that promise

ACKNOWLEDGMENTS

I would like to thank my committee members: Dr. Kristen Parrish for her support, it is an honor to have worked with her and learned from her; Dr. Steven Ayer, for taking the time to guide me in the right direction and provide me with advice on my work. I am fortunate to have worked alongside such outstanding academic mentors. I am also thankful for Ms. Elizabeth Irish for willing to be part of my committee and providing me with feedback based on her on-the-ground experience and invaluable expertise in industrial construction.

I would like to thank AlGhurair Foundation for Education (AGFE) for my scholarship to study at Arizona State University. Without the foundation's financial support and its advisors' academic and extracurricular support I would have never been here.

I would also like to thank all the people and friends I met at Mortenson Construction. In particular, I would like to thank Chase Farnsworth, Karla Yanni, Mitch Transtrum and Kindell Davis. Special acknowledgments are also due to Aaron Thompson and Darin Johnson with Corbins Electric for sharing their expertise in data center construction. Representatives from these firms provided access to construction sites and facilitated interviews with personnel actively engaged in data center construction.

I am also grateful for Jeffrey Feghaly's support on this research and providing valuable advice and review of my work. Without each and every one of these individuals the completion of this research would have never been possible.

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INTRODUCTION

According to McKinsey Global Institute's digitization index, "construction is among the least digitized sectors in the world". The industry has been very slow in adopting new tools and solutions while other industries have been coming up with new and innovative ways to tackle declined productivity. McKinsey also pointed out in its 2017 report that the industry is divided into two groups. The first is the "large-scale" group that tackles the heavy construction sector; the second group is comprised of smaller specialized firms such as mechanical, electrical and plumbing subcontractors. McKinsey argued that the second group usually lags in productivity. One of the areas this report suggested as an area that could enhance the productivity by 50-60% is introducing digital technology, new materials and advanced automation (McKinsey Global Institute Report, 2017).

According to Electrical Marketing's construction project database, at least 30 datacenters either broke ground or hit the planning stages over the past two years" (Lucy, 2019). Google Chief Executive Officer (CEO) announced in a blog post that google will create new construction jobs in Nebraska, Nevada, Ohio, Texas, Oklahoma, South Carolina and Virginia (Lucy, 2019). In addition to the states mentioned earlier, several other "hot spots" for data center construction have emerged including Chicago, Arizona and many other locations around the United States (Lucy, 2019). The author also emphasized that the electrical and network cabling are considered crucial elements of any data center whether it is hyperscale or small. Furthermore, on technically complex projects housing high technology, the MEP systems can account for up to 50% of the project value (Khanzode A et al., 2008). Therefore, the data center market appears to be very promising for electrical contractors, engineers or professionals over the next few years.

Electrical activities, especially cable pulling, are often associated with multiple safety concerns to workers, in part due to weight of cables: four or five cables can weigh up to 4,000 lb. Feeding cable, despite being a non-technical task that does not need trained electrical journeymen, is associated with risks such as back injuries or strains (The secret to cable pulling, 2000). Electrical journeymen’s training can be utilized in many other aspects on the job site since the industry is facing an aging workforce. According to The Center for Construction Research and Training, the percentage of workers aged between 45 and 64 increased by 59% from 1985 to 2015 (CPWR, 2018). During the same time, the percentages of workers aged between 16 to 19 years decreased by 67%, 20 to 24 years decreased by 49% and 25 to 34 years decreased by 32% (CPWR, 2018). In addition, the industry has been suffering from labor shortage that is almost permanently at 10% (Bock, 2004).

Despite the above factors that have generated a real need for increased productivity, the construction industry has been slow to introduce automation technology especially in the United States (Paulson, 1985). Bock (2015) reinforced that by stating that “innovation in construction industry occurs extremely slowly” and that the construction industry “has been stagnating for decades”. Paulson (1985) argues that robot manufacturers have several explanations for why they have been staying away from construction. David M. Osborne, Technical Director of Swedish ASEA’s Troy, Michigan Office, “Construction jobs are not always the same, so there’s no great deal of repeatability”. Osborne argues that it would be hard for a robot to make some on-site decisions in an uncontrolled environment (Paulson, 1985). David Wisnoski, group vice president of the Industrial Systems Group based in Naperville, Illinois added that a Robot’s ideal environment is a “structured” environment (Paulson, 1985). In order to achieve greater automation/robotization in the construction industry, it is essential to create structure or impose it which will requires a closer look at how tasks are accomplished and using new technologies to assist in recognizing structure (Halpin et.al, 1989).

Therefore, there is a need for technologically advanced alternatives to accomplish scopes such as mechanical, electrical and plumbing, especially on technically-advanced projects such as data centers. This thesis uses the cable pulling and termination process as a case study to investigate how automation can be added into a reconfigured process. It is important to consider how technology impacts processes prior to utilizing new technology in the electrical construction process. The aim of this research is not to replace all manual operations, but to provide support to electricians in the most physically-demanding activities and leverage their skills to operate automated devices. By mapping the existing process and proposing a future state of practice, this thesis provides a methodology to restructure and optimize existing electrical construction process for automation. Although this thesis is focused on the electrical cable pulling and termination process, the process mapping method presented is applicable to other (electrical) construction processes.

CHAPTER 2

BACKGROUND

This chapter gives an overview of different approaches to utilize automation in construction processes that have been used in the past and introduce the rationale for applying automation in the cable pulling and termination process in data center construction sites.

The construction industry has been suffering from insufficient attention to process improvement and hence there has been a substantial amount of non-value adding activities in construction processes (Koskela, 1992). Before introducing automation in a process, it is essential to closely assess the importance of the activities involved in that process and whether they add value to information and material flow. Instead of viewing automation as a tool to accomplish tasks on a job site, it should be taken as an opportunity to optimize and improve the current practices. As Koksela (1992) argued, the industry is still missing the principles on which a construction process could be analyzed, designed, managed and improved.

Several researchers have attempted to put in place frameworks to determine the feasibility of a process for automation but most of the researchers failed to assess and improve the processes in place before attempting automation. For example, Kangari and Halpin identified three ways to assess the feasibility of a process for automation or robotization. The study looked at need-feasibility, technological feasibility and economic feasibility. According to these factors and interviews with experts from the construction industry, the researchers selected 33 construction processes as potential candidates for automation among which are drywall, pile driving, scaffolding and many more. To assess the need-based feasibility of a process, they looked at the following characteristics: labor intensiveness, vanishing skill area, high skill requirement, precision and dexterity requirement, repetitiveness, tedious and boring, critical to productivity, unpleasant and dirty, hazardous to health, and physically dangerous. (Kangari & Halpin, 1989).

Another approach was taken by Everett and Slocum (1994) where the authors established a taxonomy for construction field operations. In this study, a construction project was divided into seven levels; Project, Division, Activity, Basic Task, Elemental Motion, Orthopedics and Cell. The Basic Task level, which the author identified as a crucial level for construction automation, was broken down into a set of twelve basic tasks. The author argued any task performed on a construction field is comprised of one or more of the following basis tasks: connect, cover, cut, dig, finish, inspect, measure, place, plan, position, spray, and spread. The basic tasks can be performed by craftspeople or machines. The author also divided a construction task into two components: the physical and information components and concluded that human craft workers are more productive when it comes to information intensive activities and this is another reason why the industry should re-think the way things are done by making use of its craftspeople's skills in accomplishing information intensive tasks and limiting their involvement in physically intensive chores that can be done by robots or machines.

The approaches used are beneficial in identifying tasks for automation. However, they need to be complemented by assessing the value of the activities in a process first. An existing process must be studied more closely before deciding on its feasibility for automation or attempting to automate its individual activities. Automation should be used to facilitate division of labor between man and machine to utilize the best abilities of each. The aim should be to use automation to assist rather than replace humans, to help boost productivity. By providing more structured processes and better practices to accomplish construction chores, the skills, experience and trainings of craftspeople will be put into more beneficial use on construction sites.

2.1 Rationale for Process Improvement

The current cable pulling and termination process, which will be discussed in detail in this thesis, is problematic for several reasons that are all in favor of restructuring the process. The first reason is the physical injuries associated with the activities in the process such as pulling the cable or carrying heavy weights on shoulders. Receiving and staging the wire reels involves physical risks such as back strain, knees and hands crushing injuries (Ergonomics eTool, n.d.). Pulling the wire and carrying wire on shoulder may also cause back strain and high pulling tension recoil.

The second reason is that it is a very labor-intensive process. It requires at least 2 men to move 100 ft of medium voltage cable and at least 4 men to pull it from start to end point. An activity such as termination, requires high skills, dexterity and precision. To terminate one uninterruptible power supply (UPS), it takes an electrician a day to a day and half.

The third reason why this process should be further assessed is its cyclic nature. The process consists of cycles of general basic tasks. Some activities involve a single cycle that repeats over and over. In addition, most of the activities in the process are repetitive, tedious and boring, critical to productivity and physically unsafe. Due to the aging workforce in the industry, the skills needed for those activities are vanishing. Therefore, the activities involved in this process should be studied more closely. First, to create a more efficient process. Second, to investigate how automation can help restructuring the existing process to leverage the expertise of the industry's craftspeople. Third, to encourage young calibers to join the industry. Last, to provide a safe work environment.

CHAPTER 3

OBJECTIVE AND METHODOLOGY

This chapter will introduce the approach adopted by this research to improve the cable pulling and termination process in effort to optimize it for automation. As mentioned earlier, improving a process requires rethinking of the current practices and studying how new technologies can aid in restructuring processes. In Serpell and Alarcón's (1998) research on construction process improvement methodology for construction projects, the authors identified "Diagnostic of current situation" as the first step of the research's problem-solving methodology. The purpose of this step is to recognize as accurately as possible what is being done on the project. One of the tools they considered very useful in recognizing potential problem areas is process mapping.

The methodology for redesigning the process, as per Figure 1, started by mapping the current cable pulling and termination process. This was done by visiting data center construction sites, observing the electrical crew pull cable along cable trays for a day, and interviewing them about the most time-consuming activities and obstacles they face when pulling and terminating cable. Data was gathered on average durations of activities and the manpower required. A process map was created showing the sequence of activities required to complete the process. The process map was then reviewed by industry professionals who have 10+ experience in electrical construction and have experience working on at least three to four data center projects. The process map was modified as per the industry experts' reviews. The industry professionals review was very important in bringing up variations of activities from one construction site to another and helping identify the fundamental activities required to accomplish the process.

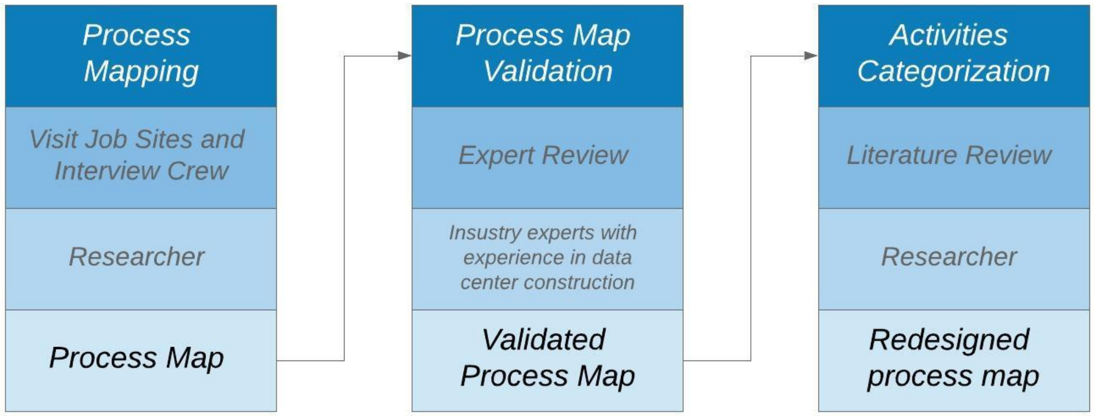


Figure 1: Research Methodology Flowchart

The next step was analyzing the activities in the process map to identify waste and non-value adding activities. The analysis started by highlighting activities that have potential to be completed offsite. This can be done by several methods, including but not limited to, pre-fabrication off site. This would not only save labor but also the space required to store and handle bulky material on site which will be explained in detail later in later chapters. After identifying methods to complete some of the activities off site, some related activities had to be eliminated from the process because they no longer fit in the overall sequence. For example, pre-fabricating cables off site means reels unloading, storage, cutting cable and moving it to the pull area will no longer be needed. This part of the process will no longer be required due to change of its predecessors. After applying the first two filters to the activities, the remaining activities were assessed for identification of improvement opportunities through automation. Precedence in the construction industry as well as other industries such as medical, manufacturing and agriculture was reviewed. The activities categorization is explained in Figure 2.

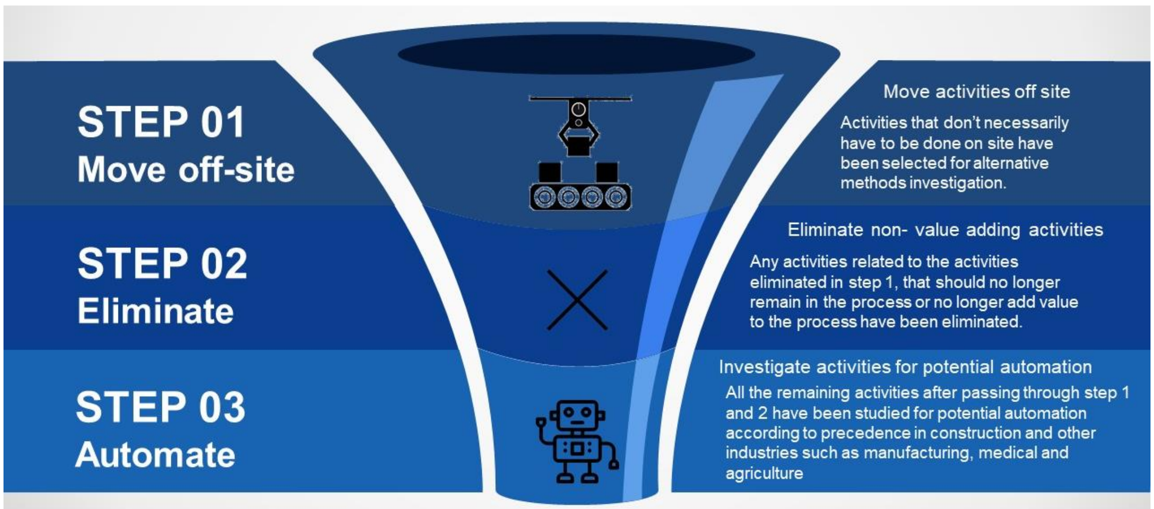


Figure 2: Process Activities Categorization

CHAPTER 4

CURRENT PROCESS

4.1 Data Center Structure Cabling Infrastructure

In data centers, there are two commonly used methods to run power and network pathways. The decision on which method to use is the designer's or owner's decision (Geng, 2014). The first method is running **overhead** cables:

Overhead power runs in conduit from a distribution frame to receptacles or wire busway above each cabinet. Busways are more flexible to future changes in the networking; however, it requires more effort in coordination with other systems so that the physical separation requirements would be met.

Network could be distributed through top-of-cabinet trough systems, basket trays and ladder racks. Cable trays are not recommended for network distribution in data center computer rooms. Top- of- cabinet trough systems require less coordination and decrease the required ceiling height, and this is why they are more commonly used in smaller data centers. In a project with many elevation changes, basket trays are easier to install.

Ladder racks are the best option in transitioning from the ladder racks to cabinets as they also allow the use of water fall accessories (Geng, 2014).

Overhead network distribution is chosen more often in data centers.

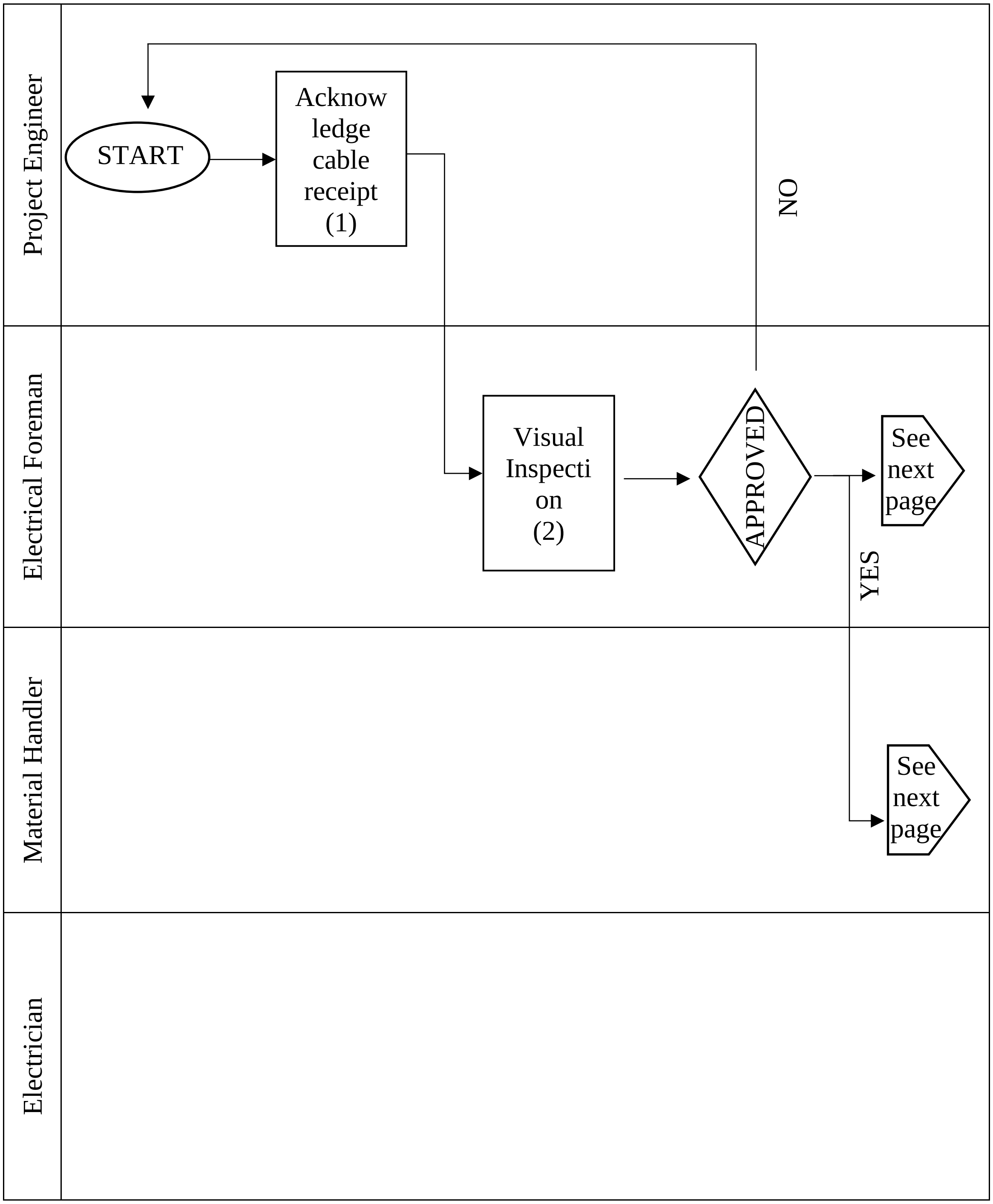
The second method is running **underfloor** cables in a data center with a raised floor:

For power cable, metal conduit is used in cases when it is required. In other cases, liquid- tight flexible cable is used. Network cable is less often run under raised floors. It requires huge coordination with other underfloor systems such as chilled water piping and fire detection.

This method is not preferable in the industry unless it is required in large-frame systems whose design calls for cable entry from below. In the event of using copper twisted pair cabling, wire baskets are preferable. When it comes to fiber-optic cabling, metal troughs are problematic to use because they are made of light gauge sheet metal that is hard to handle and can easily be cut in narrow spaces (Geng, 2014). Metal troughs are used when underfloor space is utilized for air distribution and therefore the pathway is rated.

As the demand to upgrade or build new data centers continues to grow, more cabling is required to meet the increased data storage and application processing needs. The larger the size of the data center the more complex the cabling gets and the more labor it consumes. To enhance the controllability of electrical construction activities in the cable pulling and termination process through variability reduction and getting rid of non-value adding activities, it is essential to determine the steps to achieve this process from start to finish and understand operation at several levels of detail. Table 1 illustrates the process map, validated by industry experts, of the current process.

4.2 Current Process Map



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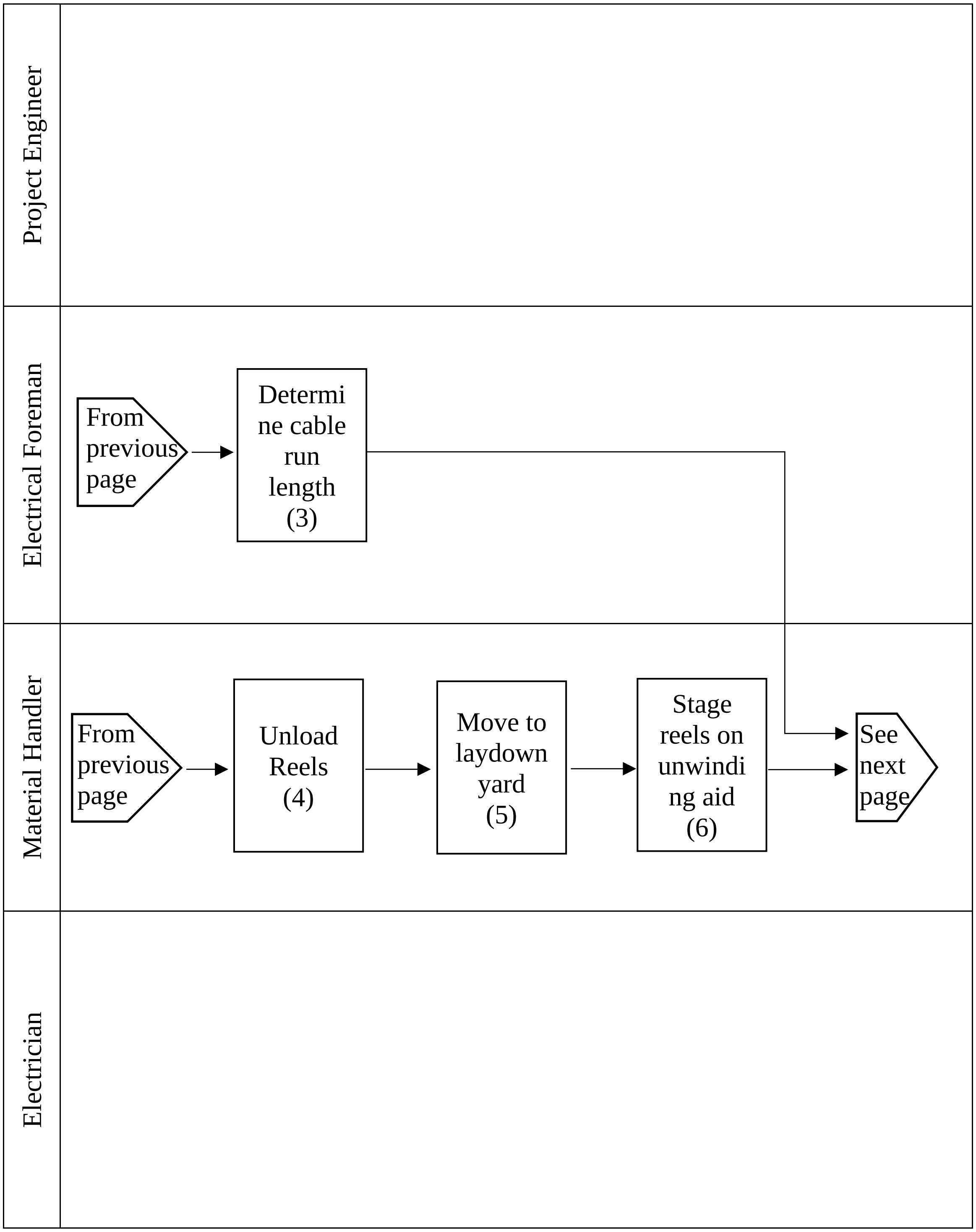

Project Engineer
Electrical Foreman
Material Handler
Electrician
From previous page
Determine cable run length (3)
From previous page
Unload Reels (4)
Move to laydown yard (5)
Stage reels on unwinding aid (6)
See next page

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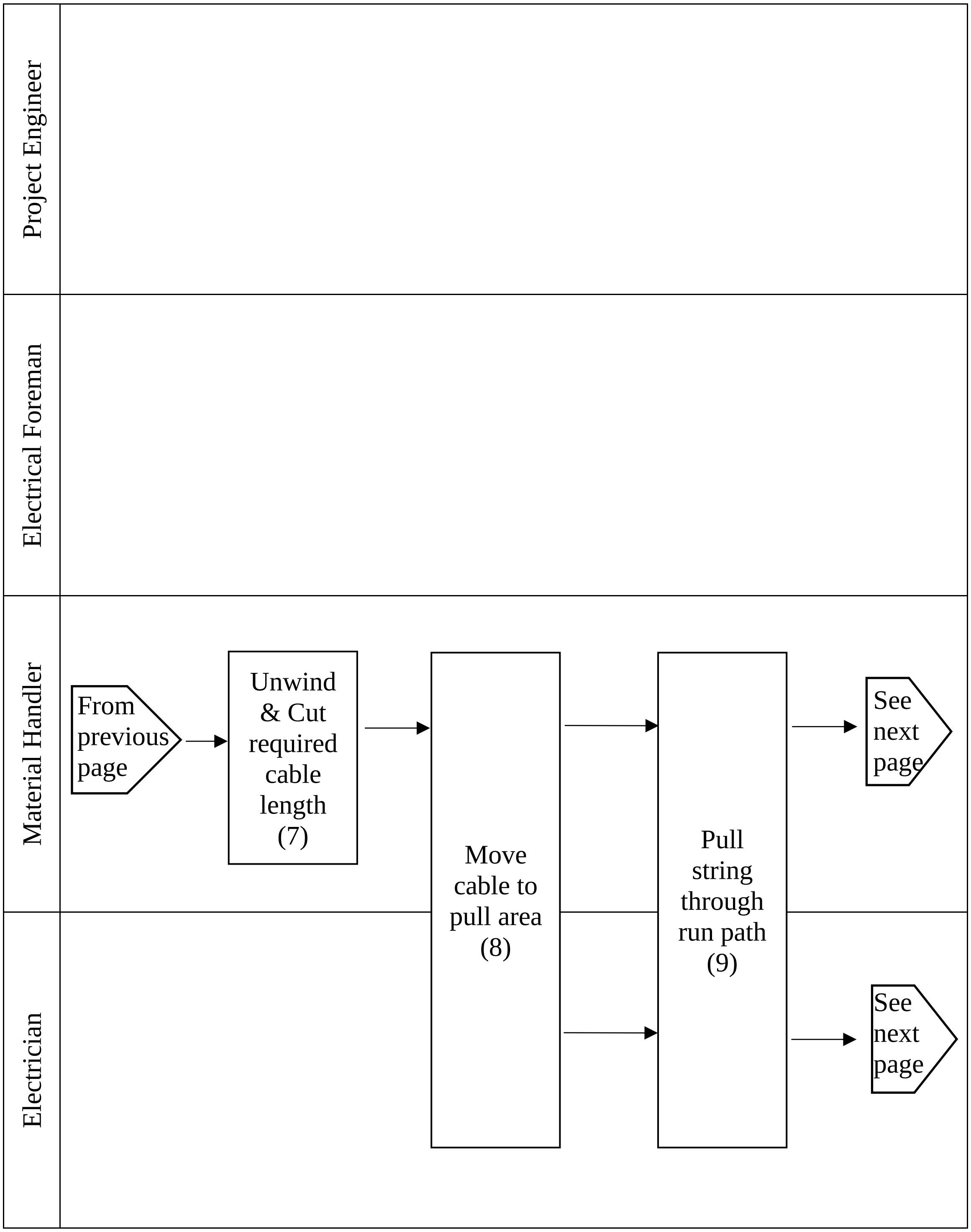
Project Engineer
Electrical Foreman
Material Handler
Electrician
From previous page
Unwind & Cut required cable length (7)
Move cable to pull area (8)
Pull string through run path (9)
See next page
See next page

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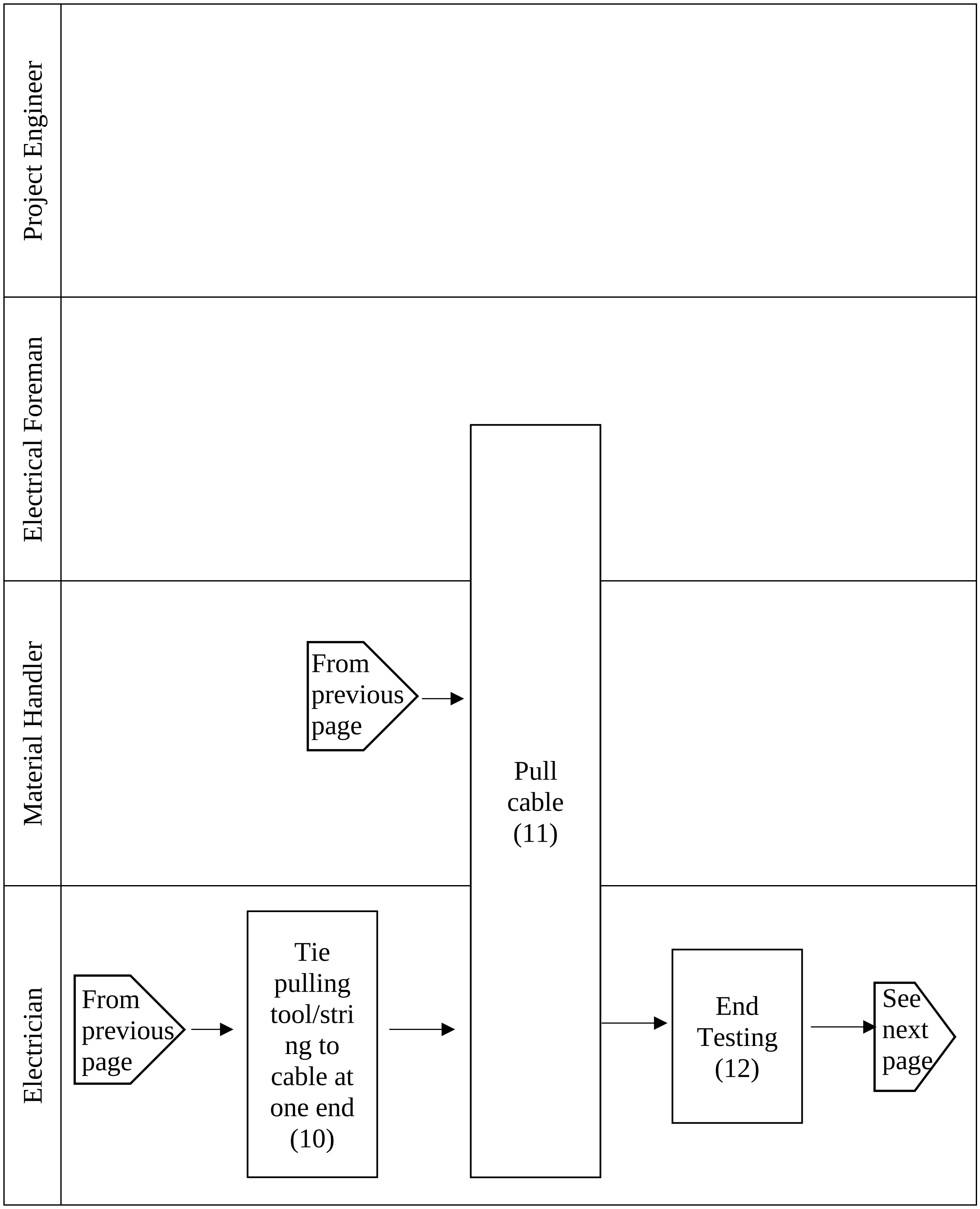
Project Engineer
Electrical Foreman
Material Handler
Electrician
From previous page
From previous page
Tie pulling tool/string to cable at one end (10)
Pull cable (11)
End Testing (12)
See next page

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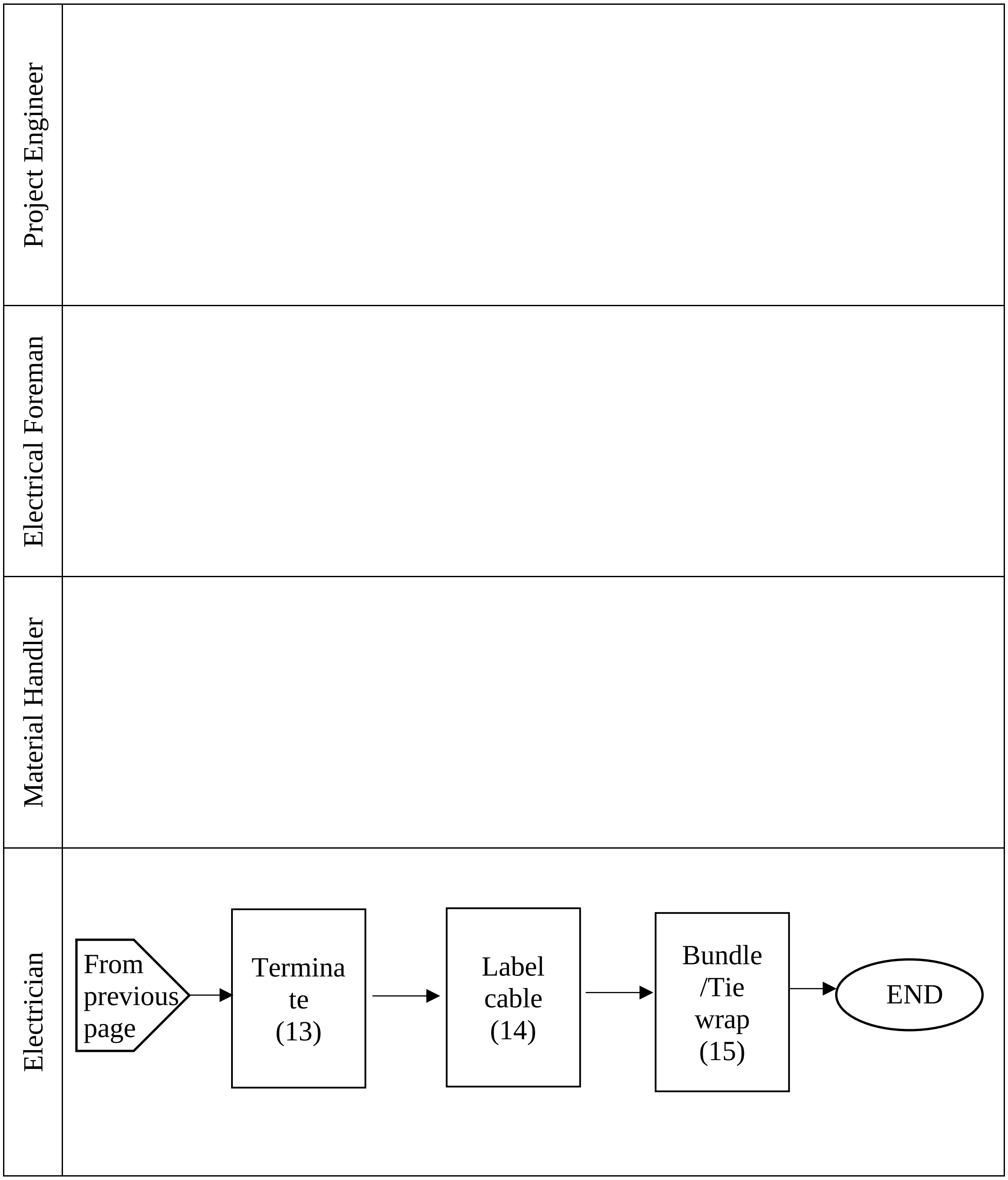


Table 1: Current Process Map

4.3 Reading the process map

Symbols used:

Process Activity	Reference to/from another page
Decision/ QC/QA	

Table 2: Process Map Symbols

4.4 Team Members Considered in the Current Process Map

Project Engineer:

On a project, the project engineer works for the general contractor and is usually in charge of making communications with the manufacturer to make sure the correct quantity of material arrives to the job site on time. The project engineer is also responsible for handling correspondences with the manufacturer if any damage is observed on the material or incorrect quantities are received.

Material Handler:

A material handler’s responsibility is to move, store and control materials on site. A material handler uses equipment such as telescopic handlers, forklift trucks, cranes, lifting devices and conveyor systems.

Foreman:

An electrical foreman’s responsibility is to manage the electrical subcontractor’s team. The foreman is usually the highest skill and knowledge and provides proper documentation and instructions to other workers to proceed with tasks.

Journeyman Electrician:

Electricians are given instructions by electrical foremen and are trained to perform tasks such as data cabling and fire alarm installation. They are given their designation after specific hours of experience and trainings.

4.5 Activities Description

Activity (1): Acknowledge cable receipt

When cable spools are delivered to the job site, the project engineer is responsible for documenting the arrival date and time to update the project schedule and logs.

Activity (2): Visual Inspection

This inspection is usually done by Electrical foreman or electrician to check for any shipping damage to the reels or cables.

Cable:

Should be free of cuts, cracks, kinks or sign of wear to the cable covering which can be detached, discolored or broken. Cable should also be checked for any signs of heating or burning (Classic Wire & Cable, n.d.) If damage is witnessed, the material is returned to the manufacturer and redelivery is handled by the project engineer.

Reels:

The foreman makes sure the reel overhangs aren't broken, reels aren't piled over one another or laying flat on their side.

Tags and Labels:

Reel tags should be checked for purchaser's name and address, purchase order number, conductor size and type, insulation thickness and type, jacket type, quantity of cable on reel, beginning and ending sequential footage numbers present on jacket (Classic Wire & Cable, n.d.).

Activity (3): Unload reels

While unloading cable reels from the truck reels should be tied with the appropriate belts and saddles. Using a shaft and spreader beam, the reels are unloaded from the truck by means of lifting or suspension equipment such as cranes or booms.

Activity (4): Move reels to laydown yard

Using forklifts, cable reels are transported from where they are delivered to where they should be stored for use. Ideally, they should be unloaded in the storage yard and as close as possible from the pulling location.

Figure 3: Forklift Ready to Move Reels

Activity (5): Determine the cable run length

Using the drawings, the foreman uses the project plans or BIM model to determine the length of cable to be pulled between two points. A threshold of +10 feet is usually added on each side of the cable when cutting cable.

Activity (6): Stage reels on unwinding aid

Due to the large weight of the reels, unwinding tools such as rollers are used to ease cable unwinding and take- up. These tools maximize safety, eliminate over torque.

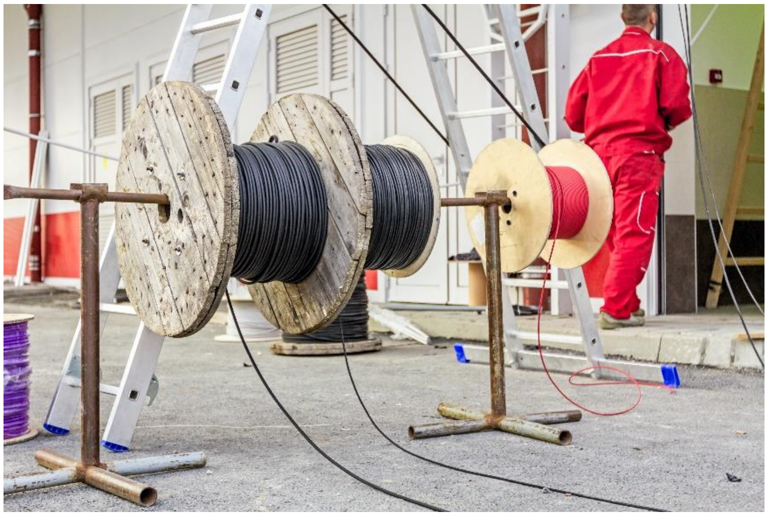


Figure 4: Wire Reel on Unwinding Tool

Activity (7): Unwind and cut required cable

Using measuring marks on cable, laborers unwind the required length of cable for a run. In case of unwinding medium voltage power cable, two to five workers are required. Although equipment such as rollers are used to ease unwinding, this activity is considered one of the most unsafe and labor-intensive activities of the process due to the large force required to unwind reels in some cases and the possible injuries associated with it.

Activity (8): Move cable to pull area:

Cable is carried by workers from the lay down yard to cable pull area. At least two to five workers are needed to carry the length of cable on their shoulders from one area to another.

Figure 5: Workers Carrying Cable on Shoulders

Activity (9): Pull string through run path

The common practice is to pull string from run start to finish. The most challenging part about this is getting through any obstacles underneath the cable tray/conduit to get the rope going. It also gets very challenging with longer runs of conduit since they are closed so a rod must be used to keep pushing the rope until it appears from the other end. The more the cable in the tray the more complicated pulling more cable gets. Scissor lifts are used by electricians to reach the cable trays and move the rope from one point to another which makes the activity very time consuming due to the time required to maneuver around rooms with the scissor lift to get the cable or rope from one point to another.

Activity (10): Tie pulling tool/string to cable at one end

For large diameter cable, tools such as Chinese Fingers or Towing Socks, which are made of braided cable, are tightened around the cable when pulled. For higher pull forces, automatic Tugger-Wire pullers are used.

Activity (11): Pull cable

This activity requires at least two workers per cable run. While the worker at the end point pulls the string, or the pulling tool attached to the cable, the worker at the starting point helps push the cable. They usually use radios to communicate in case the cable gets stuck or a pause is needed.

Activity (12): End Testing

There are several tests that must be carried out to make sure the cables are connected correctly before termination. Examples of such tests are continuity, contact resistance, insulation resistance, discontinuity and dielectric withstand (Delserro Engineering Solutions, n.d.).

Activity (13): Terminate

A certain distance from one end of the wire is measured then a stripper is placed at that location. The stripper is turned around the cable to score the sheathing. The insulation is then pulled off the cable. Cable is separated in order to make sure no cables are crossing. Cables are the connected to their respective connections on the server racks.

Activity (14): Label cable:

The Electrical foreman or electrician is responsible for creating at least two labels for each cable run to indicate information such as the starting and ending point, device number, floor number, room number. Current devices such as P- touch label makers are used to accomplish this task in the office and send readymade labels to the job site.

Figure 6: Labeled Wire

Activity (15): Tie wrap/bundle cables

The purpose of this activity is to organize and separate cable groups from one another to ease cable management and maintenance as well as allow for network expansion in the future. In the event of any future damage to the cable, having organized cable/wire makes it easier to discover and fix a problem.

Figure 7: Bundled Wire

The process map only shows cable pulling and termination activities during the construction phase. Several other tasks are required for completing this process before the cable arrives on site. Performing cable calculations to determine the forces required to pull cable or creating cable labels are examples of activities that are not included in the process map. To improve the process and optimize it for automation, the first layer of analysis was applied to the activities as per chapter 3, methodology.

4.6 Process Improvement Steps

Step one: Move off site or Pre-fabricate:

After studying the activities in the process map, it has been observed that there are several activities completed on site before the pulling activity, itself very time consuming and labor intensive. To reduce the crew size required to complete the process, attempting to move part of the process off the construction site would be an ideal scenario. If pre-terminated, labeled cable runs are fabricated by the manufacturer, there would be no need for delivering cable reels to the jobsite. Scheduling cable runs for delivery by the manufacturer according to the project progress schedule would save labor, space and reduce the costs associated with labor and storage. Cable runs would ideally be delivered the night before a pull is scheduled and directly moved to the pull area to be ready for pulling the next morning. This will relieve workers from carrying the cable on their shoulder around the jobsite and will encourage using equipment such as forklifts to move the coiled length of cable directly to the pull area. Consequently, the following activities could be moved off site: Activity (3) determine cable run length, activity (7) unwind and cut the required cable length, activity (8) move cable to the pull area, activity (12) label cable and activity (14) terminate.

However, there are several drawbacks associated with adopting this solution. First, there will be added transportation costs associated with more frequent deliveries by the manufacturer. Second, project schedules will need to be updated timely and accurately so accurate deliveries could be made by manufacturer on time and any delays would be avoided. Third, there might be some safety concerns associated with having the cable in the pull area if it is not pulled on time. Fourth, since the cables will be pre-terminated, storing extra length of cable within the cable tray or under the raised floor could be challenging. Fifth, although automating the pulling process which will be discussed later in this thesis will decrease the possibility of cable damage during pulling, if the cable gets damaged during the pull for any reason, this will cause delays since cable will not be readily available on site for replacement.

Step Two: Eliminate non-value adding activities:

After moving the activities in step one off the jobsite, some predecessors must be eliminated. The predecessors are: Activity (4) unload cable reels, (5) move reels to laydown yard, (6) stage reels on unwinding tool, could be eliminated from the process since the large reels will not be delivered to the jobsite if cable runs are pre-fabricated.

Step Three: Automate:

The last step of restructuring the process was using automation to increase the productivity in indispensable activities that did not fall under any of the previous categories. These are the activities that must be done on site and are critical to the completion of the process. Activity (1) Acknowledge cable receipt, activity (2) visual inspection, activity (9) pull string through run path, activity (10) Tie pulling tool to cable at one end, activity (11) Pull cable , activity (12) End testing and activity (15) Tie wrap/bundle cable. Activity (9) is considered a very time-consuming activity especially when a cable tray houses a lot of cable and wire. Moreover, there are some instances when there are obstacles beneath the cable trays that the worker must get through to pull the string through the path. The process of pulling string through the run path is an inefficient process. Pulling the string through the cable run path and then using the string to pull the cable through the same run is double work. Depending on the size of the cable, activity (11) is considered one of the most labor-intensive activities in this process.

Depending on the size of the cable and the length of the run, it usually takes between two to six workers to pull 100 ft of cable.

To investigate the potential of automating the above activities, two areas were studied. First, the basic tasks that these activities are comprised of. Second, research about automation in other industries has been conducted to find activities that are comprised of the same or similar basic tasks that have been successfully automated.

CHAPTER 5

PROPOSED PROCESS

This chapter will identify the decision-making process used to arrive at which activities, out of the remaining seven activities discussed in the previous chapter, could be automated. Then, a new electrical cable pulling and termination process that utilizes automation will be proposed.

Following Everett's (1994) methodology, the basic tasks involved in each of the seven activities were identified as shown in table 3. The sources of physical and information components were also outlined.

Activity	Operation	Basic Task	Physical Input	Information Input
1	Acknowledge cable receipt	Plan	None	Human
2	Visual Inspection (damage and qty)	Inspect	Human	Human
9	Pull string	Position	Human	Human
10	Tie pulling tool	Connect	Human	Human
11	Pull cable	Position	Human/Machine	Human
12	End testing	Measure	Human	Machine/Human
13	Terminate Cable	Cut	Machine/Human	Human
		Connect	Machine/Human	Human
15	Bundle/ Tie wrap Cable	Cover	Human/Machine	Human

Table 3: Basic Task, Physical and Information Input of Activities

As shown in the table, three out of eight activities depend, the remaining five activities depend on human in at least one of the components. Activities that involve tools or machines provide some help to human. One of the goals of this chapter is to provide automation solutions that can offer some division of labor between the machine/robot and human. Using conventional tools is a way to reassign physical effort which means that human still supplies all the physical and information input (Everett, 1994). Power tools on the other hand contribute to some of the physical input while the human operator makes decisions and directions. When it comes to automatic tools, a portion of both the physical and information component is supplied by the tool such as laser guided graders and dozers. Robots contribute with all the physical and information components of the work. Some pre-programmed robots can proceed with completing tasks without any human input by making their own decisions.

Robots are classified into three types: The first is teleoperated robots, which are operated by humans. The second is preprogrammed robots that are usually programmed with instructions. The third is the cognitive robots which can act and react to their surrounding environment (Everett, 1994). The goal of this research is to assess the feasibility of transforming the human input into a machine, tool or robot input whether it is physical or information and investigate if robots can be used in heavy manual labor to relieve construction workers. To accomplish that, literature of automation in other industries was reviewed to find proven success of automating similar tasks to the ones involved in cable puling and termination. By finding potential in automating the individual activities, the process would possibly be restructured in its entirety.

5.1 Team Members Considered in the Proposed Process Map

VDC team:

VDC stands for “Virtual Design and Construction” which is the team responsible for Building Information Modeling applications on a project, using advanced software such as Revit.

Scheduler:

A scheduler creates a comprehensive project schedule where individual trade activities are arranged in a specific sequence that ties into the whole project.

Manufacturer:

The manufacturer is the cable producer which engineers the cable and wire and makes deliveries to the job site. Cable manufacturers use the project specifications as guidelines to the properties and types of cable to manufacture.

Spot:

Spot is a robot by Boston Dynamics that is equipped with stereo cameras to enable 360-degree vision and helps react to obstacles and people when maneuvering around. It can move with a speed of up to 1.6 m/s. Its ability to withstand dusty environments makes it suitable for industrial sensing and remote operation needs. Spot is used in construction, oil and gas, public safety and entertainment. On a construction site, it can currently perform progress inspection and comparing as-built to BIM. Its high-resolution camera enables it to magnify features with 30x optical zoom which would be useful in cable inspection in the future. In addition, its ability to climb stairs, navigate through rough terrain, compare as-built to BIM and its flexibility to be customized according to the user's needs, can make it a great candidate for locating areas and distributing cable runs across the job site.

5.2 Proposed Process Brief

The proposed process would start with the VDC team modelling the cable runs, using software such as Aeries to model the cable in a 4D model where cable runs are linked to the project schedule.

After the BIM model is completed by the VDC team, the scheduler would be expected to revise the sequence proposed by BIM model to verify that it ties into the overall project sequence correctly.

The manufacturer, through the 4D model, will have access to the cable pulling schedule and accordingly will be able to deliver cable runs accordingly. The aim of having a 4D model is providing the manufacturer with the following information: Cable run length, cable run start and end point, cable specifications, termination type and pull date. Consequently, the cable runs would be labeled by the manufacturer according to the project taxonomy. When cable arrives on site, spot would potentially be of great assistance in visual inspection. It would potentially be able to directly update the BIM model and hence notify the manufacturer with any cable run rejection to arrange for re-delivery after resolving the issue with the project engineer.

However, if spot would be expected to transport cable across the jobsite, then start and end points as well as area coding would be essential in aiding spot or any autonomous equipment used on the job site to locate material drop off points. It is crucial to consider patient reeducation of the craftspeople to be able to deal with the new technology. Providing workshops to convey how automation can possibly help in completing tasks more efficiently and safely will encourage the workforce explore what technology can offer. Adopting new technology might also encourage younger generations to join the construction industry and hence help with training older crews. It is essential to provide the workforce with the education and training that makes it comfortable with using new technology more frequently. Trainings would ideally be paired with progress monitoring and evaluation to reinforce the value of the gained skills. Crew members who prove interest and enthusiasm in adopting, testing and implementing innovative solutions to daily challenges using technology and automation, can be promoted to act as catalysts for change within their teams.

5.3 Pulling Cable: Snake Robots

Snake robots are inspired from biological snakes. They are typically long, flexible and have small cross-section to length ratios to enable them to move like snakes, move over irregular terrains and in tight spaces (Bogue, 2014). The purpose of putting research efforts in snake robots is their potential in offering help to humans in accessing unknown and challenging environments (Bogue, 2014). The robots have been developed for a variety of applications including but not limited to firefighting, cardiac surgeries. OC Robotics implemented a robotic system to clean and inspect the cutting head of a tunnel boring machine (Bogue, 2014). Snake robots can be powered by electric motors, pneumatics, hydraulics and mechanical methods.

The problem cable pullers are currently facing is the human reaction time between detecting the obstacle, notifying the pulling partner to stop pulling. In the current process, there are instances when the person pulling the cable would be standing behind a wall and cannot see the complete path of the cable, the guide in this case is usually the pulling partner's directions which are usually provided by radio. In this case the puller depends on a notification from the pulling partner to stop the pull. By the time the partner is notified to stop the pull, and reacts to the notification, the cable would be damaged already.

ROBOTNOR Centre for advanced robotics, based in Norway, is one of the leading labs conducting research on snake robots and the developer of the Kulko Robot shown in Figure 8. "Kulko" is an experimental platform developed for environments with obstacles. Such type robots have the potential to be useful in pulling cable through cable trays or underneath the raised floor since these robots are equipped with contact force sensors to detect obstructions. Other snake robots are equipped with cameras that enable them to capture high quality images of steam vessels and pipes which could also be useful in capturing obstructions for faster troubleshooting.

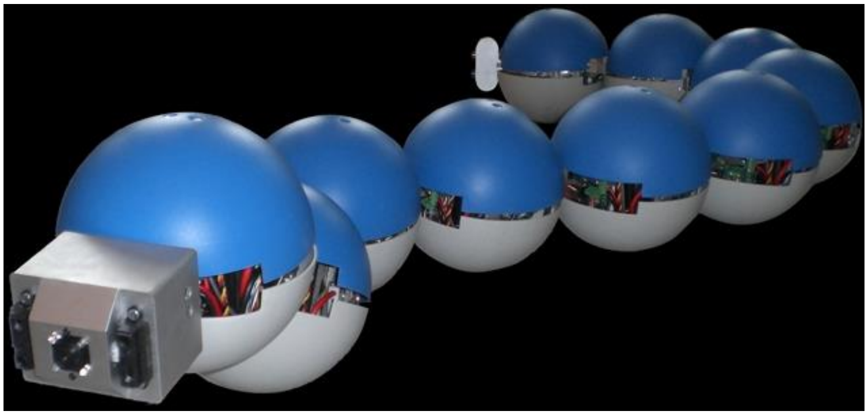


Figure 8: The Kulko Robot

Pre- programming snake robots to run paths would be an ideal scenario in most cases. In more complicated runs, they would possibly be run by an operator similar to how drones are currently operated. So far, snake robots have been developed for inspection and maintenance applications. No proof has been found of snake robots performing any cable pulling, which is an area of possible future research.

5.4 Termination: Surgical Assistants

Termination is a unique and challenging activity because it involves more than one basic task, a high information input by human. It is not a move from point A to point B type of activity. It is rather an activity that requires experience, dexterity and precision.

The two basic tasks involved in termination are cut and connect. If pre-terminated wire and cable are delivered to the job site then the cut part of the task no longer requires as much work, the challenge would be where to connect and how to connect.

Surgical assistants such as DaVinci Xi shown in Figure 9 would be supportive of the electrical team. They are robots that are currently used in various surgical operations. The surgical assistant acts as the surgeon's eyes and hands, which are designed to work in tight space inside the human body. During a surgery, one hand holds a lighted, high definition camera that acts as the surgeon's hands when the other hands hold the rest of the surgical tools. In this case, the robot is operated by the surgeon from the high-tech station. Surgical assistants at the operating table are responsible for observing the patient and making any necessary changes to the tools on the robotic arms (Robotic- assisted Surgery – How it works).

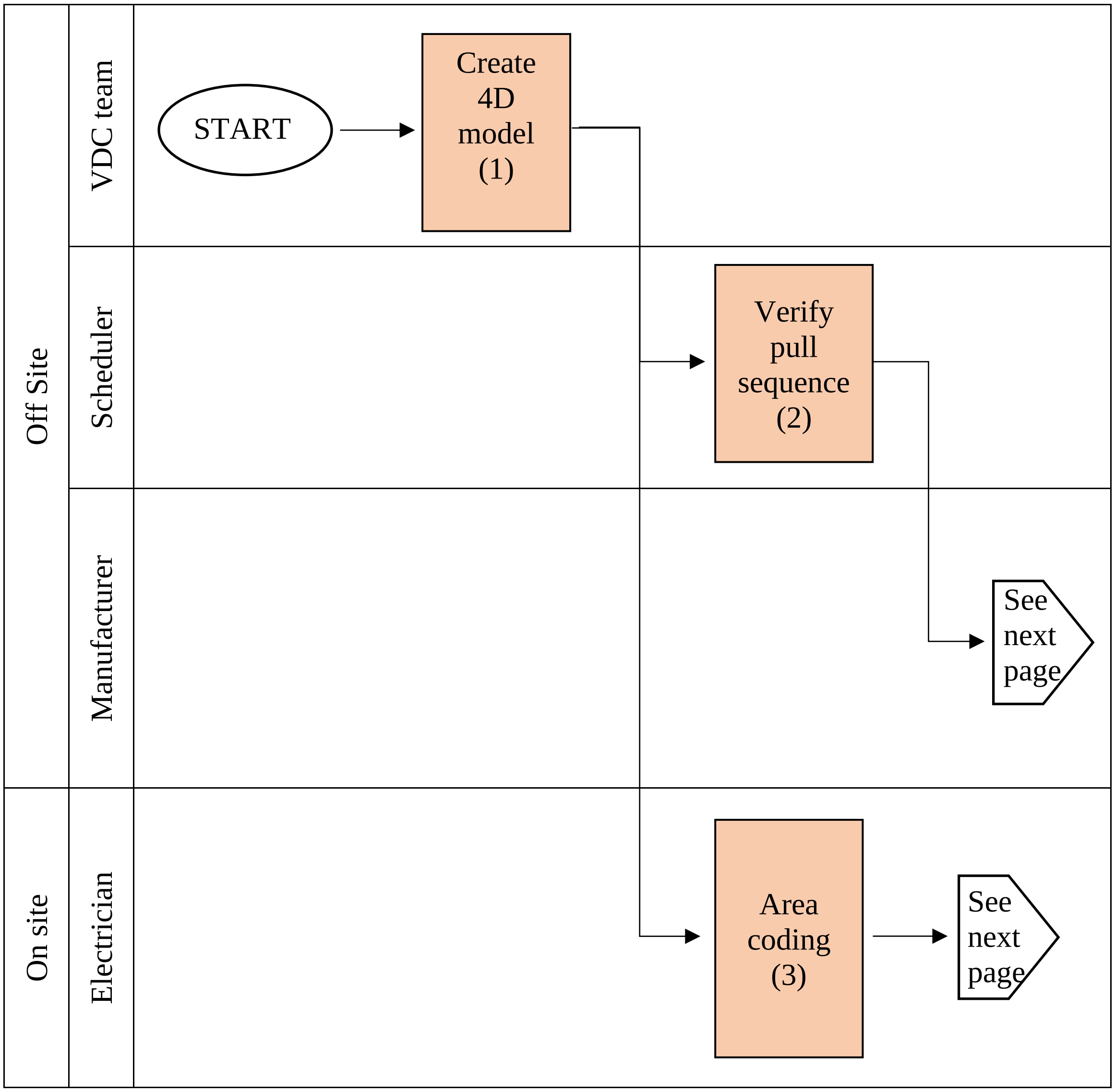
Figure 9: Da Vinci Xi Surgical Assistant

Although the surgical robots are teleoperated by a human (the surgeon) that directs the robot, an apprenticeship learning approach has been proposed (Van Den Berg et al., 2010) to extract smooth reference trajectories by recording the human guided back-driven motion of the robot. This enables the robot to be programmed for several scenarios. Literature demonstrates how human behavior can be translated into patterns that can be used by robots.

A mobile version of the robot would integrate tools required to connect the cables to the patch panel or servers (instead of having staplers or grippers, as required for medical applications). The robot could be programmed to bundle wires together as well, since there are already existing tools for this task. Having one robot accomplish several tasks would be advantageous. A robot can also work all the time without getting distracted or taking breaks, thus, it can reduce overall construction time. In short, a robot can relieve workers from overworking themselves to meet high pressure deadlines.

The proposed cable pulling and termination process is illustrated in Table 4. The following new activities were introduced to the process. Activity (1) Model cable runs, activity (2) Confirm pull sequence, activity (3) area coding, activity (4) Fabricate pre-terminated cable, activity (7) Update BIM model. The activities highlighted in orange are new activities while the activities highlighted in yellow are existing activities that have potential of being automated as per precedence provided from other industries.

5.5 Proposed Process Map



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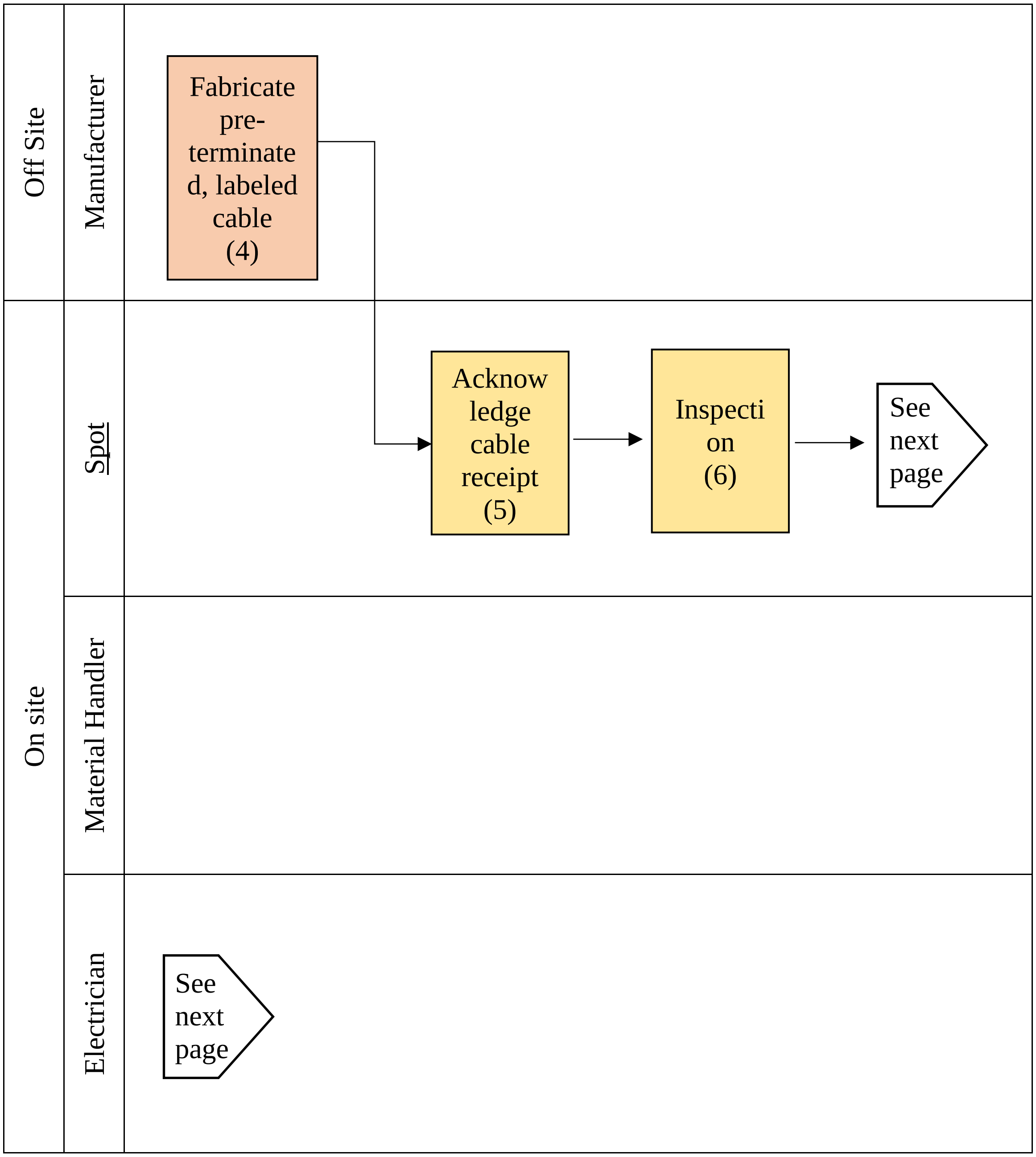
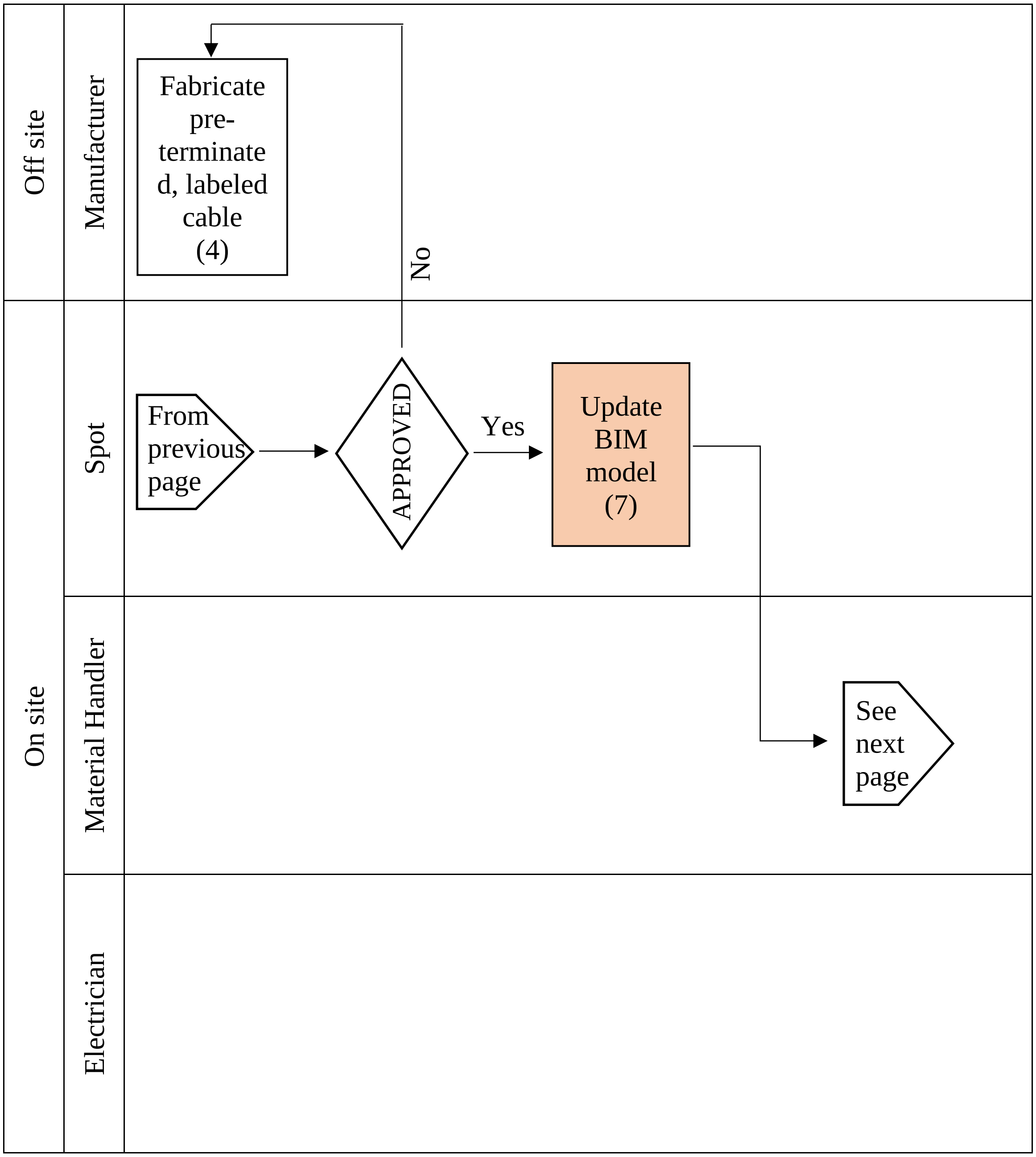
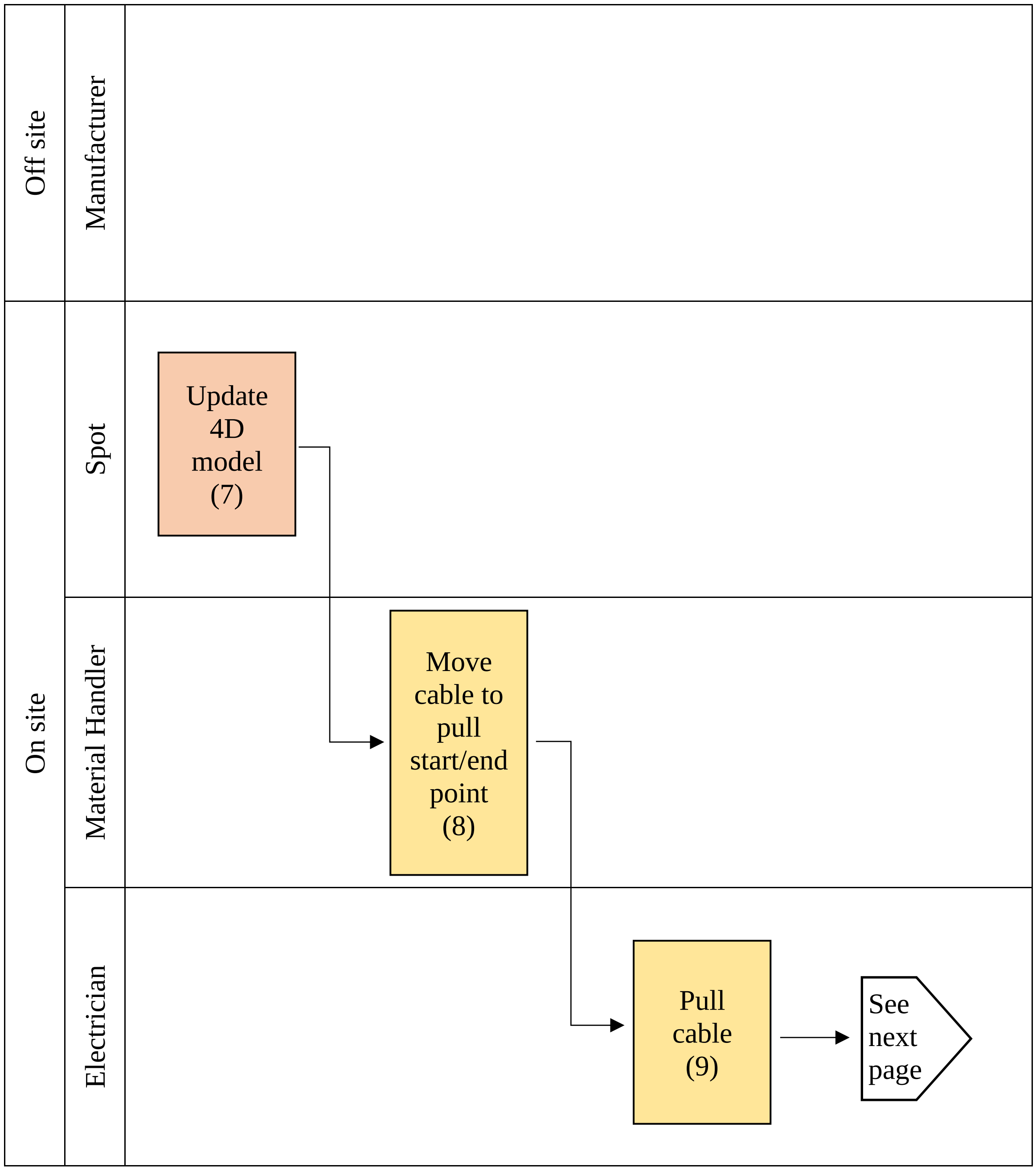

Off Site
Manufacturer
Fabricate pre-terminated, labeled cable (4)
On site
Spot
Acknowledge cable receipt (5)
Inspection (6)
See next page
Material Handler
Electrician
See next page

(continued)


Off site
On site
Manufacturer
Spot
Material Handler
Electrician
Fabricate pre-terminated, labeled cable (4)
From previous page
APPROVED
No
Yes
Update BIM model (7)
See next page

(continued)


Off site
Manufacturer
On site
Spot
Material Handler
Electrician
Update 4D model (7)
Move cable to pull start/end point (8)
Pull cable (9)
See next page

(continued)

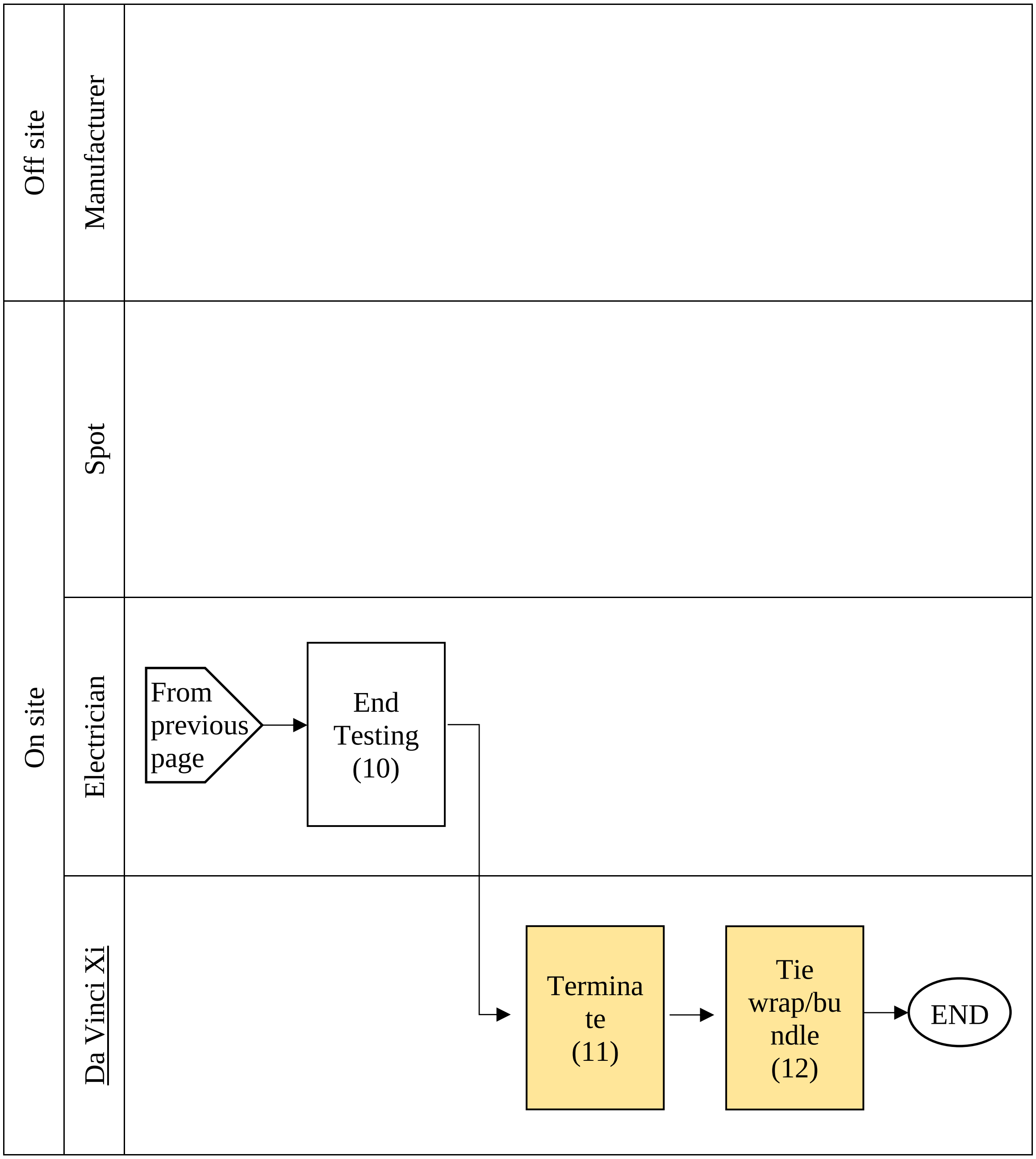


Table 4: Proposed Process Map

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

Cable pulling and termination is one of many construction processes that need an improvement effort. The growing demand for data centers has created a more urgent need to start analyzing processes that make up a huge scope of data centers construction work. The current cable pulling and termination process was mapped to understand the complete picture of what is happening, then it was analyzed through several layers to determine waste and areas of possible improvement. Automation was also explored as an opportunity for improvement and was re-injected to restructure the process in its entirety.

The proposed process presented a future state of practice that would leverage the best abilities of both humans and machines/robots. However, this is not the only possible future state, nor it relates to all the phases involved in the cable pulling and termination process. This study is focused on the roles of personnel who directly handle material although there are other team members, involved in the planning and management aspect of the process, such as the Designers, Site Project Manager, Superintendent and Project Engineer who play crucial roles in the completion of the process.

A limitation of this research is that it is based on visiting three construction sites. While the fundamental process activities should be the same across all data center construction sites, there might be some practice variations based on a firm's specific procedures or project circumstances. In addition, the specific duties of each role on a job site might be different from one electrical subcontractor to another. Furthermore, the researcher assumed that the company has the capabilities to employ a VDC team and perform regular and timely updates to construction schedule. Having the capacity to pay for robot related expenses is another assumption that the proposed process has been built on.

However, the methodology used to improve the cable pulling and termination process can be applied to improve other construction processes. Future research can implement and test the proposed process on an active data center project. Investigating the extent to which the mentioned robots can be adapted and scaled for the construction industry is also an area that requires further research. Lastly, the cost-benefit of implementing the proposed process is a scope that needs careful consideration.

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