AUTOMATION OF REBAR TYING IN THE PRECAST CONCRETE MANUFACTURING PROCESS

by

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(Under the Direction of Stephan Durham)

ABSTRACT

The purpose of this research is to assess the existing state of practice for automation in the precast industry and analyze the existing workflow of producing precast double tee products at an existing precast concrete facility located in the Southeast United States. A survey instrument is used to quantitatively evaluate how stakeholders at the precast facility value various outcomes of automation. The results of this survey are used to create a decision matrix, where various solutions for automated rebar tying are evaluated. The research also includes the creation of technical standards for developing a new automated rebar tying device. The automated process established in this study is mathematically modeled for its cost and time outcomes using electrical actuator parameters, constraints of similar technology on the market, and double tee geometry and mesh patterns. This quantitative analysis reveals that the new process would result in an 89% reduction in cycle time per double tee product. Qualitatively, the risk of workers experiencing low-back disorders is reduced due to the reduction in nonneutral postures required for manually tying rebar.

INDEX WORDS: AUTOMATION, PRECAST CONCRETE, PRECAST CONCRETE MANUFACTURING, REBAR TYING, STANDARD WORK COMBINATION TABLE

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MANUFACTURING PROCESS

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1.0 INTRODUCTION

Precast concrete has become increasingly popular over the last century as a more efficient method for construction due to its high production output in a controlled, off-site manufacturing environment. Although many other manufacturing industries have seen increasing levels of automation in many areas of their process, the precast industry nationally lags in this trend due to its large variability in products, older facilities, and tight output goals. Although automation in precast concrete has been executed before, the majority of these cases involve a complete redesign of a facility or a new fully automated facility altogether.

This research assesses the current state of practice for automation used in precast concrete production and other applications. A comprehensive literature review summarizes existing technologies used in the design, manufacturing, and quality assurance of precast concrete. In addition, the literature review covers various methods for modeling and assessing the effectiveness of an automated manufacturing process. Further, the review examines precast producers that have embraced automation in their plants. After a thorough examination of the state-of-the-practice for automation in the precast manufacturing process, the scope of this research is defined as well as documenting how this research fulfills an area of critical need. The existing precast manufacturing process is observed to gain an understanding of the production environment and identify areas for improvement. In addition to physical observation, work combination data is analyzed to determine which task of the current process is the most time and labor-intensive. Based on the physical observation and work combination data, it is determined that the rebar tying step of the precast processing is the most time and labor-intensive and would benefit the most from automation. The rebar tying stage involves a worker standing on top of a horizontal concrete bed and bending at the waist. Over long shifts, this can create strain on the lower back and possibly cause injury.

Additionally, fatigue slows worker production near the end of a shift. Next, a quantitative evaluation of the various outcomes, or values, of automation is conducted. These values are defined as: economic efficiency, time, integrability, worker safety, adaptability, quality, and durability. This quantitative evaluation is accomplished through a qualitative survey completed by various stakeholders at the precast facility used in this case study. The survey results are used to design a weighted decision matrix, in which various existing technology for the specific automated task are compared against one another according to the values defined prior. This existing technology is used to inform the capabilities of a new, automated device that does not exist yet. These capabilities and specifications are outlined in the form of a technical standard, where the control mechanisms, required operating span, tolerances, and degrees of freedom of this new device are described in detail. Ultimately, the goal of this technical standard is to describe the details a designer would need to create such a device to be used in precast applications. Because investing in new technology requires a high initial investment, it is essential to assess the potential impact of the investment first. Numerous software exists for simulating the cost, duration, material usage, and a multitude of engineering properties of a manufacturing process. However, these software packages are not particularly useful for this research study due to many of the existing technology used in precast not having advanced simulation capabilities yet. Instead, a mathematical expression is developed to model the time duration of the new operation. The resulting equations serve as a function of a variety of processing parameters related to the rebar tying operation. Another important outcome to assess is safety. While safety can be challenging to model quantifiably, a qualitative assessment of the safety impact (informed by international health and safety regulations) is included as a deliverable of this research. Final recommendations to the precast facility, a technical standard for an automated rebar-tying machine, and quantitative and qualitative analysis of the proposed automation are included as deliverables of this work. While these exact results are specific to the precast facility referenced in this case study, they can be used as a framework to similar precast facilities seeking to incorporate automation of a single task into their existing process.

1.1 Structure of Thesis Chapters

This document encompasses seven chapters that explain the development of an automated task for the precast manufacturing process and its potential benefits. Chapter 2 provides background on the precast industry in the United States and a basis for the materials and typical process for precast concrete. Chapter 3 is a comprehensive literature review of the existing applications of automation in precast manufacturing as well as various analysis methods for evaluating cost, time, and safety outcomes of automation. Chapter 4 defines how this research addresses a significant need in the precast industry and contributes to a gap in the body of work on this topic. In Chapter 5, raw data and the existing manufacturing process at the precast facility is described, and the methodology for how this information will inform the final automated process and corresponding analysis is outlined. Chapter 6 contains results from the survey methodology, survey analysis, technical standards, and quantitative and qualitative benefits outlined in the previous chapter. Finally, conclusions and recommendations are summarized in Chapter 7, and potential areas for future work are described in Chapter 8.

2.0 BACKGROUND

2.1 Overview

The following chapter provides the historical context for precast concrete, particularly as it pertains to its popularization in the United States. The chapter describes the most common precast products and their demands in the industry, as well as the various materials that go into precast products. Finally, the typical manufacturing process for a precast concrete product is described.

2.2 Precast Introduction

Modern precast concrete became popular across North America and Western Europe in the early 1900s when English engineer John Alexander Brodie patented the first process of creating precast concrete paneled buildings. The first precast structure in the United states, the Walnut Lane Memorial Bridge in Philadelphia, first appeared in 1950- just a few years prior to the establishment of the Precast Concrete Institute (PCI). The precast method for manufacturing allows for continuous production off-site in a controlled environment, as opposed to traditional on-site methods. Recent decades have seen the construction industry adapt to the growing demands and changing needs of modern society. Today, precast concrete is widely considered as a cost-efficient, productive, and safer means of concrete construction.

2.3 Products

General products that come out of precast facilities include beams, structural wall panels, facades, prestressed elements, and manholes/round elements. Kuch et. al. details the different categories of precast products and their respective loading conditions below (**Figure 2-1**).

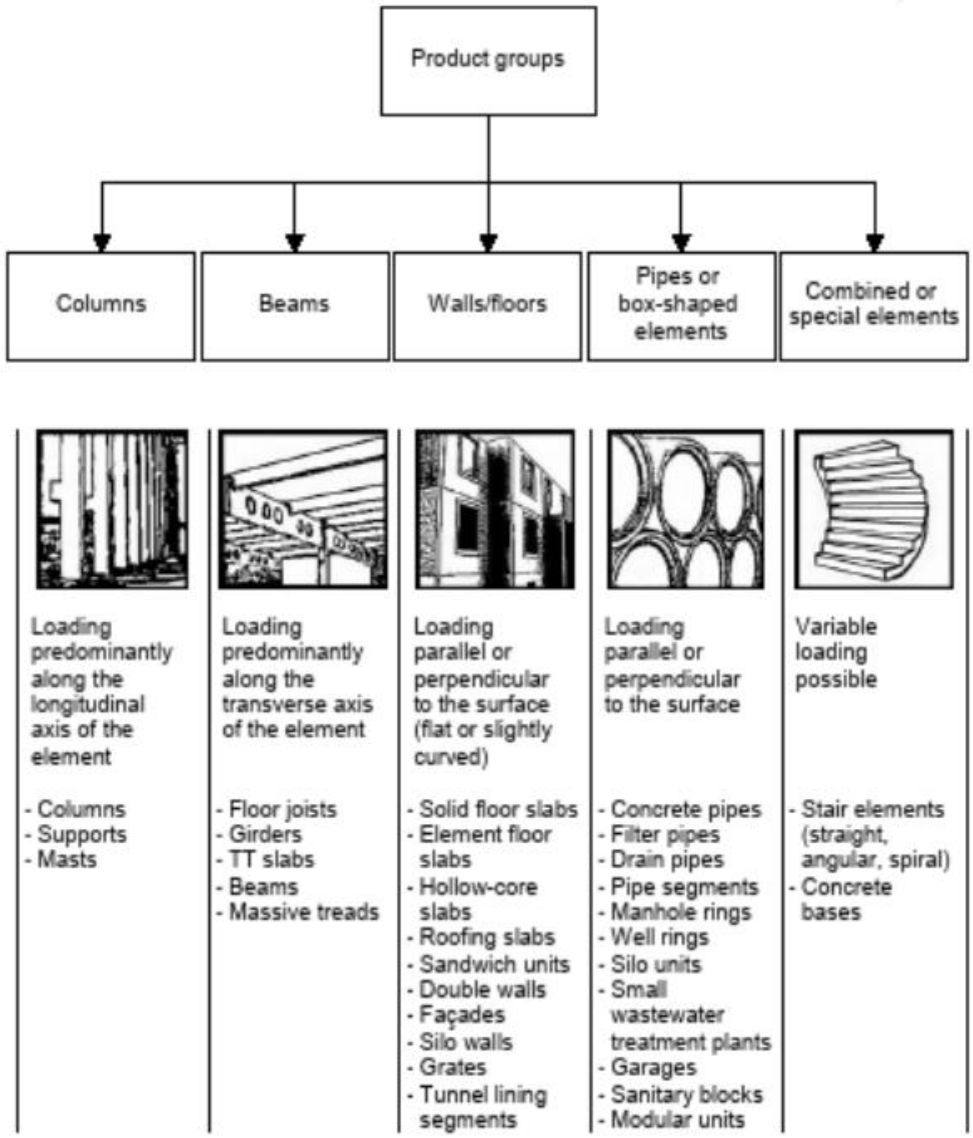


Figure 2-1. Classification of Precast Elements (Kuch et. al. 2010)

Many of these products are highly nonstandard and are made to fit the specific needs of the customer. Because of this, precast production facilities need to be highly flexible and capable of accommodating many different types of products. It is important to note that prestressed reinforcement is common in long-line bed precast processes because it improves structural performance and tensile strength. Prestressing is accomplished by inserting high-strength steel strand or wire into the formwork and tensioning it to a desired stress along the span of the precast bed.

Although many traditional precast facilities in the United States produce a wide variety of products, certain structural elements are in higher demand than others. A 2019 market study by Reports and Data consulting firm shows that columns and beams account for the largest market share (~25%) of precast products. Due to their attractive structural properties, precast beams and columns provide more expansive open spaces by reducing the number of columns present per area. Precast walls and barriers are anticipated to experience the highest growth (7.8%) during the forecast period of 2016-2026. The material's durability, thermal strength, moldability, and sound absorption properties make it an attractive choice for applications in residential streets, highways, parts, and outdoor sound barriers. As for the sector that dominates most of the market share, the residential sector has grown to account for 40% of the market in 2018 due to increasing investments in real estate and a growing need for residential buildings. The commercial construction sector, however, is anticipated to experience the highest compound interest growth rate of 6.3% during the forecast period.

2.4 Materials

Many materials go into the production of precast concrete. Not only do precast facilities need to be responsible for concrete mixtures, but rebar, high strength strand (prestressed steel), insulation, and conduit are also important elements of precast concrete.

While concrete is much weaker in tension than compression, steel reinforcement "rebar" can significantly improve tensile strength while correcting any imbalance. First, carbon steel is typically melted down to a semi-liquid state. Then, the liquid steel is pulled through small openings to give the rebar its cylindrical shape- a process known as extrusion. Once the steel has been extruded, the rebar is bent and twisted to ensure it stays secure in the concrete structure. The thickness and reinforcement ratio are selected to the structural requirements (Kuch et. al. 2010).

Welded wire reinforcement arose to correct the shortcomings of rebar (Stocking 2016). A lattice of longitudinal and transverse high-strength steel wires is welded together to produce a higher strength (by weight) final product than simple bars. The configuration of wire into sheets also makes it easier to place and secure the mesh into a precast concrete product. The tradeoff of welded wire instead of traditional rebar is, of course, a higher associated expense (Stocking 2016). Higher initial investments are needed to cut and bend the sheets of materials so it can be rolled into cylinders and cages, although many precast facilities purchase rolls of welded wire mesh from outside suppliers. Another disadvantage is its lower weight compared to rebar, as the welded wire sheets are more easily displaced during concrete placements.

Prestressing can significantly improve concrete's tensile strength. By imposing a longitudinal force in the structural element, tensile stresses are reduced at the critical midspan and support sections to prevent flexural cracking. This imposed longitudinal force is also known as prestressing force, i.e., a compressive force that prestresses the structural elements along their span prior to the application of dead and live loads (Nawy 2006). Unlike traditional concrete reinforcement, prestressing strand exerts a force of its own on the concrete member. The concept of prestressing concrete, a product of the twentieth century, was revolutionary because it allowed the designer to control the flexibility of a structural member without influencing its strength. According to AASHTO, prestressing reinforcement must be:

- High strength seven wire strand
- High strength steel wire
- High strength alloy bars of grade specified by design engineer

The steel must be stress relieved by heating the strand to approximately 662°F (350 °C) and cooling slowly, which reduces the plastic deformation of steel after yielding. Steel used in prestressed applications must be high strength, ductile, bendable, high bond, low relaxation to reduce losses, and corrosion resistant. Strands are typically made of 6 wires wrapped around one slightly larger center wire and compacted through a die. Standard specification for low-relaxation, seven-wire steel strand for prestressed concrete are included in ASTM416.

Self-consolidating concrete (SCC) is an advanced concrete material that can flow and consolidate under its own mass without vibration and resist segregation. (Koehler et. al 2007). In the precast industry, self-consolidating concrete is on the rise to increase productivity, improve safety, and enhance concrete quality. Three attractive properties of SCC are its ability to flow under its own mass, ability to pass through congested reinforcement, and its ability to resist segregation (Koehler et. al 2007).

Concrete additives are small quantities of powders or liquids that are included in the concrete mixing process. They modify the chemical or physical properties of fresh and/or hardened concrete. **Table 2-1** demonstrates the range of possible additives:

Table 2-1. Types of Concrete Additives (Kuch et. al. 2013)

Type/mechanism of action	Abbreviated designation
Concrete workability agents	CWA
Plasticisers	P
Air-entraining agents	AEA
Waterproofing agents	WPA
Retarders	R
Setting/hardening accelerators	S/HA
Shotcrete setting accelerators	SSA
Grouting aids	GA
Stabilisers	ST
Sedimentation reducers	SR
Chromate reducers	CR
Foaming agents	FA
Elastic hollow spheres for air-entrained concrete	
Expansion aids	
Sealants	
Passivating agents	

Insulating precast concrete wall panels is common industry practice. Insulated precast concrete provides many benefits in energy efficiency structural versatility, since they can often resist seismic and wind forces and therefore reduce the need for additional structural columns. The National Precast Concrete Association defines an insulated precast wall panel as two layers of concrete separated by a rigid layer of insulation, as shown in **Figure 2-2 (**Handorf 2012).

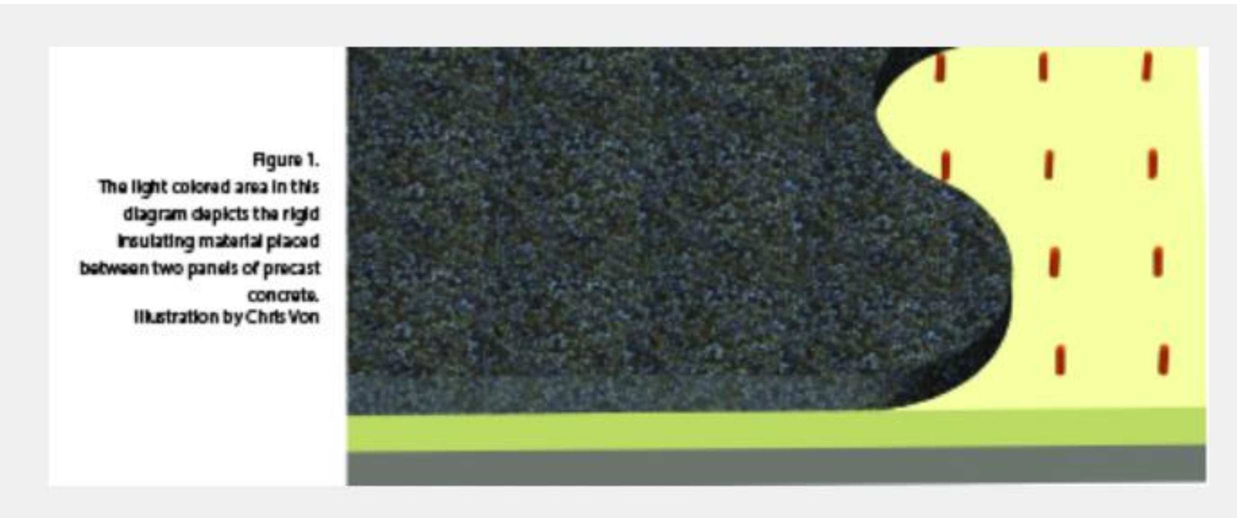


Figure 2-2. Insulated Concrete Wall Panel

The common types of insulation in precast insulated wall panels are:

1. Expanded polystyrene (EPS), R-value: 3.85/in (1.52/ cm). to 4.35/ in. (1.71/cm) (varies with material's density)
2. Extruded polystyrene (XPS), R-value: 5.0/in. (1.97/cm)
3. Polyisocyanurate, R-value: 6.0/in (2.36/cm). to 8.0/in. (3.15/cm)

2.5 Precast Concrete Production

Prefabrication has become popularized as an efficient alternative to traditional construction (Pan et al. 2012). For one, the controlled environment of a prefabrication facility offers several advantages, such as increased material efficiency, increased workflow continuity, increased safety, and reduced time wastage. Precast concrete is one application of prefabrication, where a construction product is produced by placing concrete into a reusable mold and curing it in a controlled environment. The general precast production process is as follows:

1. Assemble the rebar cage by cutting rebar to appropriate lengths according to the bill of materials and then bend and tie them together.
2. The form is prepped by looking for knockouts (thinner wall sections that allow for openings to be knocked out) and applying form oil.
3. The rebar cage is lifted using a crane and lowered down into the form. Each product undergoes pre-pour inspection.
4. If prestressed reinforcement is used, high strength steel wire is placed in the pre-determined locations within the form and tensioned to desired jacking stress with hydraulic jacking device.
5. Concrete is placed into the formwork. In some instances, vibrating tables are used to ensure concrete is completely settled into form.
6. The concrete product is left to cure overnight. The controlled environment of factory enables the product to properly cure and reach the full design strength.
7. The outer jacket of the mold is opened, and final product is moved via crane to the inspection area.

3.0 LITERATURE REVIEW

3.1 Overview

This literature review defines automation at a high level and discusses various types of automation that are suited to precast concrete manufacturing as well as specific operations that can be improved upon with automation. The literature review examines common problems associated with the precasting/prestressing process in addition to trends and challenges of the precast industry. Several case studies of existing facilities that have implemented automation are discussed at the conclusion of the chapter.

3.2 Automation Overview

Automation can mean different things to people in different industries. It has expanded beyond its roots in manufacturing to industries such as healthcare, transportation, agriculture, energy, construction, and more (Goldberg et. al. 2011). Automation first began as the implementation of robotics to perform specific tasks, but now has distinguished itself from robotics alone. According to the Institute of Electrical and Electronics Engineering (IEEE) field of interest statement, "...Robotics focuses on systems incorporating sensors and actuators that operate autonomously or semi-autonomously in cooperation with humans. Robotics research emphasizes intelligence and adaptability to cope with unstructured environments. Automation research emphasizes efficiency, productivity, quality, and reliability, focusing on systems that operate autonomously, often in structured environments over extended periods, and on the explicit structuring of such environments." While robotics focuses on feasibility of new operations, automation focuses on improving quality and efficiency, although the two fields are closely related.

Generally, the type of automation is categorized in terms of the production volume and product variety. The distinction is shown in **Figure 3-1**.

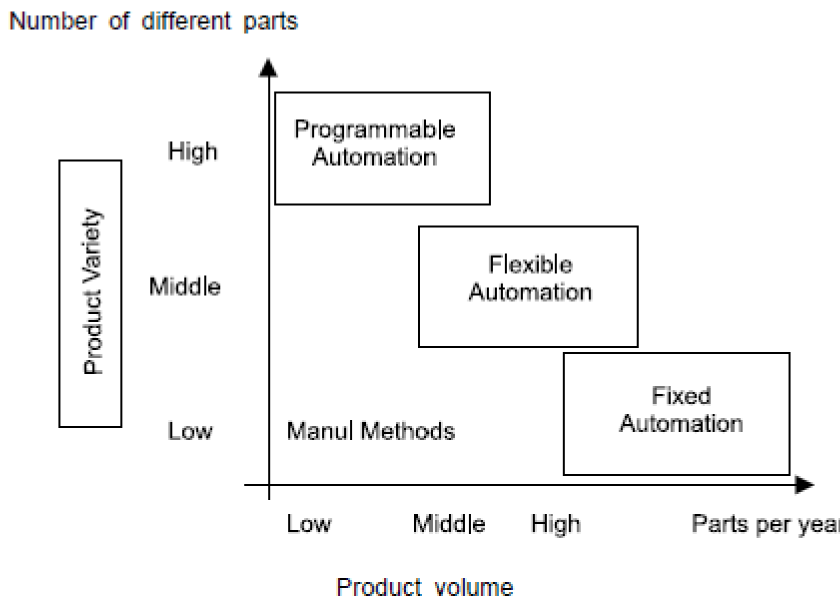


Figure 3-1. Levels of Automation (Groover 2019)

3.2.1 Fixed Automation

In manufacturing, fixed automation (also called hard automation) refers to an automated production facility where the sequence of operations is fixed according to the equipment configuration. This type of automation is most known for high initial investments and high production volumes. Automated assembly machines and machining transfer lines found in the automotive industry are examples of fixed automation. When a new car model is created, the entire production line needs to be reprogrammed and reconfigured to meet new model specifications. In fixed automation, programmed commands are not easily changeable from one product to another (Groover 2019).

3.2.2 Programmable Automation

With programmable automation, products are produced in batches (Groover 2019). For each new product batch, equipment must be reconfigured and reprogrammed to accommodate a new style. Compared with fixed automation, production rates are much lower since there must be time allotted for changeover. In the construction industry, however, many different customized products are produced. Any precast plant may produce the breadth of products described in **Figure 2-1.** Even for one specific precast product, a facility would need to accommodate a variety of sizes, geometries, and reinforcement patterns. Therefore, the precast industry is more suited to programmable automation.

3.2.3 Flexible Automation

As shown in **Figure 3-1**, flexible automation offers a lower product variety and, consequently, a higher production volume than programmable automation. In other words, the variety of products offered by flexible automation is limited so that changeover can be executed quickly and automatically (Groover 2019). The reprogramming of the equipment is accomplished at a computer terminal rather than the equipment itself. Because of this flexibility, a variety of products can be produced sequentially without having to group batches of products together.

Depending on the task, flexible automation is possible in the precast industry since it allows for some product variety without slowing down production significantly. Flexible automation is not feasible for every task in the precast process, however, and there may be some level of equipment configuration necessary.

3.3 Automation Used in Precast Manufacturing

Automation is not as widely adopted in the construction industry as other industries because it tends to favor productivity over innovation. The construction industry is marked by tight deadlines and output goals to meet consumer needs. At-large, the construction industry is operated by small and specialized subcontractors who typically do not have the technological advancements to embrace automation (Neelamkavil et. al. 2009). The exception, however, is the sector that represents factory-built construction, which includes precast, prefab, panelized, etc. Since the use of mass production and mass customization is characteristic of a manufacturing environment, the use of robotic technology is on the rise in the prefab industry. Many aspects of the precast concrete manufacturing process can be made safer, more efficient, and less expensive with automation. One of the largest driving forces for automation in the precast concrete industry is lack of talent available. In their skills gap study, Deloitte Consulting and The Manufacturing Institute reported that 67% of the respondents from the manufacturing sector have a "moderate to severe shortage of available, qualified workers" (Deloitte 2018). This Deloitte study also shows that 2.6 million people are expected to retire from the manufacturing jobs over the next decade. More than half of the open manufacturing jobs in 2028 could remain unfilled due to shifting skill sets due to the introduction of advanced technologies and the retirement of a large generation of workers. Consequently, the manufacturing industry at-large is moving quickly toward a future where automation is "embedded across functions, and humans may need to work alongside robots and machines to deliver higher productivity" (Dollar et. al 2018). Even design and quality assurance stages can have elements of automation with new technology and AI algorithms.

Pan et al. (2012) defines four generic, multipurpose robots that can execute ten basic tasks: positioning, connecting, attaching, finishing, coating, concreting, building, in-laying, covering, joining. Automation in precast concrete production covers a broad spectrum of mechanized systems, whereas robotics is an advanced form of automation to replace or assist humans in specific tasks or functions, generally for the circulation production system (Pan et al. 2012). Pan details examples of well-known robots applied in real-world precast production settings (**Figure 3-2)**.

In **Figure 3-2**, the leaning and plotting robots are used in the preparation step to conduct tasks such as cleaning and oiling of pallets, outline plotting of concrete elements, and collecting and installation of latitudinal anchors (Weckenmann 2017). Shuttering robots, also known as formwork robots, are the leading robotic technology in precast concrete production (Bock and Linner 2015, Weckenmann 2017). Robotic reinforcement production systems (reinforcement robots) are used to automate rebar cutting, bending, and binding, which could also be an on-site application or conducted by a specific reinforcement supplier (Neubauer 2017).

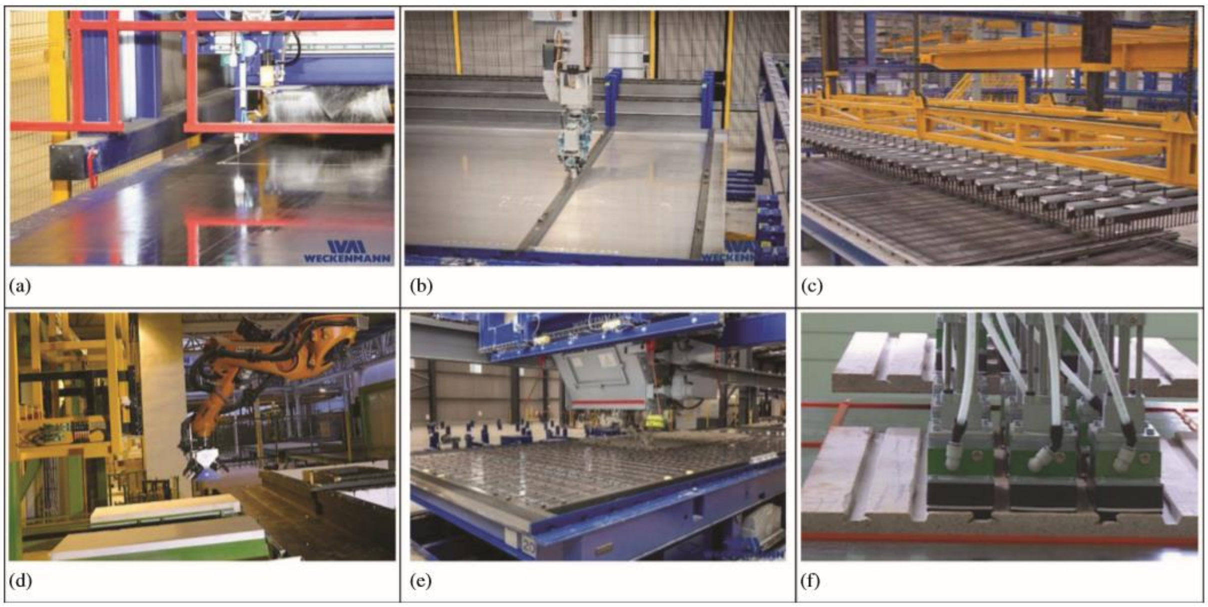


Figure 3-2. Robotics Applied in Precast Production – (a) Preparation, (b) Shuttering Robots, (c) Reinforcement Robots, (d) Insulation Robots, (e) Robotic Concrete Spreaders, and (f) Cladding Robots

Robots for insulation cutting and insertion are used to cut the size of insulating materials according to CAD data to fit the precast concrete elements, place insulation parts, and mount the wall connectors (Neubauer 2017; Sommer Precast Technology 2018). Robotic concrete spreaders are used to automatically control the discharge of the concrete and surface smoothing in casting for the optimum production of concrete elements (Bock and Linner 2015; Weckenmann 2017). Precise casting can be achieved, resulting in substantial concrete saving. Robots for cladding can quickly and precisely apply tiles or clickers onto the concrete surface (Sommer Precast Technology 2018; Weckenmann 2017).

The manufacturing flow can be either a stationary or a circulation system (**Table 3-1**). Stationary production is the traditional approach, in which elements are manufactured on stationary tables with exclusive molds made in advance, allowing for greater product variety (Pan et al. 2012). This type of production is based on the principle of cell production and accommodates a wide range of precast concrete parts with different shuttering concepts. Although stationary facilities have lower output per hour, they allow for more flexible production. **Figure 3-3** illustrates a typical layout of equipment in a stationary production facility. Increasing labor costs and high-quality requirements led to the rise of carousel (circulation) systems. In a similar fashion to automobile production, circulation production uses pallet carousel devices for a higher production system, which is suited for only uncomplicated, standard products. (Pan et al. 2012). **Figure 3-4** is an example of a pallet circulation system, or carousel plant. This is a highly automated system for mass-production of reinforced concrete precast elements (Carousel Plant). As circulation factories become more advanced, they are beginning to integrate concepts of Closed Loop Production (CLP). A closed-loop supply system involves both forward production activities and product back-flow to the manufacturer (Cerdas et. al. 2015). A circulation factory will recycle material and remanufacture in house.

Table 3-1 Characteristics of Production Principles (Kuch et. al. 2010)

	Carousel Production	**Stationary Production**
Work Stations	Stationary	Mobile
Workforce	Stationary	Mobile
Work Equipment	Stationary	Mobile
Formwork	Mobile	Stationary

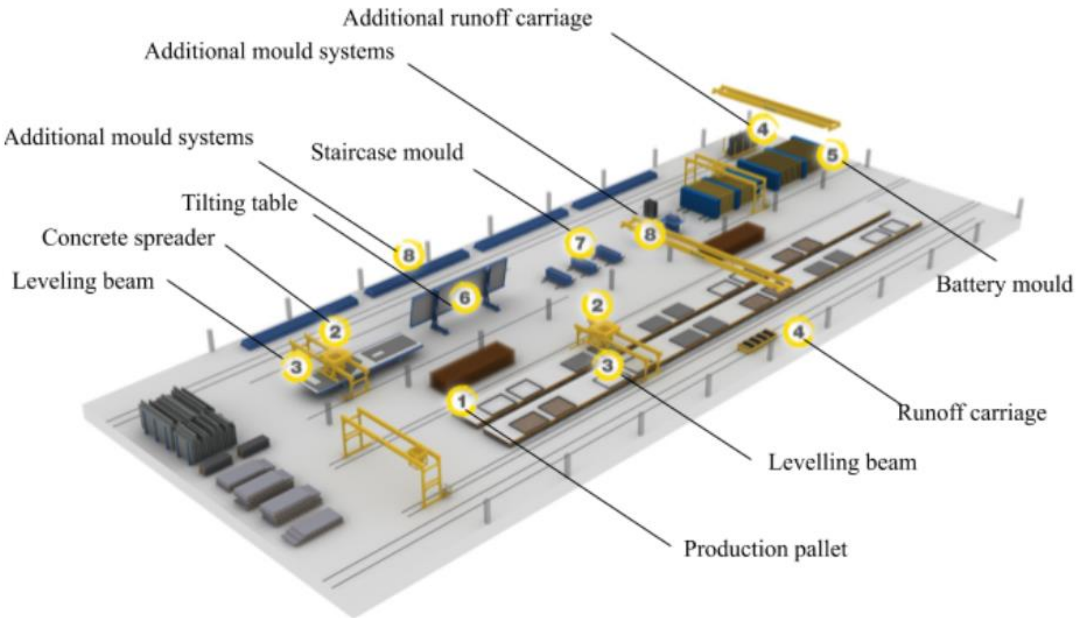


Figure 3-3. Ebawe Stationary Production (Stationary Production Plants)

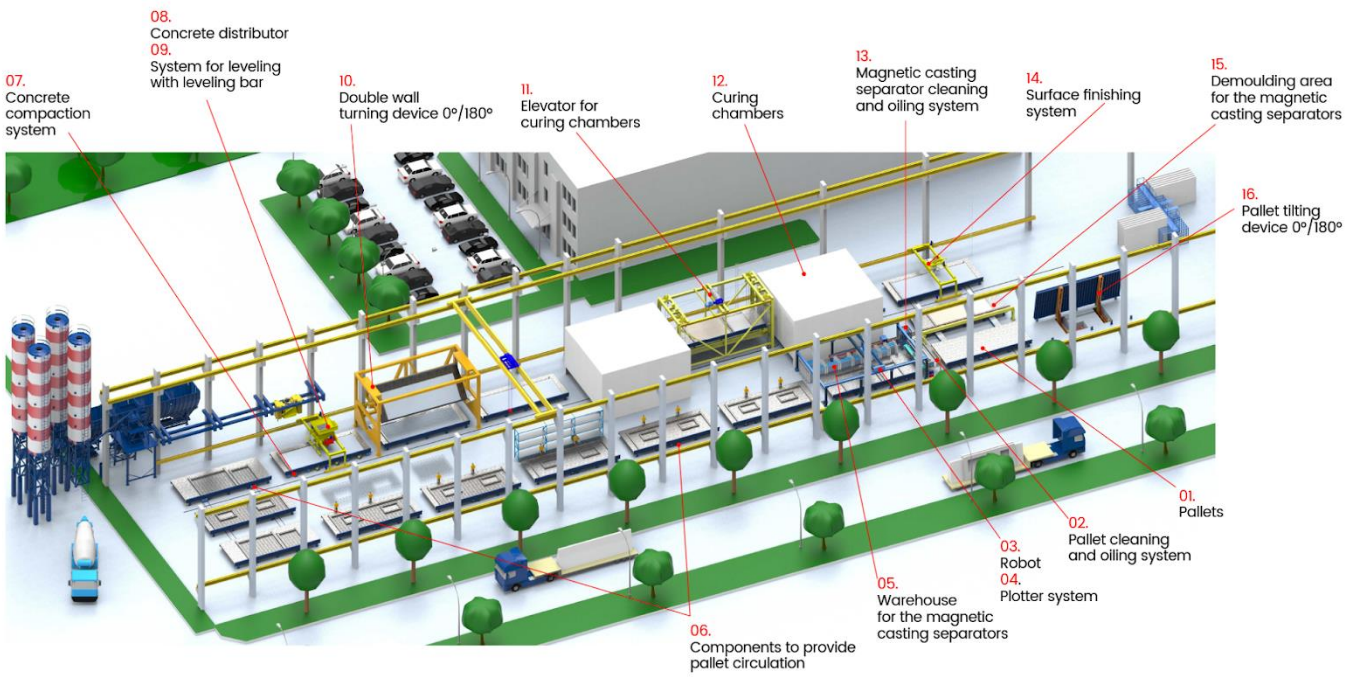


Figure 3-4. Olmet Carousel Production (Carousel Plant)

3.3.1 Automation Used in Rebar Bending

There are many opportunities for automation in metal works as well. Shah et. al (2018) discusses the design and working of an automated rebar bending system that uses 0.12 in. (3mm) diameter wire to create rectangular frames. **Figure 3-5** depicts a Solidworks rendering of the machine and its major elements These rectangular frames are used in concrete columns and beams to secure rebar in the desired position. The feeding mechanism consists of two rollers actuated by a stepper motor. The bending of the wire is accomplished with a bending die and punch, and a traditional cutter is used at the end to cut the product.

Because the motions of the machine are provided through Arduino-controlled stepper motors, it is possible to reprogram the machine to produce different sizes of frames as well (Shah et. al 2018).

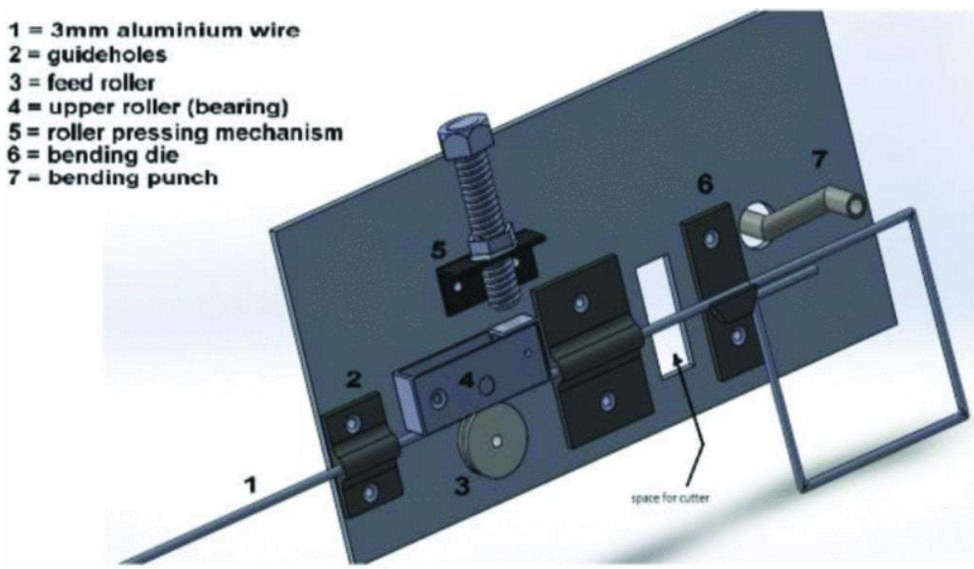


Figure 3-5. Automated Rebar Bending Machine (Shah et. al 2018)

3.3.1 Automation Used in Masonry Work

Masonry work is one of the most arduous tasks in construction (Cavieres, Gentry, & Al-Haddad, 2011; Spath & Andres, 1997) due to it involving the operator to stand, kneel, and lift. Many research studies during the past two decades focus on the development of robotic technology for bricklaying. Bricklaying work is a favorable candidate for automation because it follows predefined steps. However, it still requires supervision and control of a nearby worker and therefore cannot be fully automated. SAM100, short for Semi-Automated Mason, is a bricklaying robot designed by construction robotics. This machine is capable of laying 800-1200 bricks a day and includes a binder in the laying process.

3.3.2 Semi-Automated Rebar Tying

Altobelli (1991) developed a semi-automated device to assist workers in rebar tying. The reinforcing steel in a precast product is typically assembled by hand tying intersections of the bars with wire. Because about 75% of precast products are flat, horizontal work, workers must bend over for long periods of time to hand tie the rebar, putting large strains on the lower back over time (Altobelli 1991). **Figure 3-6** depicts the mechanisms of the rebar tying device.

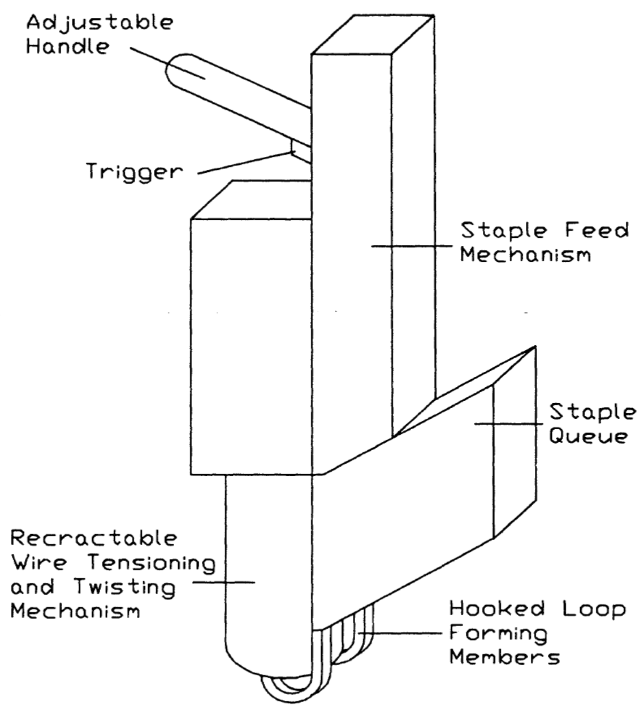


Figure 3-6. Semi Automated Rebar Tying Device (Altobelli 1991)

The machine is a handheld tool, allowing the operator to tie rebar from the standing position. The major features of this device are the staple feeding mechanism and the retractable wire tensioning and twisting mechanism. The worker pulls a trigger, and the device automatically initiates a series of actions resulting in a tied connection (Altobelli 1991). The pneumatically actuated feeding mechanism functions much like a common stapler

This device was designed with several criteria in mind. First, it is imperative that a semi-automated device for this purpose is used while the operator is standing up. Not only does this reduce the risk of injury, but it prevents the inevitable slowdown due to fatigue over long shifts. Another criterion is the ability to produce a strong, tight tie to keep the reinforcing steel from moving during construction. While tying the rebar adds no strength benefit to the finished product, it must be able to resist the dynamic load of pumped concrete and the weight of workers standing on top of it. Finally, one of the most important criteria is speed. Union steelworkers average between fifteen to thirty diagonal steel ties by hand per minute. Therefore, this device must be able to complete a tie in two seconds to remain a competitive alternative. The last criterion is durability to survive harsh plant environments. The tool must be designed to handle rain, dirt, dust, vibration, shock, and general rough handling.

3.3.3 Automation of Rebar Placement

The Shimzu Corporation has developed a “bar arrangement” machine for placement of reinforcing bars. Placing reinforcement bars is typically a long and laborious task carried out by workers. The proposed system has two vehicles, each moving along the x and y directions on a steel-frame support base. One vehicle is for arranging bars in the longitudinal direction and the other for arranging bars in the transverse directions. The vehicles carry the reinforcing bars and place them one at a time in correct positions. The entire work productivity increases to twice the manual capability (Yamashita et. al. 1990).

3.3.4 Fully Automated Mesh Welding Machine

An alternative to individually placed reinforcement bars is welding a mesh of reinforcement beforehand. As mentioned in Chapter 2.4 (Materials), welded wire mesh offers ease of placement into the concrete product compared to rebar. The tradeoff, however, is a higher associated cost due to the time and resources needed to weld the mesh, especially when performed manually. A fully automated mesh welding machine can aid in the manufacturing process of CAD-based reinforcement mesh (BFT International). The DRA-M multiple rotor straightening and cutting machine provides for flexible mesh production by automated feeding of longitudinal and cross wires from the coil.

Automating the welding of the reinforcement mesh is easily integrated into an existing precast plant. The compact machine system has a small footprint and allows for product-specific solutions. In addition, the system connects to the Unitechnik CAD/CAM Interface, allowing simple integration within the precast plant. Depending on customer needs, wire mesh coils can include cutouts for doors or windows as well. The average production output is about 1720 ft^2 /hr. (160 m^2/hr.). Further product information is in **Table 3-2**.

Table 3-2. Mesh Welding Machine MSM-M (BFT International)

Size	200/250/300/350/400
Mesh width	400 to max. 4,000 mm
Shortest wire length	500 mm
Mesh length	1,000 – 14,000 mm (larger lengths on request)
Number of wire diameter	3 – 6
Wire diameter	5 – 12 mm (optional 5 – 20 mm) from coil
Longitudinal wire grid size	25 mm
Distance between longitudinal wires	depending on longitudinal wire Ø 25 / 50 / 75 / 100 … mm
Distance between cross wires	fixed in 50 mm steps, min. 50 mm, optionally infinitely variable
Welding capacity	depending on the version up to 350 kVA
Production capacity	depending on design and mesh coverage

3.4 Precast Defects

One major goal of automation is to improve the quality and reduce defects. There are many sources of error in the precast production process that can lead to problems over the life of the concrete element.

3.4.1 Cracking from Strand Corrosion

Strand corrosion is one of the main causes of deterioration in prestressed concrete structures (Dai et. al 2020). Corrosion reduces strand cross sectional area, induce concrete cracking, degrade bond strength, and eventually deteriorate the structural capacity of prestressed elements. Ordinary corrosion is an electrochemical process in which environmental conditions affect the prestressing steel and result in a considerable loss of metal (Schupack et. al 1982). Concrete cracking due to corrosion is illustrated in **Figure**

3-7, Where R_o and R_p= radii of wire before and after corrosion, R_u= radius of the cracked region, P_u= expansive pressure at the interface between cracked and uncracked regions, C=concrete cover, R_c=R_o+C, R_t= radius of the wire with corrosion products.

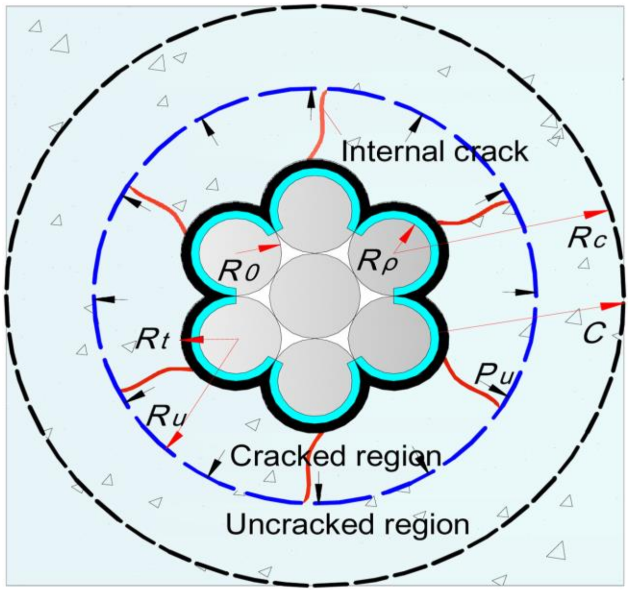
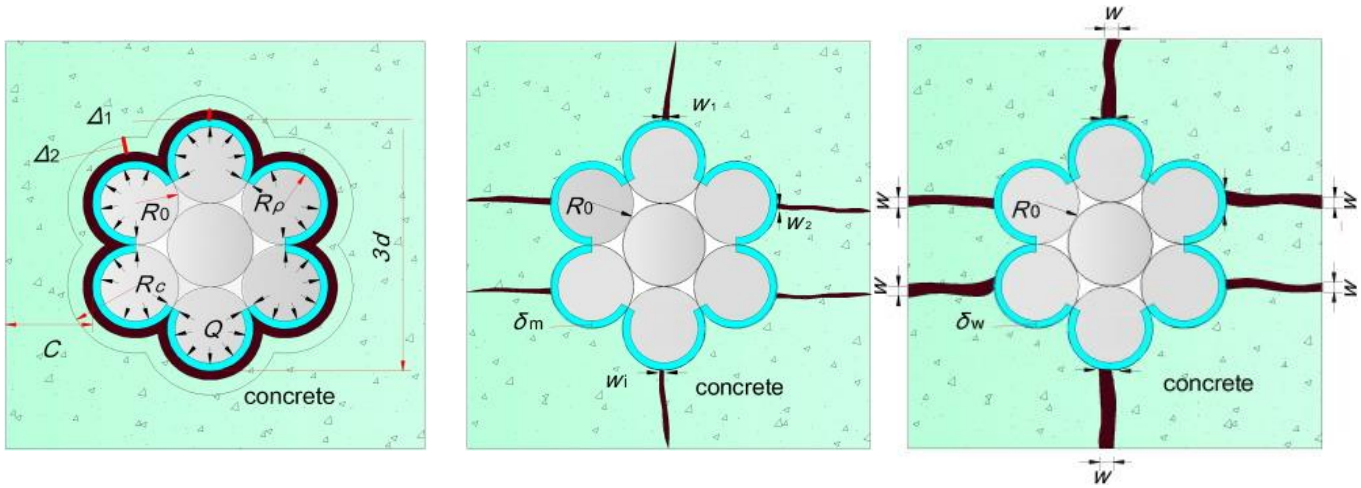


Figure 3-7. Concrete Cracking due to Strand Corrosion (Dai et. al 2020)

Practical experience and experiments show that corrosion is more likely to lead to deteriorate concrete in serviceability (i.e. cracking) than safety (i.e., strength) (Dai et. al 2016). However, the real detriment of corrosion-induced cracking is potential for harmful substances to leak into prestressed structures via channels. First, corrosion products create expansive stress at the strand-concrete interface. Since concrete is a composite material, this interface is a porous zone in which corrosion products enter. Once the tangential stress reaches the tensile strength of concrete, a microcrack forms. After microcrack formation, corrosion products build up around the strand, leading to expansive pressure-induced cover cracking. With further corrosion, the visible crack will propagate to the concrete surface. **Figure 3-8** demonstrates the progression of crack growth due to corrosion.



(a) (b) (c)

Figure 3-8. (a) Radial deformation at the strand-concrete interface (b) Schematic of cover cracking (c)Schematic of crack width Dai growth (et. al 2016)

3.4.2 Cracking in Pretensioned Anchorage Zones

One main durability concern of prestress is cracking in the anchorage zones of pretensioned bridge girders. An anchorage zone refers to the region where the transfer of force from the prestressing steel to the concrete is most concentrated, located near the ends of the structure. (Crispino et. al. 2009). These cracks form as a result of the transfer of heavy prestressing to concrete, and the size of these cracks are proportional to the amount of priestess as well as the depth of the girder (Okomus et. al 2016). Cracking appears during prestress transfer and continues to grow in width and length for months after. During the months following, prestressed girders are typically stored on simple supports with no external loading until the start of bridge construction 1-3 months later. Left untreated, these cracks would allow contaminants, such as de-icing salts, to reach the steel strands and deteriorate the structure faster than expected. Cracks in the anchorage zone tend to exhibit similar patterns, as illustrated in **Figure 3-9**.

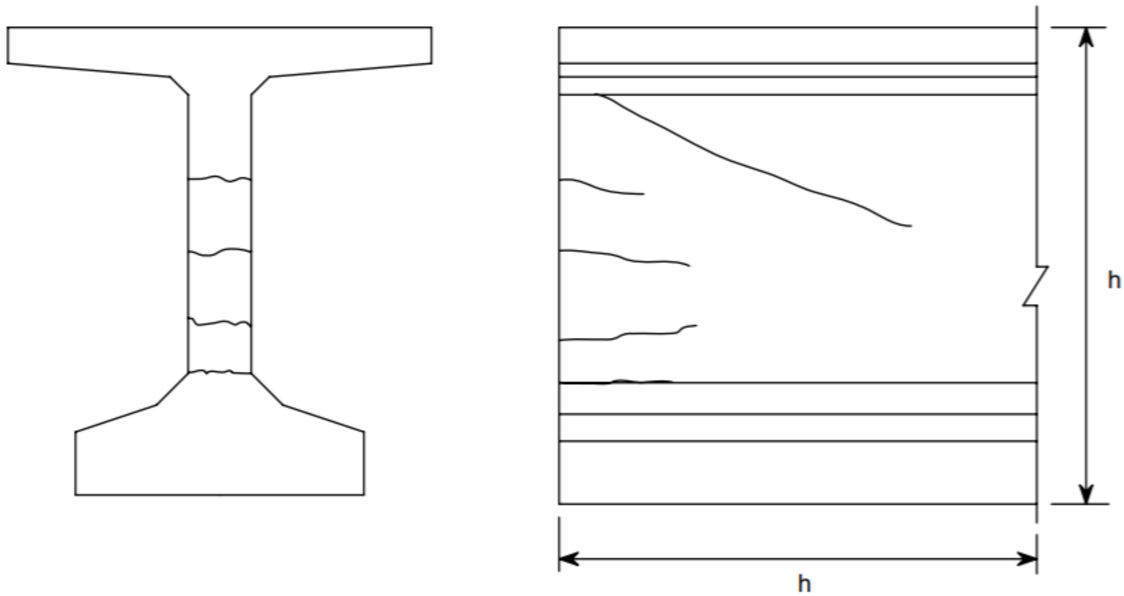


Figure 3-9. Common Crack Pattern in Precast Bulb Tee Anchorage Zone (Crispino et. al. 2009)

The crack growth is caused by thermal stresses during curing or by creep and shrinkage during the storage of the girder. A finite element method (FEM)-based investigation performed by Okumus et. al. revealed that shrinkage has the most unfavorable effect on anchorage zone cracks compared to creep and curing temperatures. However, shrinkage strains alone were not enough to cause cracking; the effects of shrinkage combined with the strains from prestress transfer cause the large majority of cracking after prestress release.

Repair of these cracks can be costly and time consuming. One common repair method is an epoxy injection along the length of the crack, which can detract from the appearance of the structure and delay production. It is worth noting that the cracking exhibited in **Figure 3-9** does not hinder the structural performance of the member (Crispino et. al 2009). Diagonal compressive struts carrying the shear force could intersect these cracks, or an additional live load could help seal the cracks. However, as investigated by Okumus et. al., these cracks can grow over time and pose a threat when they reach the steel strand.

3.5 Quality Assurance

Quality inspection of precast concrete today still relies heavily on manual inspection, which is highly prone to human error. Recently, advances have been made in the automation of quality inspection to improve accuracy and data acquisition speed. Wang et. al (2012) discusses the terrestrial laser scanner, which has been used to improve quality inspection for precast concrete. The experimental setup is demonstrated in **Figure 3-10**.

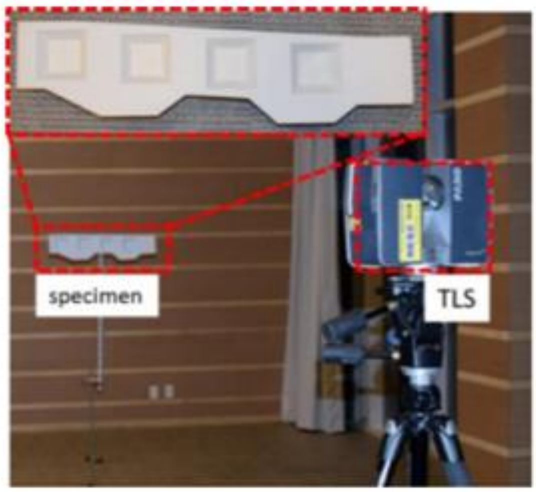


Figure 3-10. Experimental Specimen Setup for Terrestrial Laser Scanner (Wang, et. al. 2012)

The first step is noise removal, which involves a density-based clustering algorithm that removes background noise and mixed pixels from point cloud data. Then, a combination of course and fine registration is applied to best match the as-built data to the as-design object in BIM. Finally, the as-built dimensions of the precast concrete elements are extracted and compared with the as-design drawings in a building information model (BIM). **Figure 3-11** shows the four steps of the point cloud data processing obtained from the specimen. In the experiment conducted by Wang et. al, a 27.5 by 4.7 in. (700 mm by 120 mm) specimen was used to test the terrestrial laser scanner on an irregular shape.

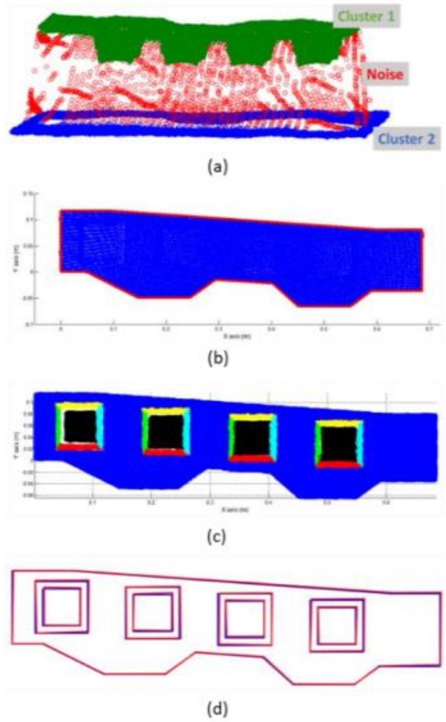


Figure 3-11. Data Processing of Point Cloud Data (Wang et. al. 2012)

Wang's experimental specimen had 14 corner points for the outer boundary and 8 corner points for each shear-key. The results of the terrestrial laser scan showed that the average distance between the as-design and as-built points was 0.04 in. (0.95 mm) and the maximum distance was 0.12 in. (2.95 mm). The average discrepancies can be calculated from there, coming out to an average discrepancy of 2.8% and 7.2%. Overall, this proposed technique proved to be effective and accurate. However, testing was only performed on a laboratory-scale precast concrete panel only and further experiments need to be examined using a full-scale precast panel. In addition, the experimental setup involved a plain background condition, whereas a real-world setting could have more complicated background noise (Wang et. al. 2012).

Automated dimension quality assurance using laser scanning and BIM was later performed on full-scale precast concrete elements by Kim et. al in 2016. Results reveal the proposed dimensional quality assurance technique achieve a measurement accuracy of around 0.12 in (3.0 mm) for dimension and position estimates (Kim et. al 2016).

The precast industry is continuing to evolve in order to keep up with a growing market and an increasingly technologically advanced world. As covered in the literature review thus far, there are many opportunities for automation in various stages of the precast process. While some of these options are in the prototype phase and others are commercially available, they all serve as a foundation to inform the decision and design process in this research study.

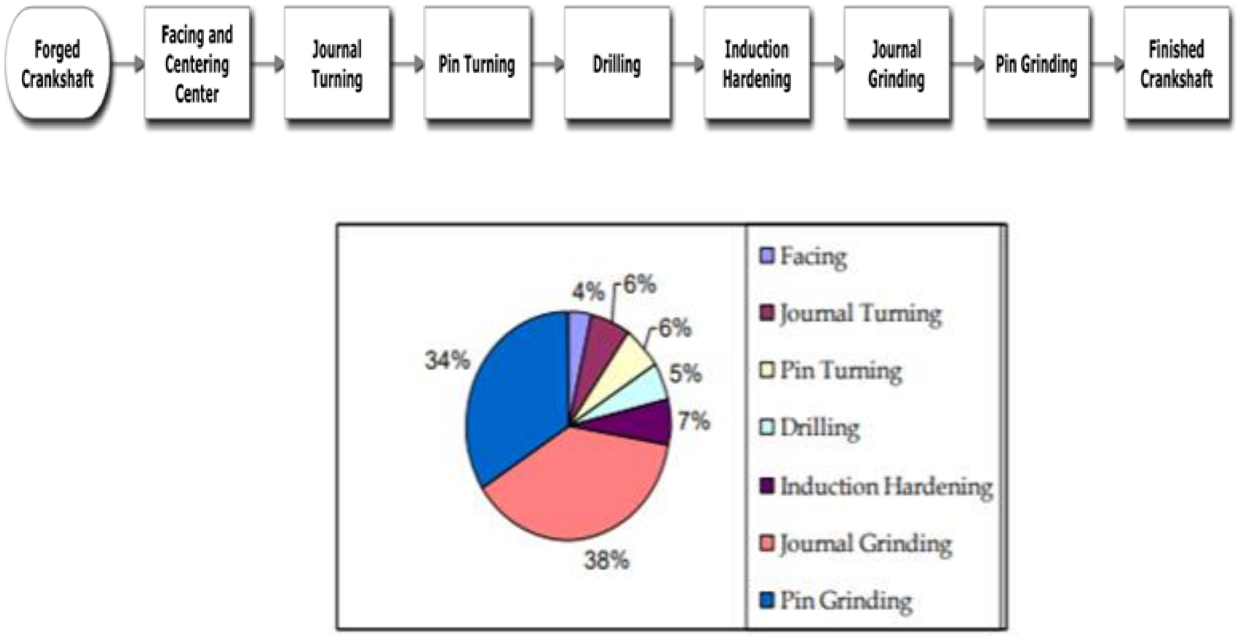
3.6 Analysis Methods

In any engineering decision, it is important to consider the potential impacts of a design decision quantitatively. This research involves the development of technical standards for an automated task. However, the proposed task must be modeled or simulated for its potential outcomes (i.e., cost savings, time savings, safety improvements). The following section focuses on various analysis methods that could be applied to the task at hand.

3.6.1 Cost Prediction

Automation requires high initial investments. When a manufacturing plant is considering automating certain parts of their operation, it is critical to have proof that the investment will pay off. There are many analysis methods that simulate cost, production output, safety, and more. Jha et. al. (2013) examined the total cost modeling for the manufacturing operations of a crankshaft. The mathematical model for multistage manufacturing is huge and highly non-linear. An automated integrated production line in a multi station computer assisted system with series operations and automated transfer of work units between stations. For each operation, a range of constraints for cutting speed, feed, and power are known. The expertise level of the engineer is incorporated into the function to create a more accurate, nuanced model. The goal is to minimize the function of these variables to determine the optimum processing parameters.

(a)



(b)

Figure 3-12. Crankshaft Manufacturing (a) Operation and (b)Total Cost (Jha et. al. 2013.)

As illustrated in **Figure 3-12a**, any multistage manufacturing operation is modeled as the sum of each individual manufacturing operation. i.e., The total cost (TC) is modeled as a function of each individual manufacturing operation, modeled as a function of its processing parameters (Equation 3-1).

$$TC = f_1 + f_2 + f_3 + f_4 + f_5 + f_6 + f_7 + f_8 \tag{3-1}$$

Note that this example of the forged crankshaft does not account for bulk deformation operations (i.e., forging) since this particular manufacturing facility only handles secondary operations (turning, drilling, grinding, etc.). When considering all the sub-processes, the grinding operations consumes a large majority of the total cost at 72% (**Figure 13-12b**). The cost function for journal grinding is modeled as:

$$f_5 = \left(\begin{array}{l} M_g \cdot \left(\frac{7.stk.d_{wg}.k_g.\pi}{1000.f_g.v_{wg}} + \frac{a_{rg}}{r_{rg}} + t_{1g} + \frac{t_{0g}}{N_g} + \frac{7.stock.d_{wg}.k_g.\pi.t_{cg}}{T_{cg}} \right) + \\ \frac{7.stk.d_{wg}.k_g.\pi}{1000.f_g.v_{wg}.T_{cg}} \cdot \left(\frac{C_{pg}}{k_{1g}+1} + \frac{C_{cg}}{k_{3g}} \right) \end{array} \right) \qquad \text{(Equation 3-2)}$$

Where, M_g = cost of grinding (dollar/min), *stk* = stock to be removed from the journal by grinding (mm), d_{wg} =initial diameter of the journal (mm), $g\ k$ = grinding constant, f_g = cross feed of the grinding wheel (mm), v_{wg} = Work speed (m/min), a_{rg}= total rapid traverse distance traveled by the tool (mm), r_{rg} = rapid traverse rate of the grinding wheel (mm/min), t_{lg}= loading and unloading time (min), t_{g0} = set up time (includes grinding wheel balancing) (min), N_{grind} = # parts to be ground, t_{cg} = wheel dressing time (min), $cg\ T$ = time between wheel dressings (min), $pg\ C$ = cost of dressing tool (dollar), k_{lg} = # the tool is used before being discarded, C_{cg} = cost of the grinding wheel (dollar), k_{3g}= # the wheel is used before being discarded. Using this mathematical model, the function is optimized once the processing parameters are constrained to a known range of values.

3.6.1.1 Application of Geometric Programming- Metal Cutting Problem

Geometric Programs are nonlinear programs in which the objective function is in the form of posynomials (i.e. functions where all coefficients are real, positive numbers) (Dupačová 2010). Dupačová examines how a number of typical metal cutting problems are modeled by geometric programs. A popular optimization criterion is the minimization of total machining costs as a function of machining tie costs, the cost of tool changing time per component, and the tool cost per component:

$$C = xT_c + xT_d\frac{T_{ac}}{T} + y\frac{T_{ac}}{T} = xT_c + \frac{T_{ac}}{T}(xT_d + y) \qquad \text{(Equation 3-3)}$$

where x is the labor plus overhead cost rate, y is the tool cost, T_c is the machining time, T_{ac} the actual cutting time, T_d the tool changing time and T the tool life. Whereas x, y and T_d are understood as a fixed input, the tool life, the cutting time and the machining time depend on the cutting conditions, such as the depth of the cut d, the feed f, and the speed v which is proportional to the number r of revolutions per minute (Dupačová 2010).

3.6.2 Life Cycle Cost Analysis

Pattanayak et. al. describes low-cost automation as “the introduction of simple pneumatic, hydraulic, mechanical, and electrical devices into the existing production machinery, with a view of improving their productivity”. This study focuses on the economic analysis of three different versions of a lathe machine: A conventional lathe machine, a Numerical Control (NC) lathe machine, and a Special Purpose Turning Machine. The cost analysis process is as follows:

- Calculation of parts per hour
- Calculation of labor cost
- Calculating the cost per part
- Calculating the break-even point
- Calculating the total savings

One method of this cost analysis type is Life Cycle Cost (LLC). Life Cycle Cost accounts for the “total costs from the starting point of equipment and projects to their disposal which is derived analytically through an estimation of the total costs for their lifetime” (Chang 2004). LLC based analysis is often used to justify the selection of equipment and process. For a valid analysis, the engineer must accurately estimate the cost and productivity of the design in terms of materials, labor, and the number of parts per hour the tool will produce.

3.6.3 Measuring Effectiveness

Several metrics have been identified across multiple industries to evaluate the effectiveness of an automated process. Of course, the return on investment (ROI) of a robotic process is a valuable metric for this type of evaluation. However, the best measurement practice is to assign priorities to each of the metrics and take a weighted value or combine multiple metrics to best reflect the needs of the company (Kasu 2017). **Table 3-3** details various metrics for measuring the effectiveness of an automated process.

Table 3-3. Effectiveness Metrics (Kasu 2017)

Percentage of Test Cases Automated	$$P.A. = \frac{A.T}{T.T}.$$ where A.T= Number of test cases that have been automated, T.T=Total number of test cases The higher the share of automated test cases, the more successful the automation is perceived.
Fragility	A measure of how much time is being spent on fixing and updating test scripts at each stage
Automated Testing Coverage Percentage(ATP)	$$ATP = \frac{AC}{TC}$$ Where AC= Automated Coverage TC= Total Coverage Measures how much of the product's functionality is being covered by automation, which helps us understand the "completeness" to which the automation is being performed
Defect Identification Ratio	$$DIR = \frac{TD}{(TD + AD)}$$ TD= Number of defects identified during testing AD= Number of defects identified after delivery Measures how effective scripts are at identifying defects
Time Saved	The difference between known manual times we can accurately estimate, and time consumed by automation. Fragility is also accounted for

Wang et. al 1998 developed a hierarchical index-based approach to measure the effectiveness of construction automation implementation in Taiwan. The Architectural Research Institute classified the construction automation plan into five components: (1) construction planning and design automation (2) construction technology automation (3) construction management automation (4) construction machinery automation (5) construction material production automation. In this study, indices were used to integrate both quantitative and qualitative data. Ten criteria were developed for the selection of indices: validity, reliability, stability, responsiveness, availability of the data, scalability, representativeness, comparability, understandability, and policy relevance. Each index is evaluated with a score of 1-4. Wang et. al defined the seven indices of benefit aspect as (1) degree of productivity improvement (2) degree of quality improvement (3) degree of cost reduction (4) degree of time saving (5) degree of personnel injury reduction (6) degree of manpower savings and (7) degree of environmental pollution improvement. The descriptions and formulas for the indices of benefit aspect are defined in **Table 3-4**

Table 3-4. Descriptions and Formulas for Indices of Benefit Aspect (Wang et. al. 1998)

Index	Description	Formula	Nomenclature
Degree of productivity improvement	Degree of saving in the project's cost compared with projects of similar quality with respect to that of the base year	$\Sigma P_o/N$	$\Sigma P_o = A\times 0 + B\times 1 + C\times 2 + D\times 3 + E\times 4$ N = sample number; A, not reduced; B, slightly reduced; C, reduced; D, very reduced; E, very much reduced
Degree of quality improvement	Level of improvement in project quality after implementing the automation with respect to that of the base year	$\Sigma Q_u/N$	$\Sigma Q_u = A\times 0 + B\times 1 + C\times 2 + D\times 3 + E\times 4$ N = sample number; A, not increased; B, slightly increased; C, increased; D, very increased; E, very much increased
Degree of cost reduction	Increment of average project output per person per year with respect to that of the base year	$(C_a - C_b)/C_b$	C_a = annual total value of project output per person in the given year; C_b = annual total value of project output per person in the base year
Degree of time saving	Degree of saving in the project's time compared to the projects of similar quantity with respect to that of the base year	$\Sigma T_i/N$	$\Sigma T_i = A\times 0 + B\times 1 + C\times 2 + D\times 3 + E\times 4$ N = sample number; A, not saved; B, slightly saved; C, saved; D, very saved; E, very much saved
Degree of personnel injury reduction	Degree of reduction in the average number of severe labour injuries or death toll of personnel involved in the project with respect to that of the base year	$\Sigma P_i/N$	$\Sigma P_i = A\times 0 + B\times 1 + C\times 2 + D\times 3 + E\times 4$ N = sample number; A, not reduced; B, slightly reduced; C, reduced; D, very reduced; E, very much reduced
Degree of manpower savings	Degree of savings in man-days required to produce a similar quantity with respect to the base year	$\Sigma M_a/N$	$\Sigma M_a = A\times 0 + B\times 1 + C\times 2 + D\times 3 + E\times 4$ N = sample number; A, not saved; B, slightly saved; C, saved; D, very saved; E, very much saved
Degree of environmental pollution improvement	Degree of annual improvement in the environmental protection problems with respect to that of the base year	$\Sigma E_n/N$	$\Sigma E_n = A\times 0 + B\times 1 + C\times 2 + D\times 3 + E\times 4$ N = sample number; A, not reduced; B, slightly reduced; C, reduced; D very reduced; E, very much reduced

Note that these formulae and indices are intended to evaluate the perceived benefit of the proposed construction automation plan. Survey questionnaires were mailed to construction firms, architects, government agencies, and consultants who had participated in construction automation plans. These survey results served as the representative data for this hierarchical method of measuring effectiveness.

3.7. Case Studies

There is a clear lack of consistency among the existing cases of automation in construction. The literature presents a variety of different cases in the automation of design, production, evaluation, and assembly of precast concrete parts. Cases of modular construction present valuable insight into the simulation of cost, time, and quality. However, it is challenging to compare the successes and failures of each case to one another due to the variety of impacts of each project. **Table 3-5** summarizes the outcomes of three different precast companies that have incorporated automation, to be described in greater detail throughout this section.

Table 3-5. Precast Automation Case Studies

Company/ Organization	Automation Incorporated	Outcome
Foley Products Co.	Flexible automation	Reduced labor cost
Molin Products Co.	Carousel Production	Higher quality, more consistency, reduced error
Betonwerk Oschatz	Carousel Production	Increased productivity

Foley Products Co.

Georgia-based Foley Products Co. specializes in producing round precast products, such as risers, manhole covers, and pipes. The regularity of the product made it well-suited for flexible automation. For Foley, a shrinking labor pool was the chief motivation for implementing automation. Further, the company wanted a more efficient way to perform vacuum testing, as manual testing was time-consuming and labor intensive. In 2004, a partnership with Schlüsselbauer led to the execution of a 27.4 m wide by 53.3 ft long (90 ft wide by 175 ft long) manhole riser plant. Foley also made adjustments in their labor and trained technical-savvy workers. Although these changes did not make production faster, it did reduce labor significantly, as originally intended.

Molin Products Co.

Molin Concrete products produces a wide range of structural products, including prestressed beams, columns, and wall panels. Its existing plant was not suited for producing high volume or high-quality panels, and the company needed to expand the range of products it could produce to remain competitive in the market. In addition, Molin aimed to decrease the safety risks associated with silica dust, noise, and strains while attracting future skilled labor. In 2014, Molin partnered with Weckenmann to convert their standard stationary system to a carousel, where workers remain stationary while pallets move the manufacturing plant system. This reduced several types of waste, such as moving and waiting. Automation has helped Molin eliminate human error and manufacture products with a higher quality and more consistent finish. Further, it enabled the company to offer more refined architectural surface finishes to the design community.

Betonwerk Oschatz

Betonwerk Oschatz has been producing precast products from floors, walls, beams, and various supports since 1995. The German precast plant has since embraced robotic technology to improve plant productivity. A robot line supplied by Vollert Group automated the deshuttering process and is controlled by a CAD/CAM, as well as the plotting system for element floor slabs and double walls (**Figure 3-14**). The new technology enables 5-6 circulation pallets through the work area every hour, according to Managing Director Birgit Zocher. The individual robots have separate safety areas such that production can continue, even if one robot area is defective.

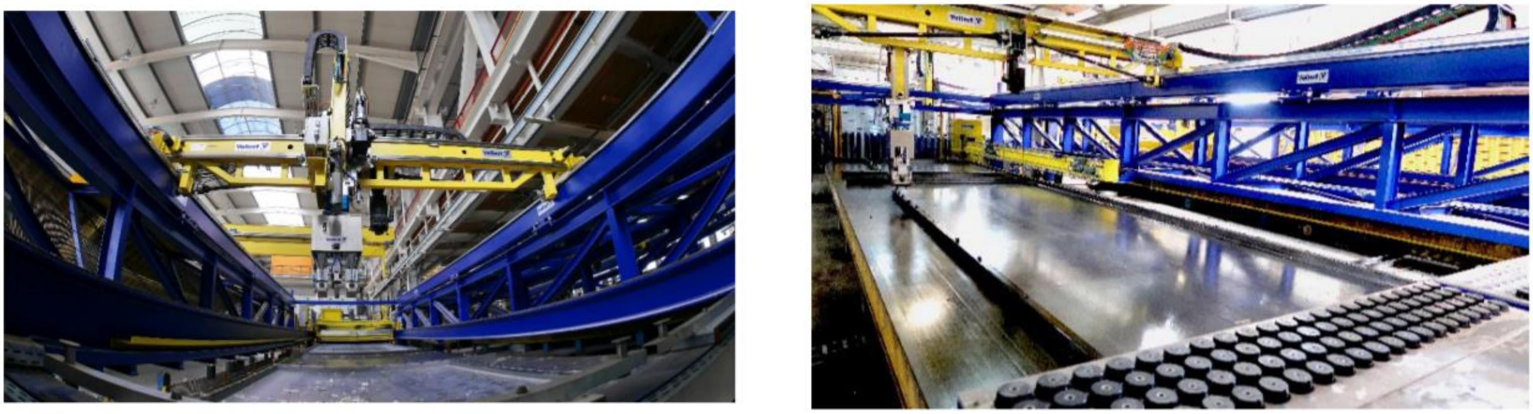


Figure 3-13 Fully Automated Deshuttering (Brost 2018)

3.8 Conclusion

A multitude of applications for automation in precast concrete production are identified in this chapter. Several precast plants have even incorporated new technology into their process, both within the United States and internationally. However, many of these robotic systems are highly advanced and require a clean, controlled facility to operate. There is a significant gap in the literature on how to integrate point automation (automation of a single task) into an existing facility without a full redesign of the plant. For older precast plants, this is an area of high need.

4.0 PROBLEM STATEMENT

Automation is not widely adopted in the construction industry compared to other industries because the manufacturing process favors productivity over innovation. The construction industry is marked by tight deadlines, output goals to meet consumer needs, and product designs that change with each project. Recently, the prefabrication industry has been the exception to this trend. Construction with precast reinforced concrete products has only been an industrial option since the 1950s. The increasing lack of skilled workers coupled with significant factory production output led to the introduction of precast concrete products. Concrete has evolved over the past 40 years from simple mixtures including cement, water, and aggregate to more complex mixtures involving advanced chemical additives and fiber reinforcement. The process of manufacturing precast/prestressed concrete products today involves a multitude of parameters and sub-stages, increasing the need for a controlled, off-site manufacturing environment. The precast concrete manufacturing environment makes it highly suited for mass production and customization of products. The precast facility used for this case study specializes in a wide variety of precast and prestressed concrete products, from architectural wall panels to double-T beams. Due to the wide variety of products produced in the Greenville, SC plant, the corporation has limited the implementation of automation techniques for producing and storing products. Several precast production process tasks could be made faster and more efficient with automation, while reducing material waste and defective products. Another challenge lies in the fact that the corporation's Greenville facility is a well-established plant with output goals that require it to operate continuously. The company was founded in 1925 and has since acquired the Shockey precast group and expanded to North Carolina, Georgia, Virginia, and Florida. While the company strives to continuously improve, it is challenging to integrate new technology into an older, high output plant. The purpose of this research study is to assess the existing state of the practice of automation both within and outside of the prefabrication industry. Previous studies have been completed on the implementation of robotic technology in various prefabrication environments. In addition, other studies have examined the implementation of automation in quality assurance and cost analysis stages. First, this study analyzes the existing workflow of the precast production system at the precast facility. Preliminary work has been performed to categorize workflow tasks and determine which section is most time and labor intensive. This preliminary analysis reveals that reinforcement placement and all related tasks take up the largest portion of the man hours, at approximately 33% of the net 43 hours it takes to complete a standard double tee (scaled by number of workers required). Within this sub-category, tying in reinforcing steel is the most intensive task, consuming about 31% of time and labor resources of the sub-category. From the plant's perspective, this is an area in high need of automation for the plant. The reinforcement tying step involves a worker bending over for long periods of time and manually tying rebar at various intersections. Because about 75% of precast products are produced horizontally, workers must bend over for long periods of time to hand tie the rebar, putting large strains on the lower back. Because of these reasons, this specific area was identified for automation with different options and degrees of automation considered in order to determine which alternative best fits the values and needs of the company. A survey instrument has been used to quantify the weight of importance for seven values of automation: economic efficiency, time, worker safety, integrability, durability, quality, and adaptability. Using this criteria, different automation options will be selected to suit the precast plant's needs. Most precast products at the facility would require a machine that can navigate in the x,y, and z directions and be capable of machine learning. It is becoming increasingly clear that the solution for automating this task does not exist commercially yet. Thus, this research focuses on establishing the technical standards and design details necessary for the development of an automation system that employs optical sensing technology and machine learning in order to meet the precast facility's fabrication needs. Analysis methods and modeling tools are used to evaluate the proposed redesign for its potential cost, time, and safety benefits. Recommendations for advancing the precast facility's automation efforts are documented as a deliverable of this work. This interdisciplinary study not only impacts the productivity and efficiency of the company used in this case study, but it contributes to a larger body of work performed on a relatively underdeveloped topic. Few advancements have been made nationally in construction automation, and this study demonstrates the potential impact of implementing technological changes to a single process of an existing facility. Current literature on automation in precast manufacturing examine facilities that were intentionally designed from the beginning to be highly automated. These facilities are often only capable of mass-producing standard, repetitive products. However, little work has been performed on automating facilities that support larger, more complicated products with high levels of variety. In addition, there is a significant gap in the literature about incorporating automation into an existing facility without completely rebuilding the plant. This study serves as a guide to precast manufacturers in the industry on the best practices for integrating point automation and which sectors of the manufacturing process can yield the highest return on investment. The technical standards and methodology developed serve as a guideline for incorporating automation into the precast/prestressed industry at-large.

5.0 RESEARCH METHODS

5.1 Methodology Overview

The scope of the research methodology is summarized in **Figure 5-1**. To assess the manufacturing process at the precast facility and identify areas for improvement, the full precast process must be observed in depth from start to finish. Physical observation gives insight to the plant environment and operating conditions for workers. In addition, a detailed time breakdown for a typical product is executed to give insight to which aspects of the precast process are most time-consuming and why. From there, a specific task for automation is selected, informed by the insight gained from physical observation and time data analysis. Next, a quantitative evaluation of the various outcomes of automation is conducted. This is accomplished through a survey completed by various stakeholders at the precast company. The survey results are used to design a weighted decision matrix, in which various existing technology for the specific automated task are compared against one another. This existing technology is used to inform the capabilities of a new, automated device that does not yet exist. The outline for the technical standards of the new device is then developed as a deliverable in Chapter 6. Finally, an analysis method is selected to evaluate the cost, time, and/or safety impact of implementing this point automation.

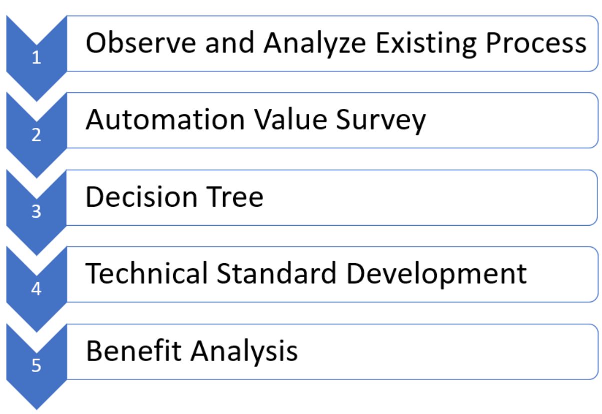


Figure 5-1. Summary of Research Methodology

5.2 Physical Observation of Precast Facility

Observing the manufacturing site of the precast concrete plant is essential to the task at hand. Insights are gained on 1) the types of manual labor typically required for the precast process, 2) safety conditions and concerns, 3) the scope of products produced and most importantly, 4) the operating environment that the proposed automation would integrate into. As discussed in Chapter 3, a handful of precast plants have implemented high levels of automation at various stages of their process. However, many of these examples involve a complete redesign of the plant or a brand new facility intentionally designed for full automation. Since neither of these options are feasible nor practical for a large existing facility like the one used in this case study, it is important to understand the context of the physical environment, shown in aerial view in **Figure 5-2.** This study addresses that gap of knowledge and serves as a procedural guideline for incorporating automation into similar manufacturing plants and the potential benefits of doing so.

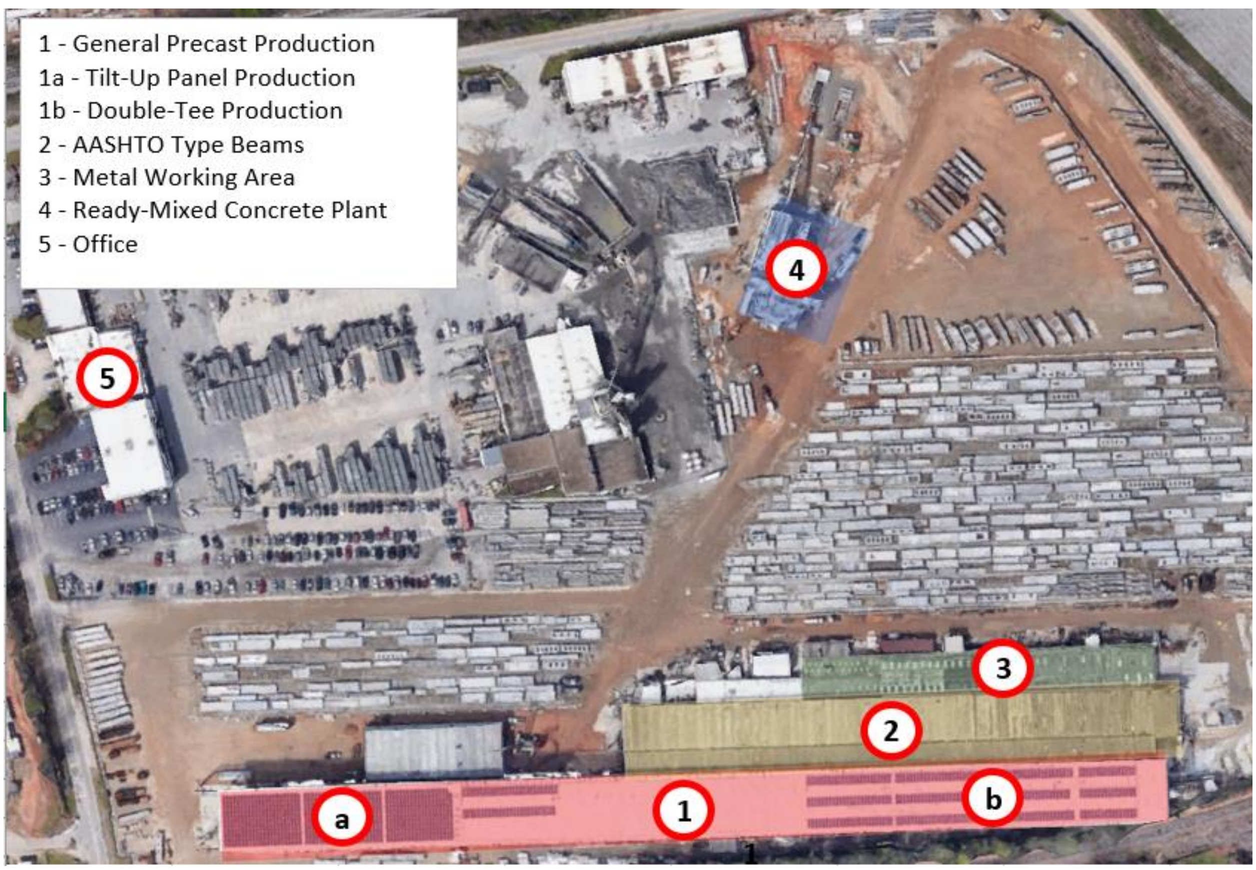


Figure 5-2. Arial View of Precast Facility (Southeastern United States)

As shown in **Figure 5-2**, the majority of the site area is dedicated to the storage of completed products. Finished products are located using GPS tracking methods and shipped off to their respective construction sites when needed. The stationary manufacturing process of prepping the formwork, placing reinforcement, and placing and curing concrete occurs under a covered area, marked as Location 1. This is important to consider when introducing new automation into the process. Any new equipment would need to fit within these parameters. This area is approximately 425 yd (388 m) long and 30 yd (27 m) wide. The majority of the general precast process, as outlined in Chapter 1, occurs at a stationary location with various tools stored in a moving cart. The left side of this area (Location 1a) is primarily where tilt-up panels are manufactured while the right side (Location 1b) is primarily double tee production. Location 2 is secondary covered area dedicated to making larger AASHTO Type Beams. The metalworks area is located in Location 3. Here, rebar is stored, cut, and bent to meet specifications using a semi-automated rebar bending machine. In addition, metal inserts are manually welded in this area. Ready-mixed concrete is produced at a new state-of-the-art batch plant at Location 4 and transported to Locations 1 or 2 using a front discharge ready-mix truck.

Like most manufacturing environments, the plant area is not a clean environment by any means. In the metalworks area, finished metal pieces are temporarily stored in piles and handled haphazardly. In the main precast production line, tools, rebar insets, and other precast elements (see section 2.4) are spread along either side of the main precast bed. Lastly, there is very little automation used onsite, apart from an automated rebar bending machine. As a result, nearly the entire precast process is accomplished by workers standing atop of the precast bed and bending over for long periods of time during the prefabrication, placement, and deconstruction phases of double tee prestressed concrete beam production.

5.3 Double T Standard Work Combination Table

One specific plant of the company specializes in batch producing precast double tee structures. Double tees are often used in applications that require long, open spans and high strength, such as parking decks. The final geometry of the DT1-510' is illustrated in **Figures 5-3a** and **5-3b**. This product has an overall width of 13.0 ft and 3.5 in. (approximately 4 m) and a deck thickness of 2 in. (5 cm).

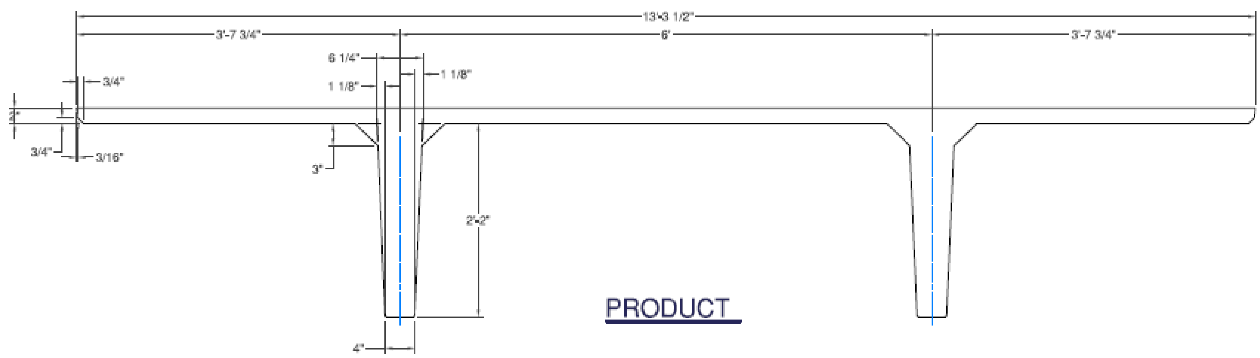


Figure 5-3. Double Tee Product Geometry

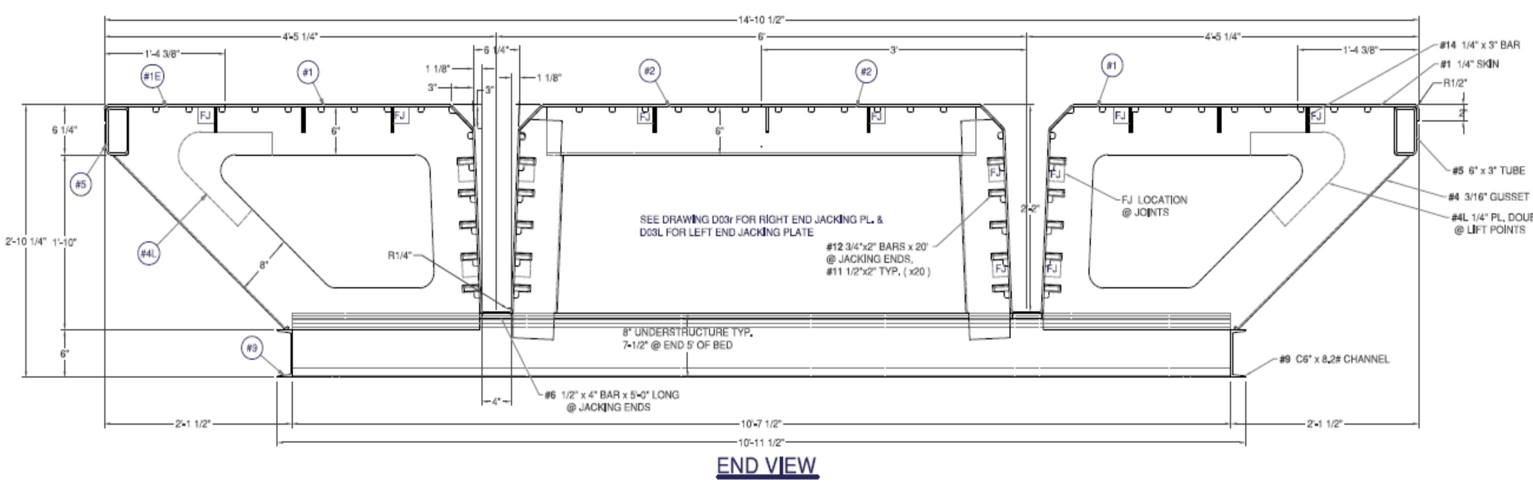


Figure 5-4. Double Tee End View

The double tee beam contains many subcomponents that require their own subtasks to complete. At the Spartanburg, SC, plant, the total production time for one DT1 510 ft bed with wire mesh is 7.5 hours with six crew members. The work combination data presented in **Table 5-1** was provided by company's data acquisition group. The table details the full procedure for manufacturing the double tee product shown in **Figure 5-3**, the approximate length of time required for each task, and the personnel required for each task.

Table 5-1. DT1 510’ Standard Work Combination Table

Standard Work Combination Table

DT1 510' Bed, Factory Top DT w/ Wire Mesh, Experienced 6 Man Crew, No Recesses Down the Side, No Cord Steel, No Daps, No Cut Downs, One Piece Header System, A-Frame Material Cart.

Tasks	Task #	Crew #	Cycle Time
Pre-op Dyna Cart	1	1	15
Scrap Concrete off Rails/Sweep Floor	1	2	60
Scrap Concrete off Rails/Sweep Floor	1	3	60
Clean Rails/Sweep Bed	1	6	45
Get/Stage Trash Dumpster	1	4	15
Drawing Review/Production Planning	1	5	15
Pick up, clean, load headers on cart	2	1	35
Bed Cleaning (sweep, trash pick-up, clean stems)	2	2	30
Bed Cleaning (sweep, trash pick-up, clean stems)	2	3	30
Bed Cleaning (sweep, trash pick-up, clean stems)	2	6	45
Bed Cleaning (sweep, trash pick-up, clean stems, clean rail Caulk)	2	4	75
Bed Cleaning (sweep, trash pick-up, clean stems, clean rail Caulk)	2	5	75
Header Layout	3	5	10
Header Layout	3	2	10
Stem Cleaner, Pre Op, Move, Run	3	3	15
Oil and Thread Headers	3	1	30
Set Rails (510' per side Mark, Chalk, & Set)	3	6	80
Set Rails (510' per side Mark, Chalk, & Set)	3	4	80
Oil Stems	4	2	10
Mop Stems	4	3	10
Layout Embeds (Mark Off)	4	5	70
Layout Carpenter Shop Material for Stems	4	1	30
Set Headers (header cart)	5	1	25
Locate Headers & Mark Stem Blockouts	5	3	20
Watch Cable Reels	5	2	25
Drop in stem materials on cart return trip	6	1	35
Set-up Jack w/ Safety Requirements & Pre-Jack Inspection	6	2	35
Caulk Side Rails (Until Break)	6	3	35
Break	4	6	30
Break	4	4	30
Break	7	2	30
Break	7	3	30
Jack Cable	7	1	20
Jack Cable	5	5	20
Break	8	1	30
Break	6	5	30
Finish Caulking Side Rails	8	3	40
Put in Stem Mesh, Knocking Up Bearing Plates, Cable Shielding	5	6	30
Put in Stem Mesh, Knocking Up Bearing Plates, Cable Shielding	5	4	40
Put in Stem Blockouts	8	2	40
Oil Deck & Side Rails	9	1	30
Mop Deck	7	5	30
Place Mesh Cart on Bed and layout Mesh	6	6	60
Place A-Frame Material Cart on Bed & Place Steel, Plates, Mini-V's, etc.	9	3	120
Tie In all Reinforcing Steel, Embeds, Laps in the Wire Mesh	6	4	130
Tie In all Reinforcing Steel, Embeds, Laps in the Wire Mesh	9	2	140
Bolt On Mini-V's and Chair Up Wire Mesh	10	1	130
Bolt On Mini-V's and Chair Up Wire Mesh	8	5	120
Chair Up End Steel & Install Recess Tubes	7	6	90
Oil Screed, Oil Rakes, Get Vibrator	10	3	20
Inspect/Knock Up Heel Plates	7	4	10
Crew Leader Final QC Inspection	9	5	15
Pour Concrete - Run Dyna Cart	8	6	120
Pour Concrete - Rake Concrete	11	3	120
Pour Concrete - Rake Concrete	8	4	120
Inspect/Fix all Embeds behind Dyna Cart	10	5	120
Return / Clean Dyna Cart	9	6	20
Clean / Store Tools	12	3	20

Minutes: 5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 55, 60, 65, 70, 75, 80, 85, 90, 95, 100, 105, 110, 115, 120, 125, 130, 135, 140, 145, 150, 155, 160, 165, 170, 175, 180, 185, 190, 195, 200, 205, 210, 215, 220, 225, 230, 235, 240, 245, 250, 255, 260, 265, 270, 275, 280, 285, 290, 295, 300, 305, 310, 315, 320

Hours: 0.1, 0.2, 0.3, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.8, 0.9, 1.0, 1.1, 1.2, 1.3, 1.3, 1.4, 1.5, 1.6, 1.7, 1.8, 1.8, 1.9, 2.0, 2.1, 2.2, 2.3, 2.3, 2.4, 2.5, 2.6, 2.7, 2.8, 2.8, 2.9, 3.0, 3.1, 3.2, 3.3, 3.3, 3.4, 3.5, 3.6, 3.7, 3.8, 3.8, 3.9, 4.0, 4.1, 4.2, 4.3, 4.3, 4.4, 4.5, 4.6, 4.7, 4.8, 4.8, 4.9, 5.0, 5.1, 5.2, 5.3, 5.3

Crew Members	
1	Nestor
2	Mario
3	Cody
4	Angel
5	Pedro (Crew Leader)
6	Juan

Using this raw data, the tasks are further broken down into the following main categories: cleaning, rail setting, inspection, cable jacking, meshing, concrete pouring, header and stem layout, and other miscellaneous preparatory tasks (**Table 5-2**). The net cycle time is calculated by multiplying the length of the task multiplied by the number of crew necessary to complete each task. Each category is further broken down into their individual tasks to reveal which steps of the subprocesses are the most time consuming, presented in **Chapter 6.**

Table 5-2. Overall Double Tee Task Breakdown

Category Totals (from Grouping Tasks)	**Net Cycle Time (Minutes)**	**Percentage of Total Time**
Cleaning	500	18.90%
Rail Setting	265	10.02%
Inspection (Total)	180	6.81%
Jack Cable	65	2.46%
Reinforcement Placing and Tying	860	32.51%
Pouring Concrete	360	13.61%
Header/Stems	305	11.53%
Misc. Prep	50	1.89%

Each category will be further broken down into their individual tasks to reveal which steps of the subprocesses are the most time consuming, presented in **Chapter 6.**

5.4 Methodology for Decision Analysis

In manufacturing, it is known that every process method and piece of equipment offers its own benefits and drawbacks. The manufacturer selects processes/equipment based on their desired outcomes. The manufacturer must consider which drawbacks they are willing to accept based on their selection. When making a decision about a new process or equipment, it is important to consider how the company values outcomes based on importance levels. In this research, a value assessment is performed to evaluate the potential impacts of incorporating automation. Based on the precast facility's needs and overall trends in the precast industry, automation design criteria are presented in **Figure 5-9.** Through the assessment process, the criteria can be evaluated against one another utilizing value engineering methodology.

Economic Efficiency

Economic efficiency accounts for not only the initial investment but also maintenance costs to the automated technology and finished precast product. There is risk in investing in more advanced and automated equipment and the precast plant not realizing their return on investment (ROI). Life Cycle Cost Analysis (LCCA) is often used to justify the selection of equipment and process.

Time

Time is one of the most valuable factors to consider in a manufacturing plant. The precast industry is marked by tight deadlines and time-sensitive projects. When examining certain tasks to be automated throughout the precast process, it is critical to ensure the automated process results in a production time that is equal to or greater than the manual process. However, there is risk associated with reducing the production time too much. Under no circumstances should a reduction in time be at the expense of quality. Time is evaluated through modeling functions and equipment data as well field testing.

Worker Safety

Worker safety is paramount in the precast manufacturing process. Many of the existing processes for precast production is labor intensive and with the possibility of leaving workers prone to injury. The rebar tying stage involves a worker standing on top of a horizontal concrete bed and bending at the waist. Over long shifts, this can create strain on the lower back and possibly cause injury. In addition, fatigue can slow worker production near the end of a shift. When looking to incorporate automation, it is important that the process improves the worker's health and safety.

Integrability

Integrability is a measure for how easily the automated process is incorporated into the existing workflow of a plant. In many existing cases of automation in precast concrete, precast facilities are redesigned with an entirely automated, streamlined process. In the case of long-standing precast facilities in the United States, this type of ground-up overhaul is not feasible. Therefore, integration must be taken into consideration. There are many facets of integrability. First, any software-based automation must be compatible with the existing drawing and file types in the plant (i.e., CAD/CAM, BIM). Integrability also reflects how easily the automation is incorporated into the existing space parameters of the facility. There is considerable risk in unsuccessful integration. If a certain task of the process is temporarily out of service due to integration, then overall production goals may not be met. This risk is even more drastic if subsequent operations are impacted by integration issues.

Durability

Although a precast facility is more controlled than a construction site, the precast environment can be extremely harsh. Equipment and tooling are routinely exposed to rain, dirt, dust, rough handling, vibration, and shock. Any tool or automated equipment must be designed accordingly. Because there is an upfront investment involved, it is important to understand the risk involved with unforeseen maintenance needs. The risk associated with durability issues may affect other criteria such as quality, time, and economic efficiency.

Quality

While the primary goal of automating a task is to save time and money, and create a safer working condition, the desired quality of the finished precast product should not be compromised. One of the most important measures of quality of the final product is the compressive strength at time of release (when the prestressing strands are cut). Other assessments of quality include surface quality, such as surface cracks and voids. In addition, final product geometry and tolerances are integral measures of quality, as the final precast product must fit within the intended structure, such as a bridge or parking deck. When assessing the best choice for automation equipment in the precast process, all of the aforementioned assessments of quality must be met.

Adaptability

Many precast facilities produce a wide variety of product geometries with their own unique customer needs. The precast facility used in this case study produces a wide variety of precast products, from prestressed concrete beams to architectural wall panels and parking garage double tee structures. Besides the varying geometries, each precast product has its own requirements for reinforcement, prestressed strand, and even insulation. This variety and customization require that any automation must be flexible to accommodate different products with adaptability a measure of how easily equipment can be adjusted to accomplish a change in product. Adaptation error (i.e., the failure for the automation to adapt to different inputs) is detrimental to the finished product and can possibly result in wasting time and materials from starting a product over.

The various criteria are evaluated against each other with value engineering methodology (**Figure 5-9**).

5.4.1 Value Survey Methodology

The following sections describe the content and methodology behind the three sections of the value survey. The full survey can be found in the Appendix, and the results will be presented in Chapter 6.

This survey is anonymously administered to various stakeholders at the precast facility through Qualtrics Survey Software. Although contact information of the respondents is not collected, the survey's intended audience is the leaders of the Continuous Improvement group and the VP of Corporate services. The Continuous Improvement group members contain backgrounds across mechanical and civil engineering disciplines. The VP of Corporate services has an extensive background in civil engineering and years of experience in the precast industry. This selection of respondents offers a variety of perspectives with various backgrounds from different areas of the company.

The format of the survey takes three sections, explained in more detail in sections **5.4.1.1, 5.4.1.2,** and **5.4.1.3.** The purpose of the three-part format is to present a series of similar questions in slightly different ways. Survey methodology reveals that the way a question is presented can influence the response. By providing a variety of question formats, this bias is reduced. The goal of this survey is to establish a weight of importance to each of the seven previously defined criteria of automation using a quantitative analysis of the results.

5.4.1.1 Section 1: Multiple Choice

In this section, the respondent must select which of two options are more favorable in a precast manufacturing context. Each answer choice corresponds to one of the seven automation values. The intention of this question format is to force a stronger response from the respondent and compare two different values against one another. **Figure 5-5** shows an example of this type of question.

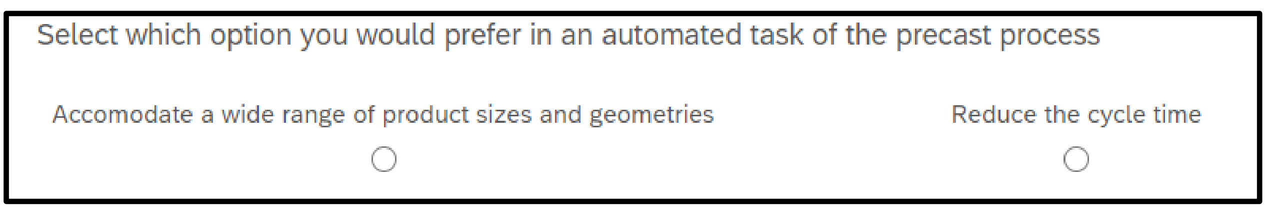
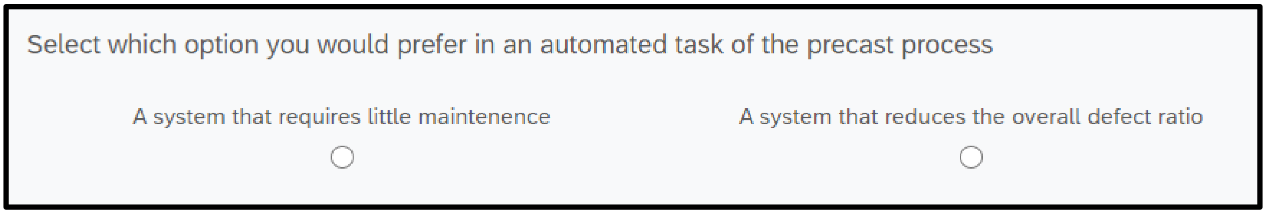


Figure 5-5. Multiple Choice Question

The “reduce cycle time” option clearly corresponds to the Time value. However, “accommodate a wide range of product sizes and geometries” more subtly suggests the value of adaptability. Another feature of this section is the use of parallel wording in answer choices. Consider the question in **Figure 5-6**. This question compares the manner in which the respondent values durability and quality. The parallel wording creates neutrality between the two statements to reduce bias from the survey author.



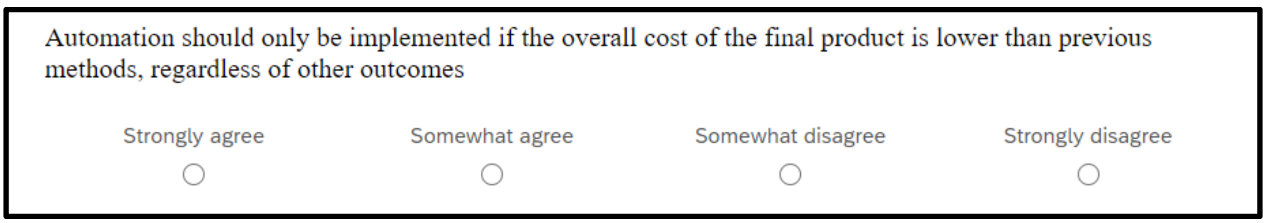
Select which option you would prefer in an automated task of the precast process

A system that requires little maintenence | A system that reduces the overall defect ratio

Figure 5-6. Parallel Wording in Survey Questions

5.4.1.2 Survey Section 2: Agreement Spectrum

The agreement spectrum section allows the respondent to give more nuance to how they value certain characteristics of automation. Each question presents an opinion statement and asks the respondent to select how strongly they agree or disagree with the statement. Like the previous section, each question corresponds to one of the seven values. **Figure 5-7** presents an example of this questioning technique.



Automation should only be implemented if the overall cost of the final product is lower than previous methods, regardless of other outcomes

Strongly agree | Somewhat agree | Somewhat disagree | Strongly disagree

Figure 5-7. Agreement Spectrum Example

This question evaluates the value of cost efficiency. In its simplest form, this statement could have been presented as “cost efficiency is an important outcome of automation”, to which the respondent would most likely agree. However, the wording of this statement (“regardless of other outcomes”) presents itself in a more extreme form, forcing the respondent to consider the value of cost efficiency against all other outcomes. Figure 5-8 presents this scenario.

If the automated task cannot accommodate every product style and geometry, then it is not worth the investment

Strongly agree | Somewhat agree | Somewhat disagree | Strongly disagree

Figure 5-8. Agreement Spectrum Example

It is useful to think of the various automation criteria as functions of the initial investment. In this statement format, the respondent is forced to consider which outcomes are non-negotiable (in this case, adaptability).

5.4.1.3 Section 3: Value Sorting

The value sort section prompts the respondent to rank the seven values within three importance levels: Highest, High, or Low. The names of the values are nearly identical to the ones defined earlier, with a few exceptions such as integrability referred to as "ease of integration", durability referred to as "system durability", and quality referred to as "product quality.". This provides additional specificity to the terms such that the respondent's understanding matches the way it is defined in the decision matrix.

This section serves as a straightforward method for assessing how the company's stakeholders' value different outcomes. There is little context present here, thus it is intentionally placed at the end of the survey such that respondents do not complete the other two sections with a bias toward the values selected in this section.

5.4.2 Survey Scoring Rubric

The following sections detail how each section of the survey will be scored and scaled. These scorings will determine the weighting used in the decision tree analysis (**Figure 5-9).**

5.4.2.1 Survey Section 1 Scoring

For this section, each answer choice corresponds to one of seven values. Shown in Table 5-3, a chosen answers' corresponding value receives a score of 1, and the rejected answer receives a score of -1. Not every value category is represented equally in this section of the survey, thus the total score is scaled according to its maximum possible points (**Figure 5-9**).

Table 5-3 Survey Section 1 Scoring Rubric

Section 1	Economic Efficiency	Time	Worker Safety	Integrability	Durability	Quality	Adaptability
Question #							
1		±1				±1	
2	±1	±1					
3		±1					±1
4			±1				±1
5					±1	±1	
6			±1	±1			
7	±1	±1					
8				±1			±1
9	±1	±1					
10			±1				±1
Min/Max Possible	**±3**	**±5**	**±3**	**±2**	**±1**	**±2**	**±4**

If a category receives a raw score equal to its maximum possible points, then it receives a weighted score of 10, on a 1-10 scale. If it receives a raw score of 0, it receives a weighted score of 5, as this falls in the middle of its range of possible points. If a category receives its minimum possible raw score (i.e., a score of -5 for Time), then it receives a weighted score of 1.

5.4.2.2 Survey Section 2 Scoring

For this section, the answer choices range from “strongly disagree” to “strongly agree” in response to a series of statements about the seven values. A response of “strongly agree” receives a score of 2 and “somewhat agree” scores a 1. Similarly, a response of “strongly disagree” receives a score of -2 and “somewhat agree” scores a -1. Not all value categories are equally represented in this section of the survey, so the total raw scores must be scaled accordingly. A neutral score of 0 receives a weighted score of 5. The minimum and maximum possible points for each category in section 2 are presented in **Table 5-4.**

Table 5-4 Section 2 Scoring Rubric

Section 2	Economic Efficiency	Time	Worker Safety	Integrabilit y	Durabilit y	Quality	Adaptabilit y
Question #							
11				±2			
12						±2	
13							±2
14						±2	
15	±2						
16			±2				
17							±2
18							±2
19	±2						
20			±2				
21					±2		
Min/Max Possible	**±4**		**±4**	**±2**	**±3**	**±2**	**±4**

5.4.2.3 Survey Section 3 Scoring

The respondent's value selection ranked at the top would receive a score of 10. The remainder of the values would be ranked depending on where they were grouped. All values ranked in the "Highest Importance" category would receive scores of 7-10. The values ranked in "Average Importance" would receive scores of 5-6, and values ranked in "Low Importance" would receive scores of 3-4.

5.4.3 Engineering Decision Tree

The results obtained from the survey are used to determine the weight of importance for each value, as shown in **Figure 5-9**. As a result, this value engineering process allows for multiple alternatives to be evaluated with consideration of the seven criteria based on their level of performance for each value category. Each alternative is scored as 3-Excellent, 2- Good, or 1-Poor based on performance level.

Analysis Matrix Alternatives	Weight of Importance (0-10)	A. Economic Efficiency	B. Time	C. Worker Safety	D. Integrability	E. Durability	F. Quality	G. Adaptability	
Alternative 1									
Alternative 2									
Alternative 3									

*Selected based on weighted evaluation
3- Excellent 2-Good 1-Fair

Figure 5-9. Value Engineering Analysis

5.5 Technical Standard Development

Even the simplest of precast products at the precast facility, the double tee, is rather complicated to automate. Rebar must be placed and tied at various depths in the product. In addition, the system should be capable of navigating a large work area. A variety of alternatives exist and are evaluated for their suitability to the company's needs. However, any of these alternatives are not quite capable of meeting the technical requirements of a precast double tee. If such a technology were to be created, it must meet a multitude of standards and criteria for this application, outlined in **Figure 5-10.**

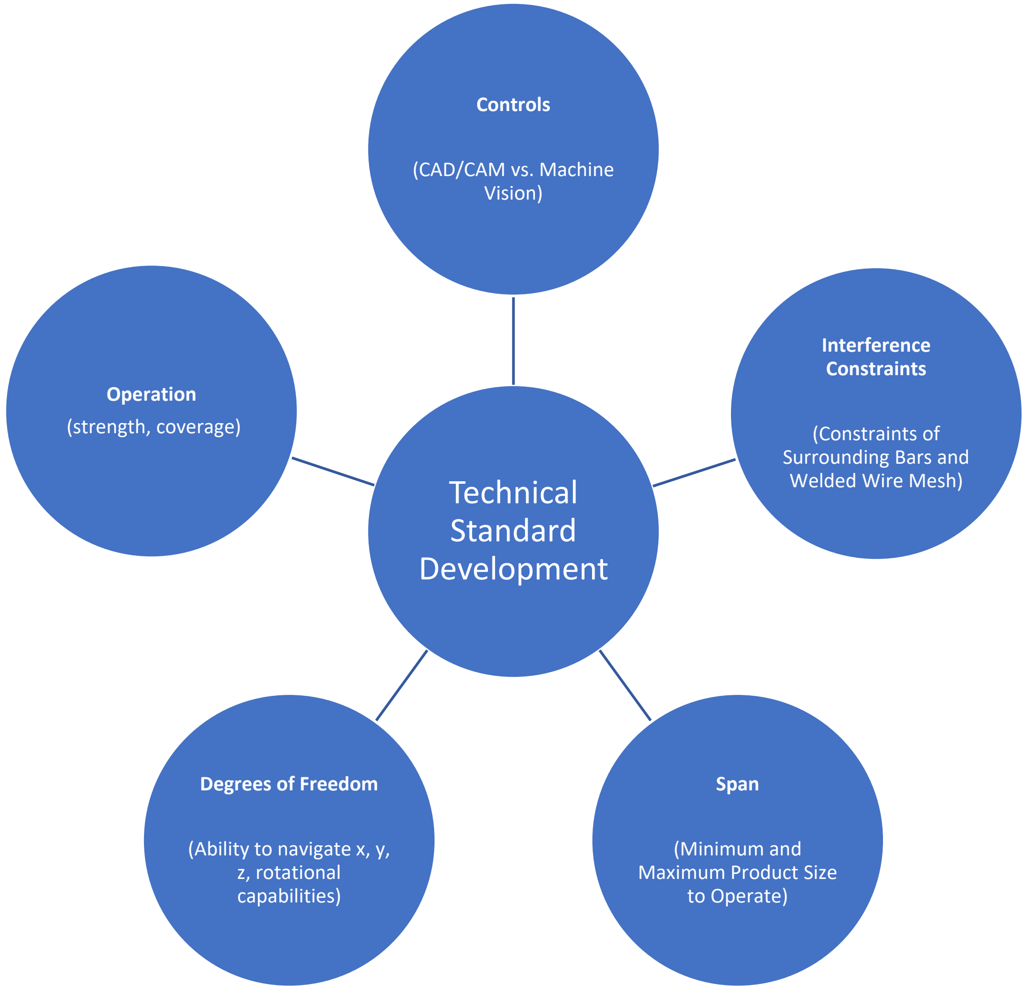


Figure 5-10. Technical Standard Format

5.5.1 Degrees of Freedom

This section of the technical standard should address the axes for which the device should be able to navigate (i.e., x, y, and z direction). Further, it should include details of rotational capabilities required for the specified task.

5.5.2 Span

This section establishes the minimum and maximum project sizes for which the device is capable of accommodating.

5.5.3 Controls

This section details the controlling system of the device. One control method is through CAD/CAM navigation, similar to a CNC machine. Another method is a machine vision system with machine learning capabilities. This section explains whether the device will be manually programmed or autonomously navigate the precast bed with no programming required. This section addresses the degree of automation and whether a quality control technician will operate the device or not.

5.6 Requirements Spreadsheet

An alternative representation of the technical standards document is the technical requirements table (**Table 5-5**). This table allows for a more consolidated representation of the various technical requirements and gives insight to the metadata that should be provided along with each requirement (Constraint/Criteria, Source, Justification, Date of Elicitation, Target Value). The Constraint/Criteria column allows for a distinction to be made between requirements that must be met under all circumstances (constraint) and requirements that would be beneficial to the overall system but not mandatory (criteria). Specifying the source of the requirements is essential since certain requirements could be inferred from the stakeholder but not explicitly given and others could be based on governmental standards or regulatory agencies. As standards evolve over time, recording the date of elicitation is important to keeping the standards up to date and keeping track of changes. As technical requirements are communicated between various designers and stakeholders, recording the justification for each requirement ensures a common understanding between all parties. Finally, the target values present a concise, quantitative summary of the requirements in one column, which is useful when the system eventually goes through verification testing. The full version of the requirements table includes additional columns on verification methods, updates and deviations, and reason for updates. However, in this preliminary stage of establishing requirements without designing how the system will meet those requirements, only the columns shown in Table 5-5 will be populated. The technical requirements spreadsheet is used as an addendum to the ISO Technical Standards and can be found in Appendix C.

Table 5-5 Requirements Template

Sr. No.	Requirement	Constraint/ Criteria	Source	Justification	Date of elicitation	Target Value
1						
2						
3						
4						
5						

5.7 Mathematical Modeling for Precast Manufacturing Process

Once the technical requirements for the proposed automated task are developed, the operation must be evaluated for its cost, time, and/or safety benefits through a quantitative and qualitative approach. One conventional method used in many manufacturing operations (such as casting, sheet metal forming, and welding) is physics-based simulation. Many physics-based simulation software exists for simulating the cost, duration, material usage, and a multitude of engineering properties of a manufacturing process. However, these software packages are not particularly useful for this research since many of the existing technology used in precast do not have advanced simulation capabilities yet. Instead, a mathematical model is developed to model the time duration and cost of the new operation. Power constraints and motor parameters are used to develop and constrain the governing equation. This governing equation provides the groundwork for what can eventually become a more robust model for the system.

5.8 Methodology Conclusion

The results of the work combination table analysis are used to determine which task could be most effectively automated and create the most impact. Any change in the current manufacturing process involves a tradeoff, and the various outcomes of incorporating automation must be considered. The responses from the various stakeholders to the value assessment survey give insight to which criteria are non-negotiable and which are of lesser importance. While this survey is intended for the stakeholders of the precast facility used in this case study, the seven criteria defined can be used in any precast facility seeking to implement point automation within their existing process. The survey question format and structure also serve as a framework for the types of questions precast facilities should ask themselves to better understand their motivations and goals for incorporating automation. These criteria are quantitatively evaluated in Chapter 6 and used to populate a decision matrix, where various equipment options are assessed according to these criteria.

Technical standards are used to outline the requirements of an automated rebar tying machine and provide a designer with everything they need to know to create such a device. To assess the potential impact of changing this step of the manufacturing process, a mathematical representation of the operation is developed using the formulae for the conversion of electrical to mechanical power. When process parameters and constraints of the system are applied to the expression, it is used to model the time (and by association, the cost) of the operation. This function is used to depict the benefit of a single automated task to the overall process.

6.0 RESULTS

6.1 Double Tee Work Combination Table Analysis Results

Figure 6-1 illustrates task categories for constructing a double tee and the percentage of production time for each category. It is evident that placing the wire mesh and all related tasks are the most time and labor-intensive part of the process. Wire mesh provides reinforcement to the double tee structure and increases its tensile strength capabilities. The material is produced from a series of longitudinal and transverse steel wires, welded at intersections into a mesh.

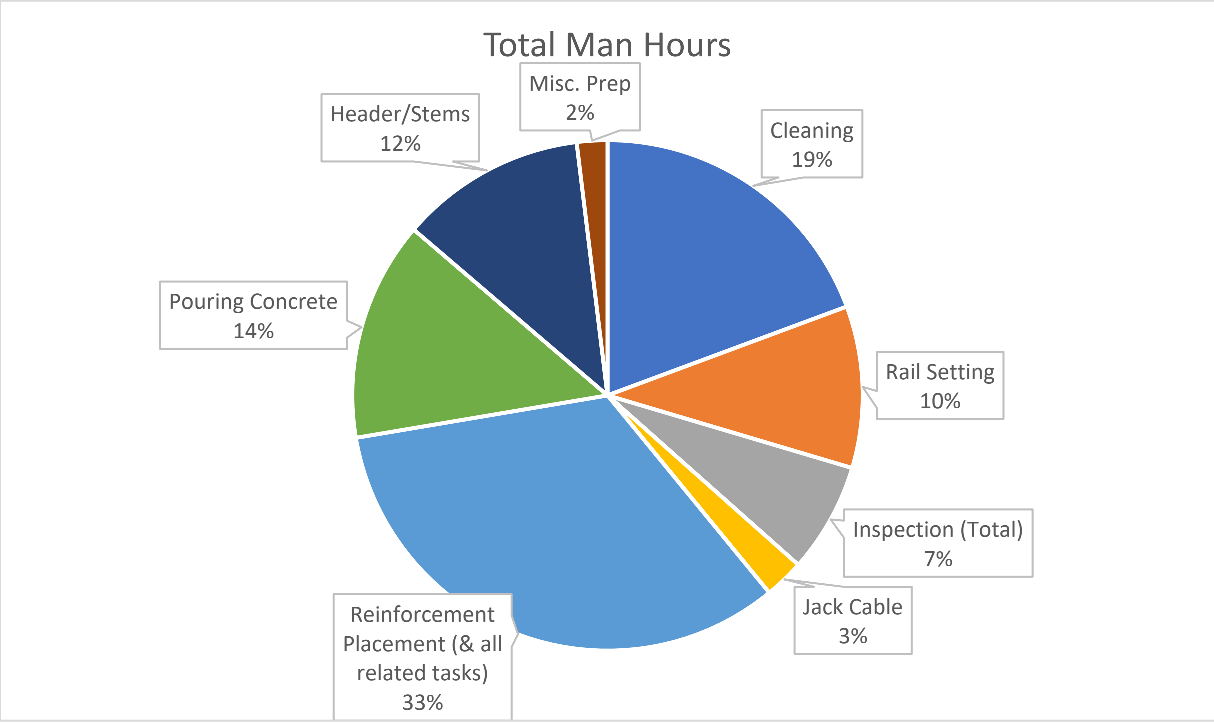


Figure 6-1. Overall Double Tee Task Breakdown by Category

As shown in **Figure 6-2**, the rail setting includes three primary tasks of marking, caulking, and oiling the formwork. Marking the appropriate locations for beam components takes approximately two-thirds of the rail setting time, requiring two crew members for 80 minutes each.

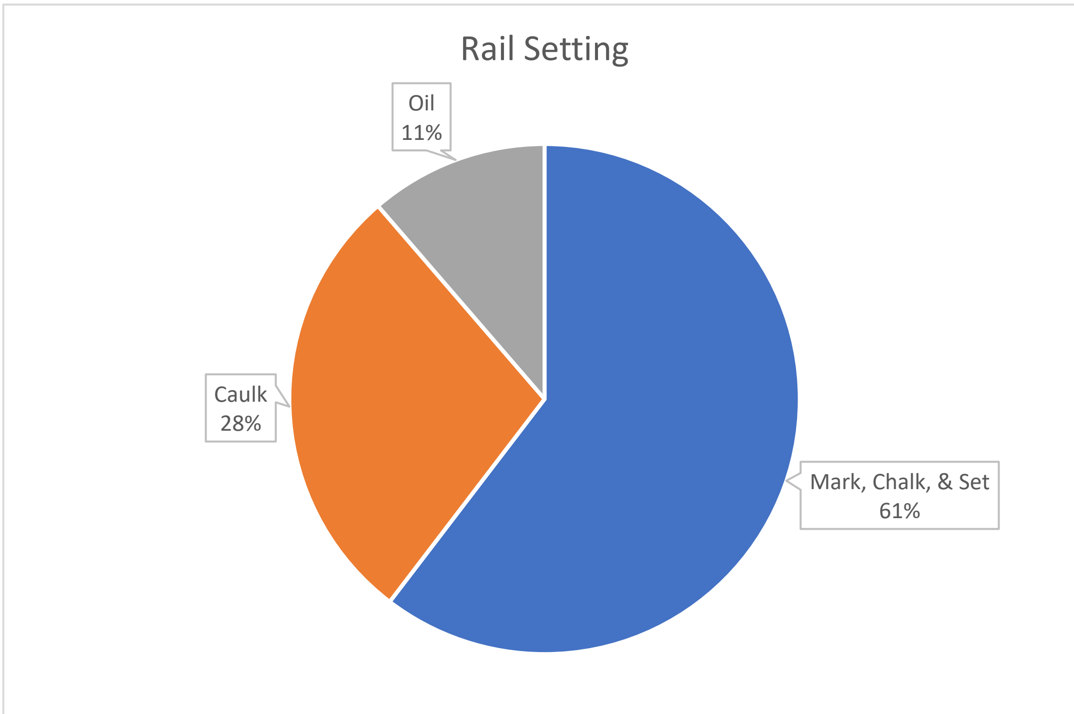


Figure 6-2. Rail Setting

The next set of tasks, shown in **Figure 6-3**, include prepping a cart with all the necessary reinforcement materials, layout out the reinforcement mesh, inserting reinforcing steel and plates, tying reinforcing steel and mesh at intersections, and bolting and chairing the wire mesh. The most time-consuming steps of the reinforcement placement process is tying in the reinforcing steel. The tying step adds no strength to the finished structure but adds more security to the wire mesh. In most cases, bars are tied at every second, third, and fourth intersection of the steel bars. It is worth noting that the tying process involves a worker standing on the combination table and bending over manually tie at the intersections, placing strain on the lower back. For a standard DT1 510', two workers are required to tie in reinforcing steel and mesh for approximately 135 minutes each. The group of tasks represented in **Figure 6-3** contribute about 14.3 net hours to the total 43 hours of the precast process (scaled by the number of people required for the tasks). The cable jacking step (**Figure 6-4)** takes up only 65 net minutes of the overall time, taking up only 3% of the process. The concrete placement step (**Figure 6-5**) takes up 360 minutes of the total man hours (3 crew members at 120 minutes each).

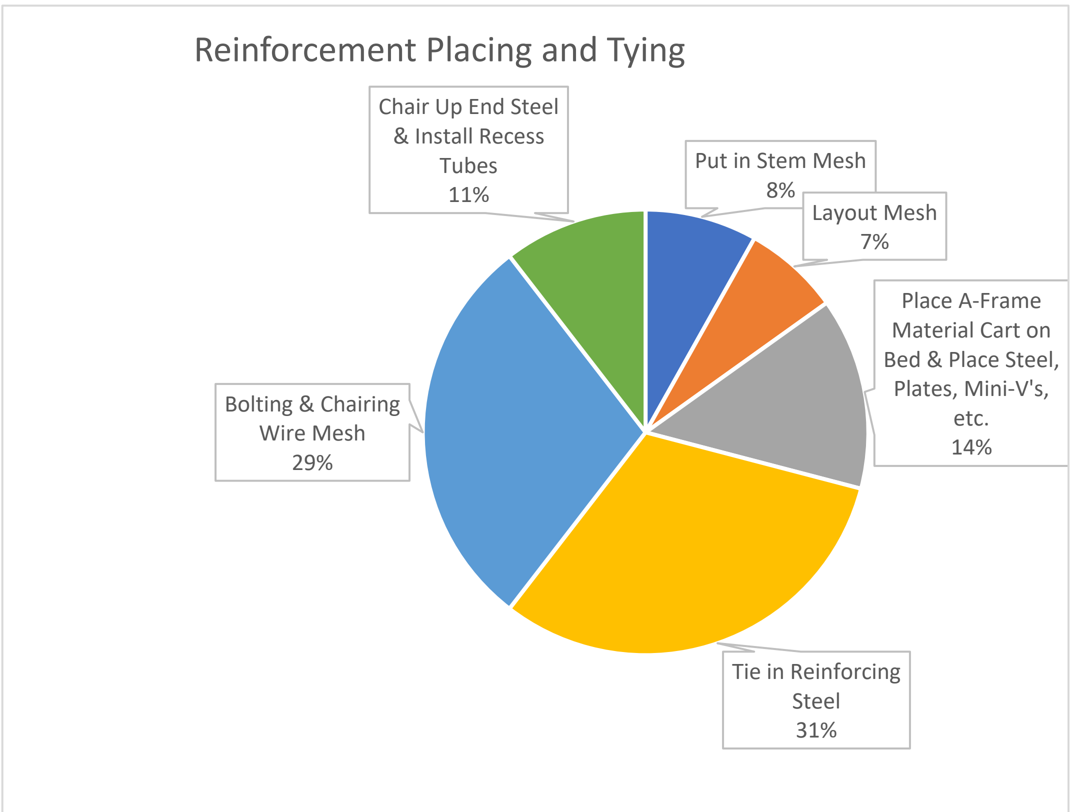


Figure 6-3. Reinforcement Placing and Tying

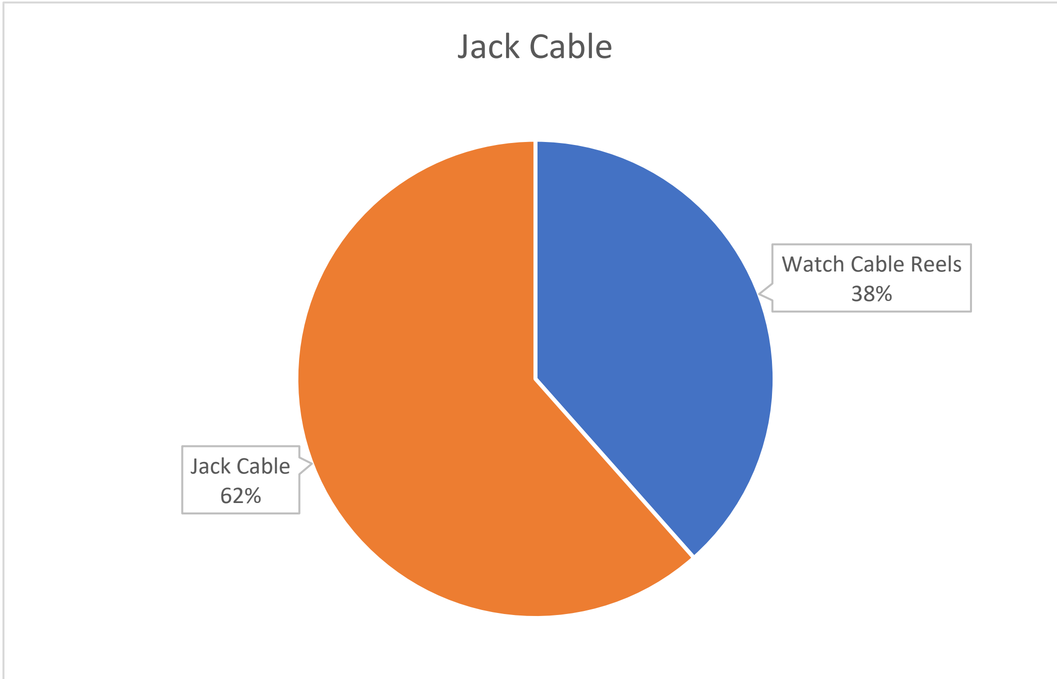


Figure 6-4 Jack Cable

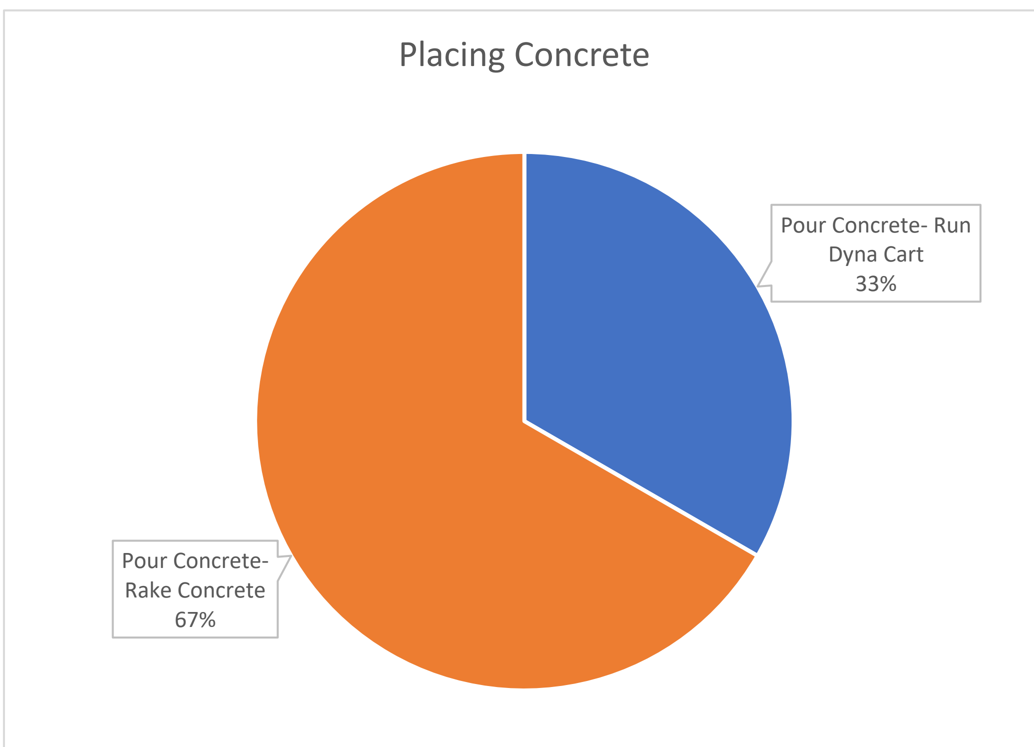
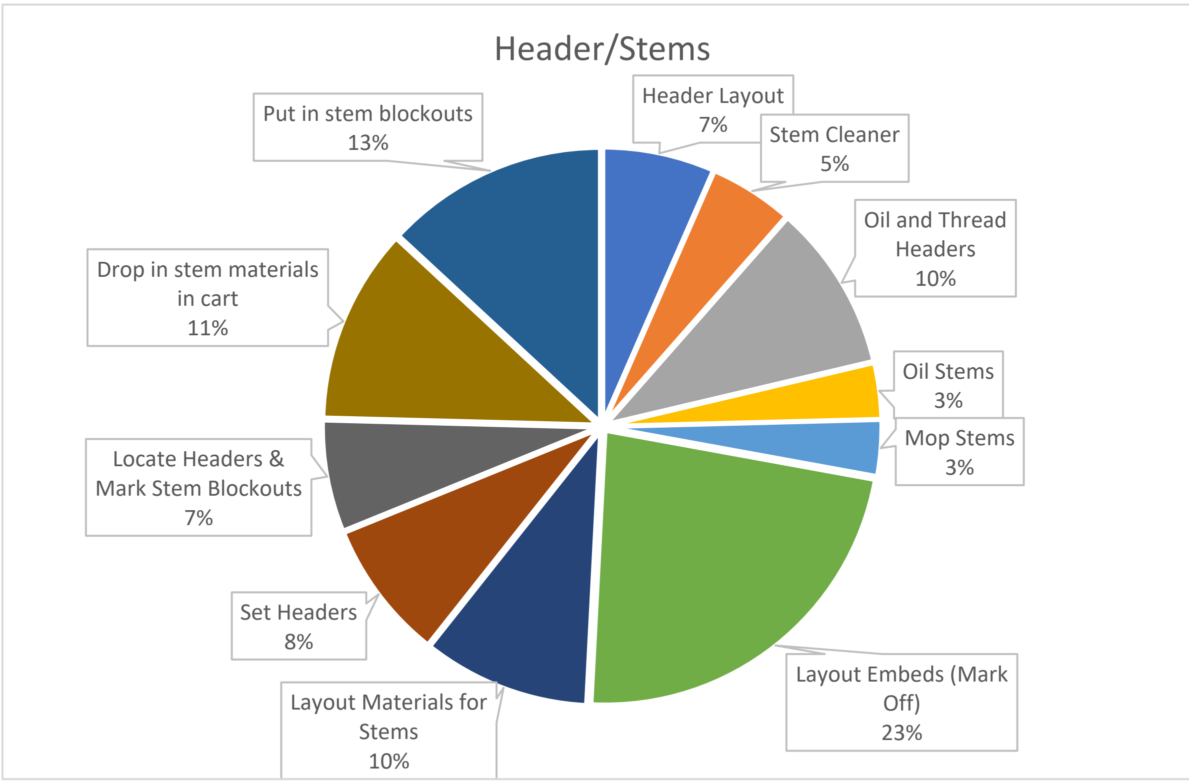


Figure 6-5 Placing Concrete

The group of tasks related to header and stem placement take up approximately 305 net minutes of the total process (11%). As shown in **Figure 6-6,** These tasks include laying out, oiling and threading, and setting the headers. The stems are cleaned and mopped, and blockouts are mopped and placed. The most



time-consuming task, however, is marking out the locations for embeds (i.e., metal plates with connected bolts).

Figure 6-6 Headers/Stems

The tasks presented in **Figure 6-7** are miscellaneous preparatory steps in between tasks. These tasks include preparing the dynamic cart, reviewing drawings, and planning, and oiling the rakes and screed and retrieving the concrete vibrator.

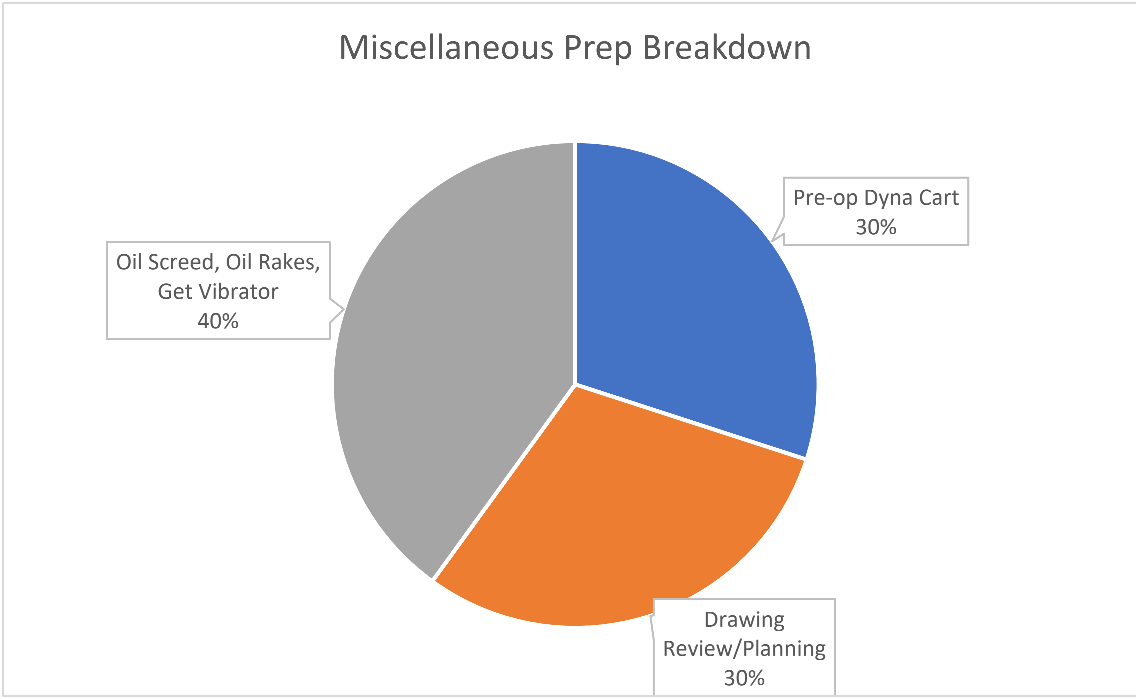


Figure 6-7. Miscellaneous Prep Breakdown

6.1.1 Work Combination Table Analysis Conclusion

Based on the assessment of the double tee production time data, it is evident that placing the reinforcement bars and mesh are the most time-consuming stage of the process. While all tasks of the precast process would benefit from the use of automation, it is important to consider which task has the highest need for it. Due to the repetitive, uncomplicated nature of tying reinforcing steel, it is a good candidate for flexible automation. Incorporating point automation into this task would offer many labor, cost, and safety benefits.

While it is challenging to quantify the impact of this change, one quantitative measure would be reducing labor costs and addressing labor shortage. Over time, as an aging generation of skilled workers becomes scarcer (see Deloitte data in Chapter 2.5.), lower-skilled labor can be used with a semi-automated device. If a labor-saving device could reduce labor costs by 10%, then resulting yearly savings would be between 162 and 220 million dollars. Other potential benefits are improvement in quality and consistency and improvement in worker health. This device will be able to produce the same quality tie in the same amount of time and reduce impending worker fatigue over long shifts.

6.2 Decision Analysis

This section presents the results of the values survey described in section 5.4.1 by respondent and superscored. The purpose of these results is to quantify the weights of importance of each of the seven criteria (economic efficiency, time efficiency, integrability, adaptability, durability, worker safety, and quality) used in the decision matrix (**Figure 6-8**). This section describes three candidate solutions to automating the rebar placement or tying task. These three solutions are then evaluated according to the seven criteria, based on the researcher's interpretation of product specifications and capabilities. Using the weights of importance established from the survey results, each of the three candidate solutions receive a total weighted score. The solution with the highest weighted score, Autonomous Rebar Tying Robot (TyBot), is selected as the starting point for a new automated system.

6.2.1 Survey Results by Respondent

The results of the values survey are analyzed by category and by respondent. The methodology for how each section is scored is described in **5.4.2- Survey Scoring Rubric**. Raw scores for each category are then scaled out of their maximum possible points to convert to the 1-10 scale represented in **Tables 6-1**, **6-2**, **6-3**, and **6-4.**

The results in Table 6-1 reveal that the first respondent value worker safety/autonomy and ease of integration the highest. Adaptability, on the other hand, is not of concern to the first respondent. This reveals that a new automated system would still be of value even if it cannot accommodate every product type and geometry. The results are consistent across all three sections, with a bias towards economic efficiency in Section 3.

Table 6-1 Respondent 1 Survey Results

	Weighted Score (1-10)						
Category:	Economic Efficiency	Time	Worker Safety	Integrability	Durability	Quality	Adaptability
Section 1	4	8	10	10	10	3	4
Section 2	4	N/A	5	6	10	5	2
Section 3	7	7	10	9	8	6	5
SuperScore	**5**	**7.5**	**8.33**	**8.33**	**8.33**	**4.67**	**3.67**

Respondent 2 valued integrability and worker safety the highest on average (**Table 6-2**). However, they showed a higher preference toward durability in Section 2 and a higher preference toward worker safety in section 2 and 3. Respondent 2 did not provide rankings for all categories in section 3.

Table 6-2 Respondent 2 Survey Results

	Weighted Score (1-10)						
Category:	Economic Efficiency	Time	Worker Safety	Integrability	Durability	Quality	Adaptability
Section 1	6	3	4	10	3	10	5
Section 2	5	N/A	9	10	7	10	5
Section 3*			10			5	2
SuperScore	**5.5**	**3**	**7.67**	**10**	**5**	**8.33**	**4**

*Respondent did not provide rankings for all of the options in section 3.

The results in **Table 6-3** reveal a strong preference toward economic efficiency in Section 1 and Section 3. Respondent 3 tended to strongly disagree with most statements across Section 2, resulting in relatively low scores across all categories. It is possible that the use of absolute wording in the statements deterred this respondent from agreeing (see **5.4.1.2- Agreement Spectrum**).

Table 6-3 Respondent 3 Survey Results

	Weighted Score (1-10)						
Category:	Economic Efficiency	Time	Worker Safety	Integrability	Durability	Quality	Adaptability
Section 1	6	3	2	5	10	5	10
Section 2	2	N/A	2	4	2	5	4
Section 3	10	6	9	3	7	8	7
SuperScore	**6**	**4.5**	**4.33**	**4**	**6.33**	**6**	**7**

Respondent 4 demonstrated a strong preference toward durability and worker safety throughout the sections. The relatively low results for time and adaptability reveal that even if the new automated process cannot accommodate every single product type and reduce overall cycle time, it is still worth pursuing because of the safety outcomes.

Table 6-4 Respondent 4 Survey Results

	Weighted Score (1-10)						
Category:	Economic Efficiency	Time	Worker Safety	Integrability	Durability	Quality	Adaptability
Section 1	6	4	6	10	10	2	4
Section 2	5	N/A	5	3	7	8	3
Section 3	8	5	10	6	5	7	9
SuperScore	**6.33**	**4.5**	**7**	**6.33**	**7.33**	**5.67**	**5.33**

6.2.2 Survey Results SuperScore

Each section's weighted score is averaged across all four respondents to produce the section superscore **(Table 6-5**). It is worth noting that there is a high level of variability between each respondent, reflected in the standard deviation. One of the sections with the highest standard deviation is Worker Safety. This could be because questions on worker safety could be interpreted two different ways. Some of the questions assigned to Worker Safety suggested that automation should be made safer and less strenuous on workers. Other questions assigned to Worker Safety commented on the level of autonomy of the automation (which, in turn, requires fewer workers present to complete the task and improves overall worker safety).

The relatively low overall score for Economic Efficiency seems surprising, considering this is a common motivation for automation in other industries. Upon further discussion with one of the survey respondents, this result reveals that the stakeholders at the precast plant understand that automation is not necessarily lucrative. Rather, the other outcomes of automation (i.e. improved worker safety, improved productivity) are more practical and realistic to them than a high return on investment.

Table 6-5 SuperScore by Section

	Weighted Score (1-10)						
Category:	Economic Efficiency	Time	Worker Safety	Integrability	Durability	Quality	Adaptability
Section 1	**5.5**	**4.5**	**5.5**	**8.75**	**8.25**	**5**	**5.75**
Standard Deviation	0.86	2.06	2.96	2.17	3.03	3.08	2.49
Section 2	**4**	**N/A**	**5.25**	**5.75**	**6.5**	**7**	**3.5**
Standard Deviation	1.22	N/A	2.49	2.68	2.87	2.12	1.12
Section 3	**7.67**	**5**	**7.5**	**3.67**	**5**	**6.75**	**6**
Standard Deviation	2.05	0.82	3.77	1.70	1.63	1.09	2.55
SuperScore	**5.71**	**4.88**	**6.83**	**7.17**	**7**	**6.17**	**5**

6.2.3.1 Bar Arrangement Machine

The Shimzu Corporation has developed a “bar arrangement” machine for placement of reinforcing bars. The system has two vehicles, each moving along the x and y directions on a steel-frame support base. First, one vehicle moves longitudinally carrying the bars until it reaches a predetermined position. Then, the other vehicle transversally places reinforcing bars. Once the mesh of bars is placed, the reinforcement is tied manually. The entire work productivity will increase to twice the manual capability (Yamashita et. al. 1990).

The system requires reconfiguration of the precast bed to incorporate the vehicles and the steel frame support base. However, since the automated system requires no special skills to operate, the integrability receives a scoring of 2 (Good). Because the bars still need to be manually tied, this option receives a scoring of 2 (Good) for worker safety as well, since some lower back strain and fatigue are still of concern. This option receives a score of 3 for time, durability, and quality because the system overall productivity to nearly twice the previous level. Because the overall productivity of the system increases twofold, it receives a scoring of 3 (Excellent) for time, durability, and quality.

6.2.3.2 Semi-Automated Rebar Tying Device

Altobelli (1991) developed a semi-automated device to assist workers in rebar tying. The machine is a handheld tool, allowing the operator to tie rebar from the standing position. The major features of this device are the staple feeding mechanism and the retractable wire tensioning and twisting mechanism. The worker pulls a trigger, and the device will automatically initiate a series of actions resulting in a tied connection (Altobelli 1991). The pneumatically actuated feeding mechanism functions much like a common stapler.

This device was designed with several criteria in mind. First, it is imperative that a semi-automated device for this purpose is used while the operator is standing up. Not only does this reduce the risk of injury, but it prevents the inevitable slowdown due to fatigue over long shifts. With worker safety in mind, this device scores a 3 (Excellent). Another criterion is the ability to produce a strong, tight tie to keep the reinforcing steel from moving during construction. While tying the rebar adds no strength benefit to the finished product, it must be able to resist the dynamic load of pumped liquid concrete and the weight of workers standing on top of it. Since the overall quality of the tie is upheld but not exceeded, this device scores a 2 (Good). Finally, one of the most important criteria is speed. Union steelworkers average between fifteen to thirty diagonal steel per minute ties by hand. Therefore, this device must complete a tie in two seconds to remain a competitive alternative. Since this device completes the tying operation in the same amount of time and not much faster, it receives a score of 2 (Good) for time in the decision matrix. The last criterion is durability to survive harsh plant environments. The tool is designed to handle rain, dirt, dust, vibration, shock, and general rough handling, so it scores a 3 (Excellent) for durability.

6.2.3.3 Autonomous Rebar Tying Robot (TyBot)

The autonomous rebar tying robot (TyBot) autonomously navigates the precast bed and optically identifies and ties rebar intersections. The overhead equipment rides alone existing screed rail support used for precast finishing. Because of the ease of assembly, relatively short setup time (four hours), and functional independence from programs, this option receives an integrability score of 3 (Excellent). TyBot can execute both all-intersection and alternating-intersection patterns for project widths between 10 and 100 ft (approximately 3 and 30 m), scoring at a 3 (Excellent) in adaptability. Since this equipment eliminates the need for crew members to manually tie intersections and only requires a quality control operator, it scores a 3 (Excellent) for worker safety. Economic efficiency is determined to be 2 (Good) because while it is a costly option, it eliminates the need for time-consuming labor which reduces long term costs. **Figure 6-8** evaluates the three automation alternatives for precast double tee production.

Analysis Matrix Alternatives / Weight of Importance (0-10)	A. Economic Efficiency	B. Time	C. Worker Safety	D. Integrability	E. Durability	F. Quality	G. Adaptability	
Weight of Importance (0-10)	**5.71**	**4.88**	**6.83**	**7.17**	**7**	**6.17**	**5**	
Bar Arrangement Machine	2 / 11.42	3 / 14.64	2 / 13.66	2 / 14.34	3 / 21	3 / 18.51	2 / 10	**103.57**
Semi-Automated Rebar Tying Device	3 / 17.13	2 / 9.76	3 / 20.49	3 / 21.51	2 / 14	2 / 12.34	3 / 15	**110.23**
Autonomous Rebar Tying Robot (Tybot)	2 / 11.41	2 / 9.76	3 / 20.49	3 / 21.51	3 / 21	3 / 18.51	3 / 15	**117.68**

*Selected based on weighted evaluation
3- Excellent 2-Good 1-Fair

Figure 6-8 Decision Tree Analysis Results

The values in **Figure 6-8** are computed by scoring each alternative on a 1-3 scale for each criterion (3- Excellent 2-Good 1-Fair) and then multiplying by the weight of importance, determined by the superscore of the survey results. Then, each alternative's weighted scores are summed and reported on the far-right column of the decision tree. The autonomous rebar tying robot (TyBot) receives the highest weighted total of 117.68, followed by the semi-automated rebar tying device and then the bar arrangement machine. This ranking is congruent with the company's values, measured in the survey results. The autonomous rebar tying device offers the highest level of integrability out of the three alternatives, which survey respondents' value highly. The optical-sensing capabilities of the device render it extremely flexible to different products since no CAD/CAM data is required. The bar arrangement machine, on the other hand, is not very adaptable since it is fixed in size and is more challenging to integrate. Therefore, this solution does not offer as much benefit to an older, more established plant environment where ease of integration is of high importance.

One shortcoming of the autonomous rebar tying robot (TyBot) is its inability to navigate the z-direction. While it autonomously identifies and ties intersections in the x-y plane, it is not sufficient for the precast products produced at the precast facility used in this case study. Many precast products at this facility have multiple layers of wire mesh in the concrete deck, and an automated rebar tying device must be able to navigate this dimension.

Although none of the alternatives evaluated meet the full technical requirements for the rebar tying process at the precast facility, the capabilities of TyBot are used to inform the development of a new, automated rebar tying machine. From the decision tree analysis, it is determined that an optically sensing autonomous device best fits the integration and adaptability criteria. It must offer similar durability and final product quality to the autonomous rebar tying device. Section 6.3 details the technical standards for a new, automated rebar tying machine that meets all requirements.

6.3 Technical Standards for Automated Rebar Tying Machine

The full technical standard document is written in the style of the International Organization for Standardization (ISO) and is included in Appendix B. This section will introduce the content of each of the non-introductory sections of the standard.

6.3.1 Rebar Tying Operation

The purpose of the connection is to fix the relative positions of the rebar during construction operations. Since tying steel reinforcement offers no additional strength gain to the final product, there are no structural capacity requirements for the intersection. The strength of the tie simply must be able to support the dynamic loads of pumped liquid concrete and the weight of workers standing on the precast bed**.** This machine must be able to execute a tight tie. To make a tight tie, the wire must form the shortest path around the bars.

6.3.1.1 Number of Tied Intersections

It is not necessary for every intersection to be tied, but enough must be tied so that the steel does not move. The number of ties is based upon the configuration of the bars and proposed concrete placing method. Ultimately, it is determined by judgment. Local codes may sometimes prescribe the number or percentage of tied intersections. Washington DC codes, for example, mandate that 100% of intersections must be tied for the top layer of bridge decks and 50% of all other layers.

6.3.2 Degrees of Freedom

The tying arm of the machine must be capable of traversing the x, y, and z dimensions. i.e., the machine must be able to execute ties along a planar surface and at various depths on a precast element, as a precast element may include multiple layers of welded wire mesh. Figure 4 illustrates these degrees of freedom. The datum for the z direction is the surface of the concrete deck, and the datum for the x-y plane is in the lower-left corner of the deck.

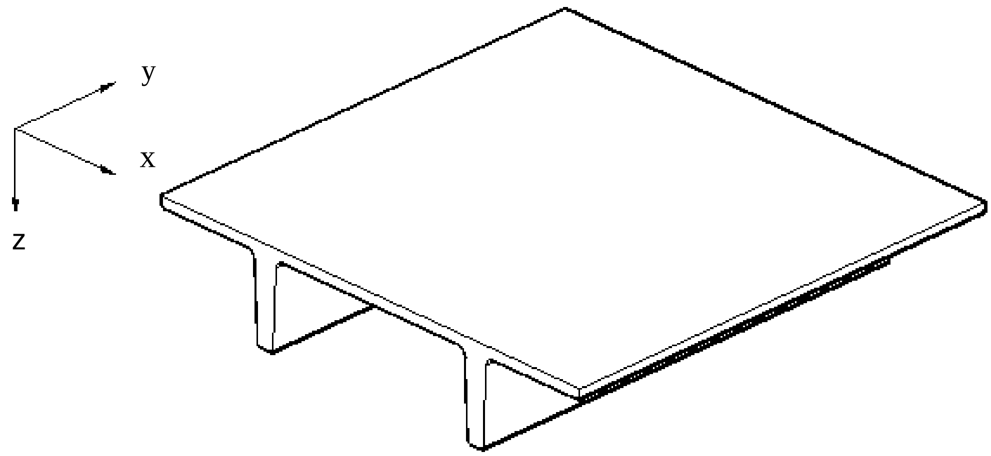


Figure 6-9 Degrees of Freedom

6.3.3 Interference Constraints

The interference constraint section addresses the possible constraints of surrounding bars or welded wire mesh. To loop the tie wire around the bars, an automated rebar tying machine must reach past the bars to execute a strong, tight tie. The tool may experience some interference with adjacent bars or lower layers of bars beneath the work surface. The required minimum clearance between layers of bars is 1 in. (2.54 cm). Therefore, the automated rebar tying mechanism must be able to operate within 1 vertical inch (2.54 cm) of the rebar intersection.

6.3.4 Span

The span dictates the minimum and maximum dimensions the machine must be able to traverse in the x y and z dimensions. In the x-direction, it must be able to traverse a minimum length of 58 ft (17.68 m) and maximum length of 61 ft (18.59 m) for typical double tee products in the x-direction. In the y-direction, the minimum distance the device must travel is 10 ft (3.05 m) and the maximum distance is 13 ft (3.96 m). The minimum distance the rebar tying device must traverse in the z-direction is dictated by the maximum vertical location of welded wire mesh and in the concrete deck. Typical double tee decks range from 2 in. (5.08 cm) to 4 in. (10.16 cm) thick. Mesh intersections typically occur from as little as 1 in. (2.54 cm) to 3 in. (7.62 cm) below the surface.

6.3.5 Controls

The automatic rebar tying machine shall not be calibrated by CAD/CAM data or pre-plotting. Instead, the machine process visual data of rebar intersections and wire mesh overlap through *machine vision.* See Appendix B for full step by step machine vision process under the technical standard document.

As for the system actuation, the chosen actuator (i.e., servo motor, stepper motor) must offer at least the precision level specified in Interference Constraints and Tolerances.

6.4 Mathematical Model for Automated Rebar Tying Operation

To evaluate the potential impacts of incorporating automation into the rebar tying stage, the process must be assessed quantitatively. First, the existing manual rebar tying process is quantified in terms of man-hours and labor cost. Standard mesh patterns for double tee products are used to depict the minimum requirements for rebar tying **(Figure 6-8**). Next, a mathematical model is developed using the power, rotational velocity, and mechanical loads of the system. For the intended use case of the system, a servo motor electrical actuator is identified as the most effective method for controlling the machine. When considering the known and estimated parameters of the system, the linear speeds are derived. Finally, the existing geometry and mesh configuration of the double tee product is integrated with the derived linear speeds to obtain a total time.

6.4.1 Modeling the Existing Process

First, the existing manual process for placing and tying rebar must be quantified. According to the work combination table data presented in **Figure 6-3**, tying rebar on a standard DT1-510’ requires about 270 man-minutes to complete (two workers at approximately 135 minutes each). In this particular plant, three double tees are manufactured simultaneously each day, yielding 810 man-minutes dedicated toward tying the reinforcing steel daily. As for the labor cost, the typical range at this specific plant is between \$22.50 and \$25.00/hour. In this calculation, the average of this range is used:

$$Cost\ per\ day\ (\$/day) = 23.75\left(\frac{270*3}{60}\right) = \$320.63/day \qquad \text{(Equation 6-1)}$$

The number of ties required per double fee product is dependent on the mesh pattern and mesh sheet size. For the geometry in **Figure 6-10**, the standard mesh sheet size is 13 ft by 10 ft (3.96 m by 3.05 m) and 13 ft by 4 ft – 2 in. for the end pieces (3.96 m by 1.27 m). While Figure 6-10 depicts the mesh, sheets tied end to end, there are typically two squares of overlap in practice. For an 8-in.-wide (20.32 cm) mesh square, the overlap distance is 16 in. (40.64 cm).

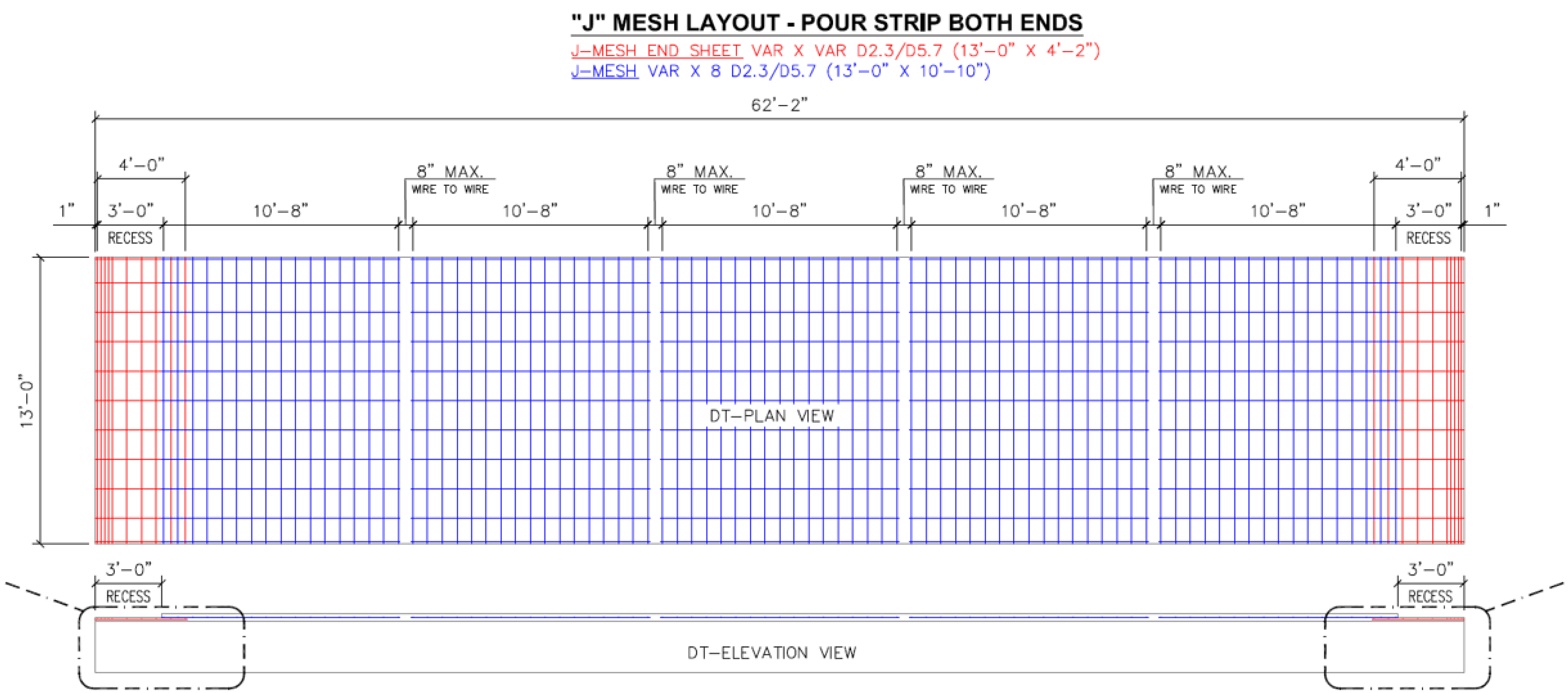


Figure 6-10 Double Tee Mesh Layout

Figure 6-11 depicts the minimum overlap and minimum tie requirements for the double tee (indicated with slash marks). In this minimally tied configuration, the minimum number of mesh-to-mesh tied intersections comprise 46 ties. In addition, the welded wire mesh must also be tied to the end flanges of the double tee. The V shaped symbols on the top and bottom edge of the elevation view in **Figure 6-12** depict the connection from the welded wire mesh to the end flanges, ultimately used to connect multiple double tee products together. Each one of these connections includes two ties. In total, the mesh to end flange connections comprise 40 ties.

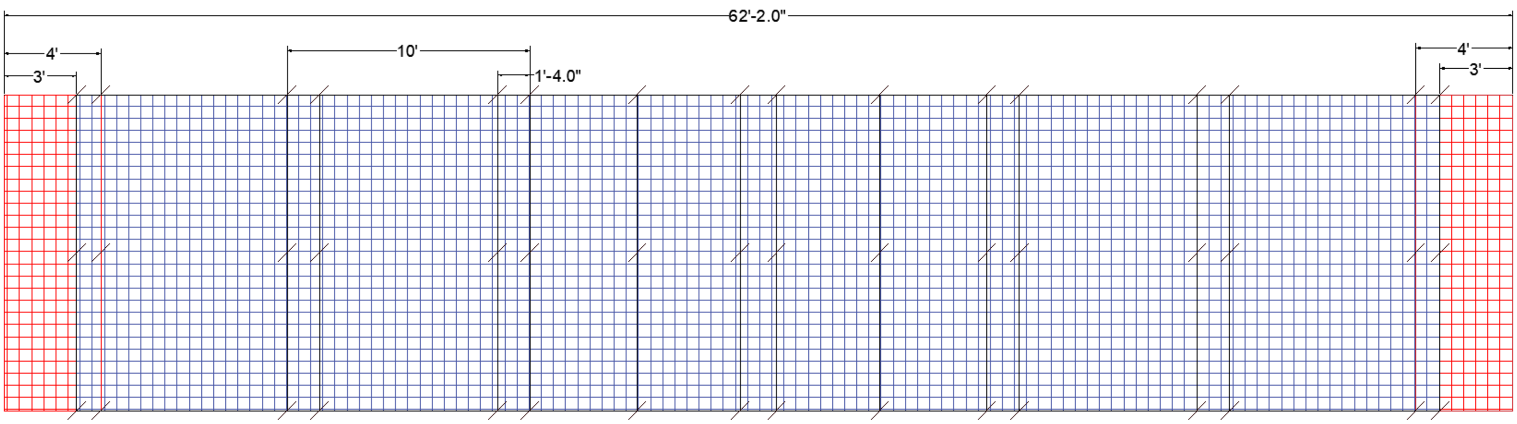


Figure 6-11 Overlapping Sheet Requirements

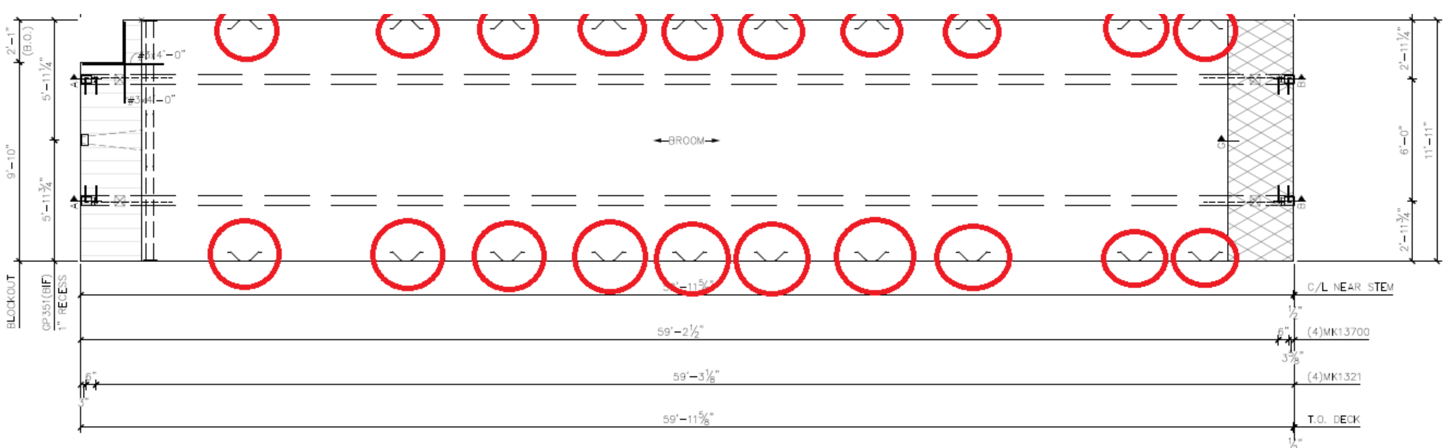


Figure 6-12 Welded Wire Mesh to End Flange Connections

6.4.2 Processing Parameters for Automated Rebar Tying Operation

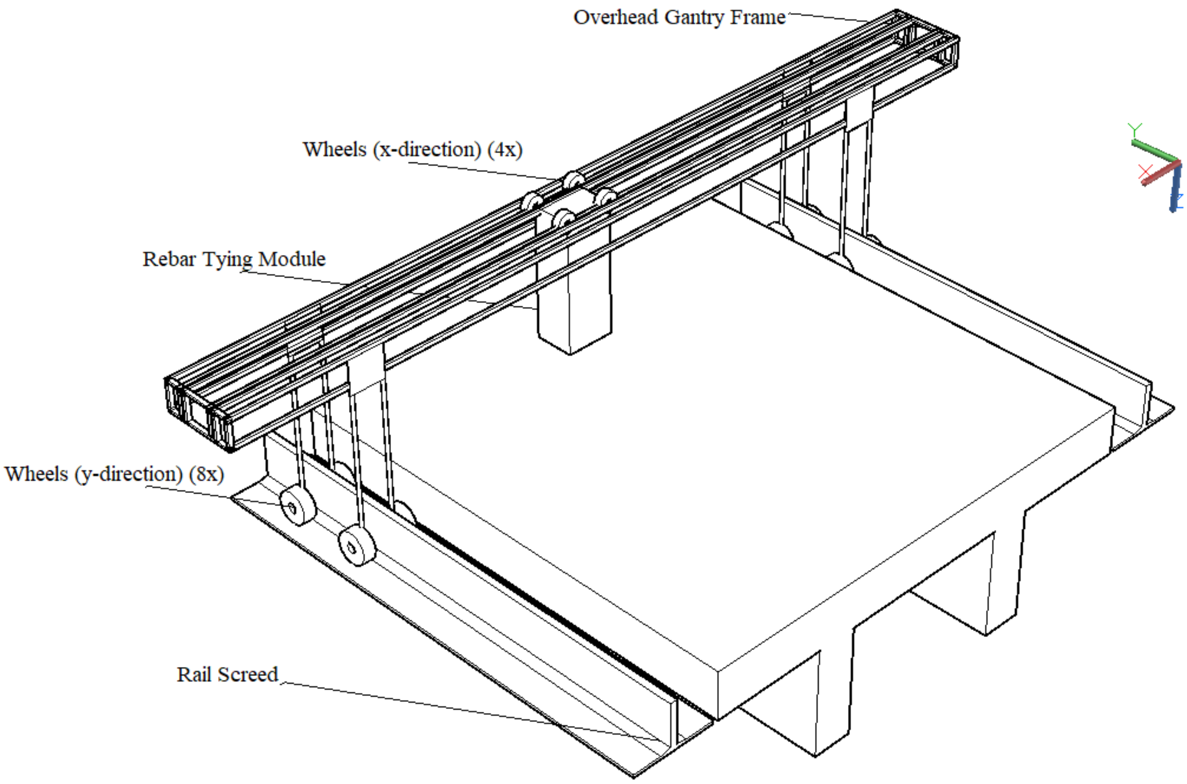
6.4.2.1 Actuator Constraints

The machine uses an electrical actuator to power the motion of the device and the tying action. Since the rebar tying operation requires precise motion to a specific location on the precast bed, an electrical actuator is advantageous since it allows for more precision than pneumatic actuators. With an electrical actuator, there are two choices for the type of motor used. A stepper motor is better suited for lower-speed operation and consequently offers the advantage of lower cost. Servo motors, on the other hand, are closed loop and provide better performance at higher speeds at a higher cost. Standard precisions, with standard components, range from a few hundredths to a few thousandths of an inch (Greenfield 2017). Since the rebar tying device must operate at a relatively high speed, a servo motor is better suited for this application since it offers a wider range of speeds.

6.4.2.2 Degrees of Freedom

For the purposes of this analysis, the automated rebar tying machine involves a frame that rides along the existing screed of the precast bed and an overhead gantry frame where the rebar tying module travels in the transverse direction (**Figure 6-13).** The linear velocities of the rebar tying device in the x, y, and z directions are controlled by three independent mechanisms.

1. x: velocity of tying device traveling along the overhead gantry frame.
2. y: longitudinal travel velocity of gantry frame along rail screed
3. z: vertical velocity of rebar tying device.



*Not to scale. Wheel and screed rail sizes exaggerated for visual aid.

Figure 6-13 Gantry Configuration

The x and y degrees of freedom are controlled by wheels rotating along a fixed track. Since the servo motor encoder does not know anything about the wheel size, it records angular position. **Figure 6-14** depicts the relationship between linear and angular velocity that will be used to develop the mathematical model for the x-y degrees of freedom.

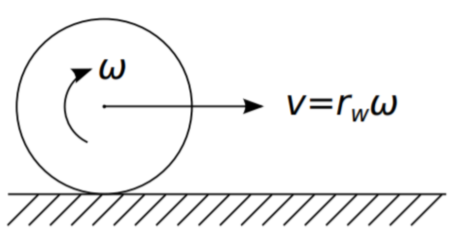


Figure 6-14 Mapping Wheel Rotation Speed to Velocity (Davison 2021)

6.4.2.3 Power Constraints

Similar commercially existing equipment can deliver 5500 Watts of power (7.38 hp) while consuming 0.95 gallons per hour of fuel at full load (3.6 L/hr.), 0.60 gallons per hour at half load (2.3 L/hr.), and 0.35 gallons per hour at no load (1.3 L/hr.). For a Servo Motor, the power equation is represented as:

$$P_{k,servo}(\omega) = P_{T,servo} + P_k(\omega) \qquad \text{(Equation 6-2)}$$

Where $P_{T\ on}$ is power consumed to maintain stability in a no-motion state and $P_k(\omega)$ is the power consumed at a specific angular speed ω. The power consumed due to angular motion is largely dependent on the mechanical load, which can be expressed in terms of torque.

$$P_k(\omega) = T\omega \qquad \text{(Equation 6-3)}$$

In a system with multiple power consuming components and mechanical and electrical efficiencies (η_{mech}, η_{el}), the equation becomes the following.

$$P_k = \sum_{i=1}^{n} T_i \omega_i \frac{1}{\prod_{i=1}^{n} \eta_{mech,i} \eta_{el,i}} \qquad \text{(Equation 6-4)}$$

6.4.2.4 Estimation of Parameters

For this analysis, the parameter of greatest interest is the linear speed in the x, y, and z directions since these have the greatest influence on overall cycle time for the rebar tying task and cost. To derive the linear speeds using equation, the remainder of the parameters must be either estimated or inferred from similar existing technology. Equation 6-4 is re-written in terms of linear speed:

$$P_k = \sum_{i=1}^{n} [F_i \times r_i] \left[\frac{v_i}{r_i}\right] \frac{1}{\prod_{i=1}^{n} \eta_{mech,i} \eta_{el,i}} \qquad \text{(Equation 6-5)}$$

The system configuration has two pairs of wheels on each end of the gantry frame riding along the existing screed. Therefore, there are a total of eight wheels responsible for carrying the frame in the y-direction. Similar existing technology rates the max wheel loading to be 960 lbs (4270 N) per wheel, thus this value is used in the analysis. A typical generator set for this machine provides 5500 Watts of power. It is assumed that mechanical and electrical efficiency of this system is 80% each for the purposes of this model. The distribution of power described in equation 6-2 is assumed to be 1500 Watts for $P_{T,on}$ (no motion state) and 4000 Watts of power for $P(\omega)$. $P(\omega)$ must be further divided to power the kinematic motion in the x, y, and z directions. Because the power consumed by each rotating component is a function of mechanical load and rotational speed, it is useful to first compare mechanical loads and desired relative speeds of the system. The wheels traveling in the y-direction along the rail screed are carrying the majority of the load of the system. However, their motion is unidirectional and is relatively slow compared to the x direction. The tying module, on the other hand, must move back and forth along the overhead frame relatively quickly to the necessarily tying locations in the x-direction. Compared to the load of the gantry frame, the load of the tying module (including the load of the tie wire itself) is estimated to be relatively low (330.5 lbs (150 kg.)). As a result of this distribution in load and desired relative speed, the total power is broken down in the following manner (**Figure 6-15**).

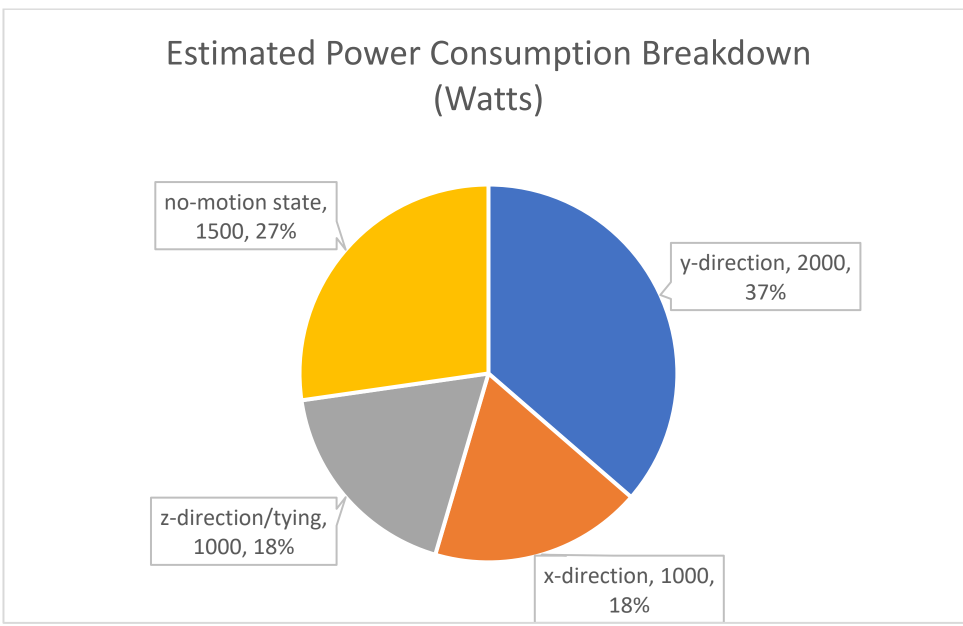


Figure 6-15 Estimated Power Consumption Breakdown

6.4.3 Mathematical Function

Using the estimated parameters from section 6.4.2.4, the linear speed of the machine in the x, y, and z dimensions is derived with Equation 6-5. An optimum path for the machine to traverse is determined based on the existing double tee geometry and mesh pattern (**Figure 6-16**). It is important to note that the system is not capable of traversing more than one degree of freedom at a time. Therefore, the total time spent navigating each degree of freedom is calculated independently and combined.

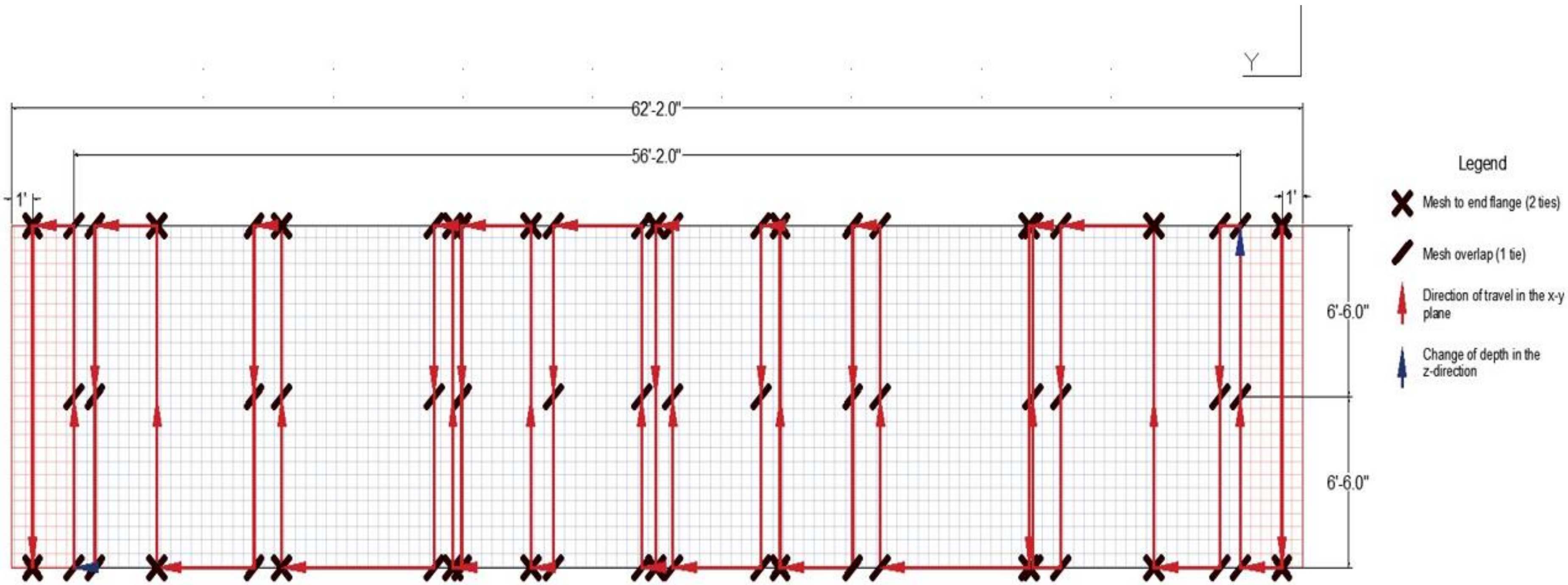


Figure 6-16. Optimum Path of Travel

Based on the path specified in **Figure 6-16**, the tying module traverses a distance of 6.5 ft (1.98 m) 50 times to travel to all mesh intersection and end flange locations in the minimally tied configuration. Therefore, the length of time spent traveling in the x-direction is the speed of the tying module in the x-direction times the total travel distance. In the y-direction, the motion of the gantry frame on the rail screed is unidirectional. i.e., the total distance traveled in the y-direction is nearly the full span of the double tee, where the end flange intersections begin and end. Using the known parameters of the system, it is difficult to estimate the speed of travel in the z direction or the length of time required to execute the tying mechanism. Based on industry data on the manual rate, the length of time required to execute one tie is determined to be 2 seconds (Altobelli 1991). The length of time required to traverse 1 inch in the z direction is approximated as 2 seconds, based on the researcher's intuition and physical observation of similar technology. N_z in Equation 6-9 indicates the number of times the device traverses between mesh layers (1 inch apart). The total time of operation for the automated rebar tying process is modeled as

$$t_{total} = t_x + t_y + t_z + t_{tie} \qquad \text{(Equation 6-6)}$$

Where each respective time in minutes comes out to

$$t_{tie} = \frac{2N_{tie}}{60} = 2.87 \text{ [min]} \qquad \text{(Equation 6-7)}$$

$$t_x = \frac{1}{60}\left(\frac{F_{x,i}}{P_{x,i}\eta_{mech}\eta_{ele}}\right)x = 3.79 \text{ [min]} \qquad \text{(Equation 6-8)}$$

$$t_y = \frac{1}{60}\left(\frac{F_{y,i}}{P_{y,i}\eta_{mech}\eta_{ele}}\right)y = 8.13 \text{ [min]} \qquad \text{(Equation 6-9)}$$

$$t_z = \frac{2}{60}N_z = 0.07 \text{ [min]} \qquad \text{(Equation 6-10)}$$

The resulting total time to locate, travel to, and tie all required connections is approximately 15 minutes. With the manual cycle time being approximately 135 minutes, the automated process would result in an 89% percent decrease in total cycle time. The MATLAB code used for the full computation is found in Appendix D.

While these results are specific to the geometry and mesh pattern of this specific double tee product, the mathematical model is modified to reflect different product types and mesh configurations. Note that these results are based on a minimally tied configuration and the times may increase with a more densely populated tying pattern. The N_{tie}, x, y, and N_z variables in equations 6-7, 6-8, 6-9, and 6-10 are subject to change based on differing product geometries, reinforcement requirements, and tying patterns.

6.5 Work Combination Table Redistribution

The introduction of a fully automated rebar tying system allows for a redistribution of labor to other aspects of the process. As shown in the existing work combination table, many of the reinforcement related tasks are executed simultaneously (**Figure 6-17**). This same structure is applied to the revised work combination table, with the exception of the rebar tying task. For safety purposes, no other tasks are performed on the precast bed during the 15-minute operating time of the rebar tying machine. **Figure 6-17** and **Figure 6-18** depict the current work combination table and the redistributed work combination table, respectively. Since the changes only impact the latter half of the total process, these figures only include the tasks after laying out the welded wire mesh. Note that each block of the table represents a 5-minute increment.

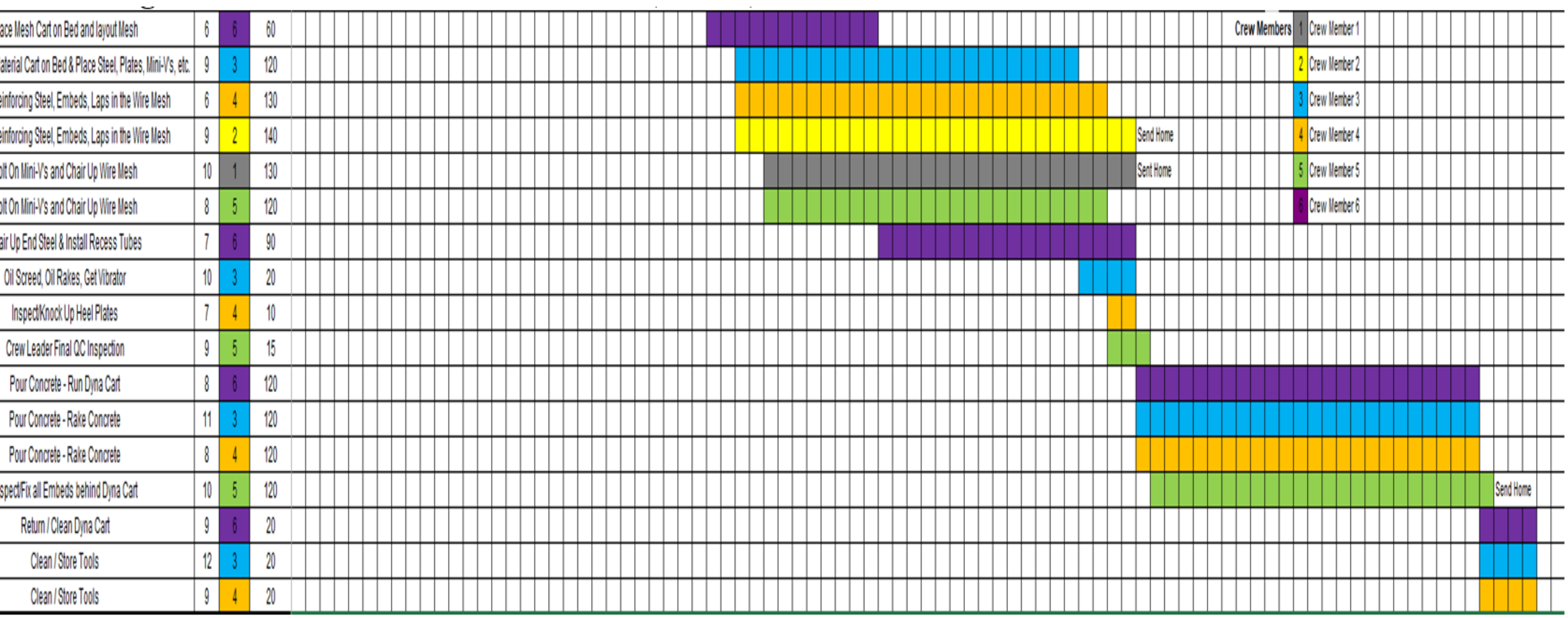


Figure 6-17. Work Combination Table (Before)

Place Mesh Cart on Bed and layout Mesh	60	6	6	40
Place Mesh Cart on Bed and layout Mesh			5	20
Place A-Frame Material Cart on Bed & Place Steel, Plates, Mini-V's, etc	120	9	3	40
Place A-Frame Material Cart on Bed & Place Steel, Plates, Mini-V's, etc.			4	40
Place A-Frame Material Cart on Bed & Place Steel, Plates, Mini-V's, etc.			2	40
Tie In all Reinforcing Steel, Embeds, Laps in the Wire Mesh	0	6		15
Bolt On Mini-V's and Chair Up Wire Mesh	250	10	1	65
Bolt On Mini-V's and Chair Up Wire Mesh		10	2	65
Bolt On Mini-V's and Chair Up Wire Mesh		10	5	65
Bolt On Mini-V's and Chair Up Wire Mesh		10	4	55
Chair Up End Steel & Install Recess Tubes	90	7	6	45
Chair Up End Steel & Install Recess Tubes			5	45
Oil Screed, Oil Rakes, Get Vibrator	20	10	6	20
Inspect/Knock Up Heel Plates	10	7	4	10
Crew Leader Final QC Inspection	15	9	5	15
Pour Concrete - Run Dyna Cart	120	8	6	120
Pour Concrete - Rake Concrete	240	11	3	120
Pour Concrete - Rake Concrete		8	4	120
Inspect/Fix all Embeds behind Dyna Cart	120	10	5	120
Return / Clean Dyna Cart	20	9	6	20
Clean / Store Tools	40	12	3	20
Clean / Store Tools		9	4	20

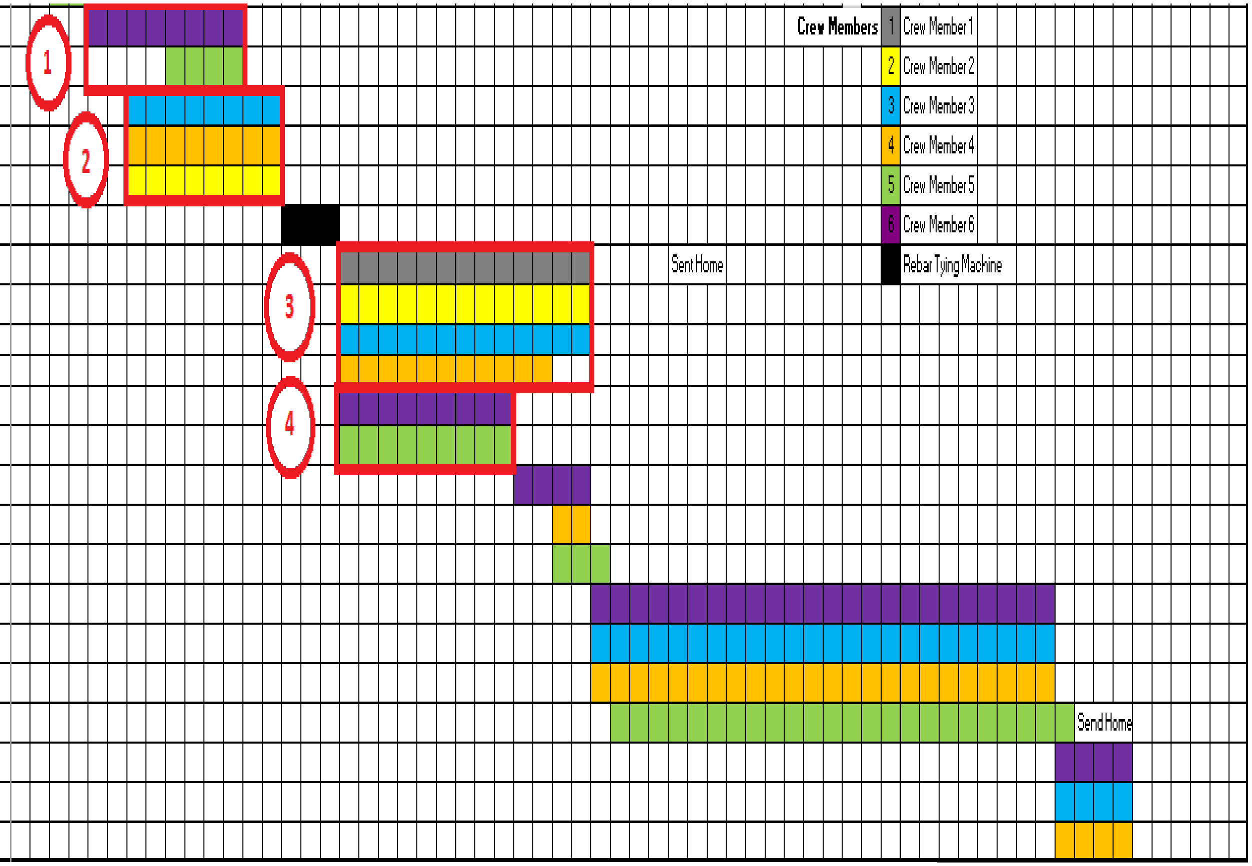


Figure 6-18. Redistributed Work Combination Table

The redistributed work combination table offers multiple benefits aside from eliminating the need for manual rebar tying and making the overall cycle time shorter (**Table 6-6**). The labor that would have been used toward manually tying rebar is now distributed to other reinforcement-related tasks before and after. The most notable changes include **(Figure 6-18)**:

- Two workers laying out mesh for 30 minutes each instead of one worker laying out mesh for 60 minutes.
- Three workers placing steel, plates, mini-V's, etc. for 40 minutes each instead of one worker for 120 minutes
- Four workers bolting mini-V's and chairing end steel for 65 and 55 minutes each, instead of two workers for 130 and 120 minutes each.
- Two workers chairing end steel and installing recess tubes at 45 minutes each, instead of one worker for 90 minutes.

Table 6-6 Reduction in Nonneutral Active Time by Crew Member

	Before	After	Reduction in nonneutral active time	% Reduction (Rebar related tasks)
Crew Member 1	130 minutes	65 minutes	65 minutes	50%
Crew Member 2	140 minutes	105 minutes	35 minutes	25%
Crew Member 3	120 minutes	40 minutes	80 minutes	66%
Crew Member 4	130 minutes	95 minutes	35 minutes	27%
Crew Member 5	120 minutes	95 minutes	25 minutes	21%
Crew Member 6	130 minutes	95 minutes	35 minutes	27%
Average Reduction	**46 minutes**			

Note that the overall reduction in total cycle time per double tee product is 20 minutes (**Figure 6-17**) (**Figure 6-18**). To a precast facility, this is not necessarily a substantial reduction. However, the results of the values survey reveal that reducing overall cycle time is not a highly valued outcome to this particular precast facility at this time (**Table 6-5**). The more practical benefit of the new automated process at this stage is realized from the redistribution of man hours and improvements in worker safety, described in the next section.

6.6. Qualitative Evaluation of Safety

Compared to workers in other construction-related trades, rebar workers have a much higher risk for experiencing low-back disorders (LBDs) (Albers and Hudock 2007). Another study on 981 American rebar workers revealed that 56% of all reported musculoskeletal disorders (MSDs) were lower-back problems (Forde et. al. 2005). While the absolute low-back loads are not substantial for rebar workers, their prolonged nonneutral working postures put them at risk for LBDs (Umer et. al. 2017). The International Organization for Standardization (ISO) has specified recommended limits for static working postures and provided guidance on the assessment of health risks for the healthy adult working population [ISO 11226:2000 (ISO 2006)]. Most notably, the internationally recommended trunk inclination angle for static working postures is 60 degrees (**Figure 6-16a**).

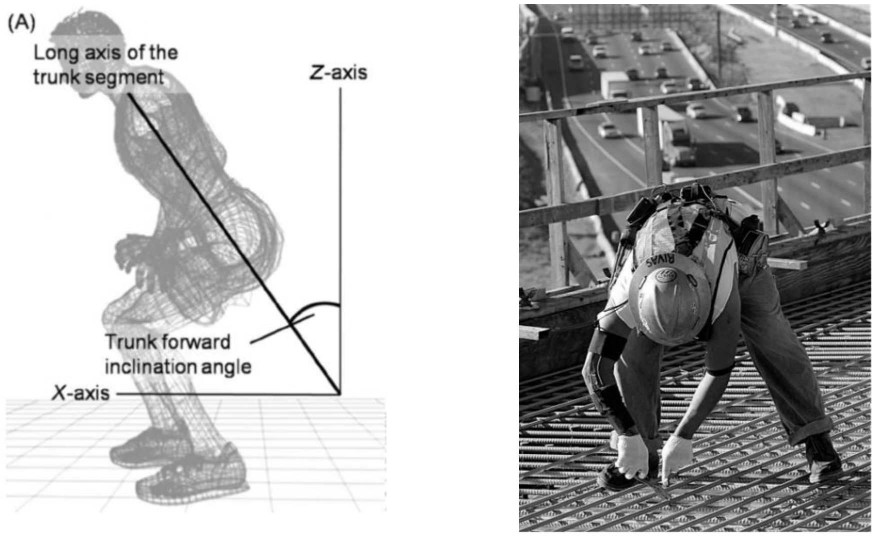


Figure 6-19. Static Working Postures (a) Trunk Inclination Angle (Nagano et al. 2011) (b) Manual Rebar Tying (Albers and Hudock 2007)

The results of the study conducted by Umer et. al. show that rebar tying demands large lumbar flexion (60-65 degrees) across all variations of working postures, exceeding the limits specified by ISO 11226:2000. A different study by Albers and Hudock examined wrist mean velocity and acceleration during the rebar tying task. The workers average wrist acceleration levels measured during manual tying with pliers exceeded the levels associated with high cumulative trauma disorder (CSD) risk in the flexion/extension. As for the compressive low-back forces, they did not exceed the NIOSH recommended spinal compression force during manual tying. However, when exerted on the low back for several hours each day, the resulting cumulative force is high over many years of activity, which is reported to increase the risk of developing low back disorders. The impact of this extends beyond just the rebar workers themselves. For rebar workers, the total median cost of lost-time injuries (LTI) and the median duration of time off work are higher than all other construction trades combined (Vi 2003) (**Figure 6-17)**.

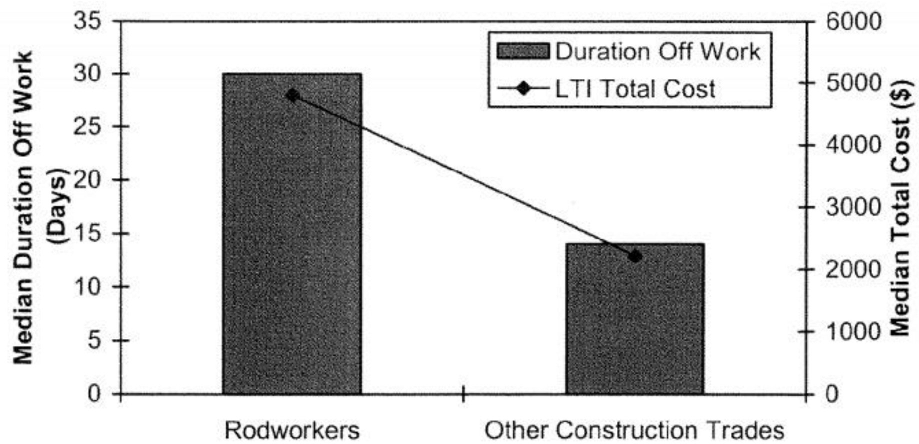


Figure 6-20. Median days off work and median total LTI cost per claim (Workplace Safety and Insurance board of Ontario Data: 1944-1998). Total cost is the sum of medical and compensation costs (Vi 2003).

With an effective redistribution of labor resulting from automating the rebar tying task, the potential safety benefits extend beyond rebar tying alone. The redistributed work combination table demonstrates that the cycle time per person for several other tasks are reduced. While the original distribution of labor designated one worker to place steel, plates, and mini-V's for 120 minutes per product, the redistributed workflow increases the labor available for the task, cutting down each worker's individual time spent placing steel by two-thirds. Further, instead of one worker placing mesh for 60 minutes, the task is split between two workers at 40 and 20 minutes each, respectively. Both tasks involve some degree of nonneutral working postures. Therefore, reducing each worker's cycle time on these tasks can contribute to a long-term reduction in risk for LBDs and other musculoskeletal disorders.

7.0 CONCLUSION AND RECOMMENDATIONS

This study examined the current state of practice for the precast concrete manufacturing process and identified areas for improvement. The objectives for this research project included identifying the greatest area of need within the precast process, developing technical requirements for an automated solution that is appropriate to the stakeholders' needs, and modeling the potential time and safety impacts of incorporating this change into an existing precast facility. The following observations are concluded from the work combination data, value survey data, and decision matrix:

- Of all the manual tasks involved in precast manufacturing process, tying reinforcing steel is the most time and labor-intensive task and would benefit the most from incorporating automation.
- Of all the various outcomes and motivating factors for incorporating automations (economic efficiency, time, worker safety, integrability, durability, quality, adaptability), the stakeholders at the precast facility valued integrability the highest, with durability and worker safety closely following and economic efficiency the least. These results conclude a general understanding that investing in automation is not necessarily economically lucrative and that previously mentioned qualities and outcomes are more practical and realistic.

The following observations are concluded from the quantitative and qualitative analysis of the automated rebar tying system:

- Due to the lack of a commercially existing system that meets all the technical requirements of the precast facility and the lack of established simulation capabilities for this emerging area of automation, the formulation of a mathematical model for operating time is largely theoretical and based heavily on the constraints of similar existing technology, the parameters of the motor, and the researcher's estimation.

- The resulting total time to tie all required connections in a minimally tied DT-510' is approximately 15 minutes. With the manual cycle time being 135 minutes on average, the automated process yields up to an 89% decrease in cycle time.
- A fully automated rebar tying system allows for an effective redistribution of man hours to other reinforcement related tasks. The redistributed work combination table reveals an average reduction of 49 minutes per crew member on reinforcement related tasks across five crew members.
- The internationally recommended limit for trunk inclination angles for static working postures is 60 degrees. All variations of manually tying rebar exceed this recommended limit and contribute to the high prevalence of low back disorders among rebar workers. The fully automated rebar tying system in tandem with the work combination redistribution would greatly decrease the risk for rebar workers to experience low back disorders and other musculoskeletal disorders, especially over long periods of time.

7.1 Further Applicability

While this investigation is a case study for one specific precast facility, the high-level procedure can be repeated at similar precast facilities seeking to incorporate point automation into part of the process. Further, the seven values/outcomes described in the value survey have a broad range of applicability to a variety of manufacturing processes, within the precast industry and outside of it. The formulation of the mathematical model for estimating time is based on the parameters of a specific product geometry and mesh configuration. However, the equations can be modified to reflect a different rebar tying pattern based on different local codes and regulations (i.e., alternating intersection, every intersection, etc.) as well as different product geometries. Further, the same methodology can be used to redistribute the man hours for a different work combination table to assess its potential benefits.

7.2 Recommendations

Based on the results of this study, the following recommendations to a precast facility seeking to incorporate point automation into their process include:

- Focusing their investment on the rebar placing and tying stages of the precast process. While this study only focused on one type of product, rebar placing and tying is typically the most time and labor-intensive stage across many different product types and geometries.
- Using the technical requirements of the system to design, build, and test a fully automated rebar tying machine.
- Aiming for full automation over semi automation of the rebar tying process. The primary benefit of automating this step is only realized by redistributing the man hours to other reinforcement related tasks and ultimately reducing the time spent in nonneutral working postures for every worker.

The precast facility used as a case study for this research is faced with a choice to make a large upfront economic investment in a new automated system. Ultimately, the results of this research are intended to help inform that decision. The work combination table analysis and decision matrix help inform where would be more beneficial to implement automation and what potential existing solutions meet the motivations and goals of the company. The mathematical model, redistributed work combination table, and safety evaluation are intended to provide quantitative and qualitative data to inform this decision to make the investment.

8.0 FUTURE WORK

Since automation used in the precast concrete manufacturing process is relatively new, the scope of this research study is largely preliminary. Using the technical requirements developed in this study, furthering the design and eventual build and test of the automated rebar tying system should be considered. Once a detail design is finalized, more advanced kinematic simulation capabilities are feasible with software such CATIA DMU Kinematics Simulator. Further, once experimental data on the constraints and parameters of the system is collected, the mathematical functions developed in this study can be used to lay the groundwork for a more robust predictive model.

Further investigation of the automation of other tasks of the precast process should be considered. Specifically, other reinforcement related tasks (i.e., placing rebar and welded wire mesh into the formwork, placing bolts on mini V's, chairing up wire mesh) are strong candidates that could benefit greatly from automation.

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APPENDICES

APPENDIX A: Qualtrics Survey Questions

UNIVERSITY OF GEORGIA

This survey will assess the values and needs of Metromont Corporation as it pertains to automating a portion of the precast production process. A series of questions will present a variety of scenarios and potential benefits and risks associated with automation. Please note that all of these questions are related specifically to the automation of the precast process, not just precast in general. These questions must be answered in a way that reflects the survey respondents' professional opinion as well as the values of Metromont as a whole. Results from this survey will be used to generate a value engineering table and will be taken into consideration when evaluating different automation solutions. These results will be included in a larger study on Automation in Precast, conducted by Mahtab Heydari under the direction of Dr. Stephan Durham for a Masters Thesis.

The survey will be open for two weeks and will close on Monday, July 13th. If you have any questions, please reach out to the survey author, Mahtab Heydari at mahtab.heydari25@uga.edu

Select which option you would prefer in an automated task of the precast process

Reduce the defect ratio of the final product	Reduce the cycle time

Select which option you would prefer in an automated task of the precast process

Reduce Life Cycle Cost	Reduce the cycle time

Select which option you would prefer in an automated task of the precast process

Accomodate a wide range of product sizes and geometries	Reduce the cycle time

Select which option you would prefer in an automated task of the precast process

Accomodate a wide range of product sizes and geometries	Reduce worker injury and fatigue

Select which option you would prefer in an automated task of the precast process

A system that requires little maintenence	A system that reduces the overall defect ratio

Select which option you would prefer in an automated task of the precast process

A system that can integrated easily into the existing plant	A system that requires little oversight

Select which option you would prefer in an automated task of the precast process

A system with a high return on investment	A system that completes the designated task in a shorter amount of time with comparable quality

Which of the following stages of automation is most worth spending time on?

Time spent integrating the system into the existing workflow	Time spent adjusting equipment to accomodate new product geometries

Select which option you would prefer in an automated task of the precast process

A higher return on investment	A higher number of products produced per day

Select which option you would prefer in an automated task of the precast process of the precast process

A system that requires fewer workers to complete the task	A system that accommodates many precast product styles

Automation should only be implemented if it can be easily integrated into the existing workflow

Strongly agree	Somewhat agree	Somewhat disagree	Strongly disagree

Automation should only be implemented if the quality of the final product is significantly improved from the previous methods.

Strongly agree	Somewhat agree	Somewhat disagree	Strongly disagree

The ability to accommodate a wide range of product geometries and sizes is more important than having a fully autonomous system.

Strongly agree	Somewhat agree	Somewhat disagree	Strongly disagree

Quality should never be sacrificed for lower production times

Strongly agree	Agree	Somewhat agree	Somewhat disagree	Strongly disagree

Automation should only be implemented if the overall cost of the final product is lower than previous methods, regardless of other outcomes

Strongly agree	Somewhat agree	Somewhat disagree	Strongly disagree

Automation should only be implemented if the number of workers required for the task is lower than previous methods, regardless of other outcomes

Strongly agree	Somewhat agree	Somewhat disagree	Strongly disagree

If the automated task cannot accommodate every product style and geometry, then it is not worth the investment

Strongly agree	Somewhat agree	Somewhat disagree	Strongly disagree

If the automated task cannot accommodate every product style and geometry, then it is not worth investing in

Strongly agree	Somewhat agree	Somewhat disagree	Strongly disagree

A high return on investment is the most important oucome of automation

Strongly agree	Somewhat agree	Somewhat disagree	Strongly disagree

Automation should only be implemented if worker health and safety is improved from previous methods, regardless of other outcomes

Strongly agree	Somewhat agree	Somewhat disagree	Strongly disagree

Equipment used for automation must be able to withstand plant conditions with little maintenence

Strongly agree	Somewhat agree	Somewhat disagree	Strongly disagree

Place the factors in the following three categories according to their relative importance within the context of incorporating automation:

Items

Economic Efficiency

Time Efficiency

Worker Safety

Ease of Integration

System Durability

Product Quality

Adaptability

Highest Importance

Average Importance

Low Importance

APPENDIX B: ISO Technical Standard

ISO #####-#:####(X)

ISO TC ###/SC ##/WG #

Secretariat: XXXX

Title (Automated manufacturing systems for precast concrete — Rebar Tying Machine)

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Contents

Foreword

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The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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This second/third/... edition cancels and replaces the first/second/... edition (ISO #####:####), which has been technically revised.

The main changes compared to the previous edition are as follows:

— xxx xxxxxxx xxx xxxx

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Introduction

In precast concrete production, reinforcement must be tied at various intersections for security within the formwork. This is a highly labor-intensive and time-consuming process for the majority of precast products. This document was developed in response to a significant need for automation of the precast concrete manufacturing process. While commercially existing solutions have rebar tying capabilities, this document was developed to address the shortcomings of existing technology and detail the technical requirements of an automated rebar tying machine for standard double tee products.

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Title (Automated manufacturing systems for precast concrete — Automated Rebar Tying Machine)

1 Scope

This document specifies the technical requirements for an optical sensing rebar tying machine. The requirements in this document are applicable. The capabilities of this machine are largely based on similar existing technology and build upon their shortcomings. These guidelines are applicable for (but not limited to) standard double tee products. The rebar tying machine is applicable for the following configurations:

- Welded wire mesh overlap
- Steel bar intersections

This document is not applicable to the placement of steel bars or welded wire mesh.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

US005193.120A: Machine Vision Three-Dimensional Profiling System
ISO 12100:2010(en), Safety of machinery — General principles for design — Risk assessment and risk reduction

IEC 60204-1:2005, *Safety of machinery — Electrical equipment of machines — Part 1: General requirements*

ISO/DIS 10218-1(en) Robotics — Safety requirements for robot systems in an industrial environment — Part 1: Robots

ISO 10218-2, *Robots and robotic devices — Safety requirements for industrial robots — Part 2: Robot systems and integration*

ISO 6935-1:1991, *Steel for the reinforcement of concrete — Part 1: Plain bars.*

ISO 6935-2:1991, *Steel for the reinforcement of concrete — Part 2: Ribbed bars.*

ISO 6935-3:1992(en), Steel for the reinforcement of concrete — *Part 3: Welded fabric*
ISO 10287:—[1], *Steel for the reinforcement of concrete — Determination of strength of joints in welded fabric.*

ISO 10544:—[1], *Cold-reduced steel wire for the reinforcement of concrete and the manufacture of welded fabric.*
ISO 11082:—[1], *Certification scheme for welded fabric for the reinforcement of concrete structures.*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in [ISO 6935] and the following apply.

3.1
Machine Vision
e.g. computer vision. A combination of camera hardware and computer algorithms that allows robots to process visual data from the world.

3.2
Degrees of Freedom
The directions that the machine has the capability to traverse in.

Examples of degrees of freedom include:

- x-axis
- y-axis
- z-axis
- rotational axes

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at http://www.electropedia.org/

3.3
Rebar Tying
Method of joining reinforcement (bars or welded wire mesh) at intersections using metal wire and a hooking tool to bend, pull, and twist thin wire.

3.4
Precast Element
A product produced by casting concrete in a reusable mold and cured in a controlled environment. Examples of precast elements include

- beams

- columns
- wall panels
- pipes

3.5.
Double Tee
A class of precast beam used for applications that require long, clear spans and extreme durability and strength. A load bearing structure that resembles two attached T-shaped structures.

4 Rebar tying operation

Tying steel reinforcement ("rebar") offers stability to a precast product when subsequent operations are performed on the precast bed. The purpose of the connection is to fix the relative positions of the rebar during construction operations. Since tying steel reinforcement offers no additional strength gain to the final product, there are no structural capacity requirements for the intersection. The strength of the tie simply must be able to support **the dynamic loads of pumped liquid concrete** and the **weight of workers standing on the precast bed.** This machine must be able to execute a tight tie. To make a tight tie, the wire must form the shortest path around the bars[2]. There must be enough tension on the ends of the wire before twisting and during the initial twisting motion to pull it securely around varying sizes of bars.

This document covers two types of reinforcement intersections that must be tied:
- Welded wire mesh overlap
- Reinforcing bar connections

4.1 Number of tied intersections

It is not necessary for every intersection to be tied, but enough must be tied so that the steel does not move. The number of ties is based upon the configuration of the bars and proposed concrete placing method. Ultimately, it is determined by judgment. Local codes may sometimes prescribe the number or percentage of tied intersections. Washington DC codes, for example, mandate that 100% of intersections must be tied for the top layer of bridge decks and 50% of all other layers[2].

4.2 Joining with tie wire

This machine shall use 16 gage wire to tie rebar, as this is the recommended size for most typical bars. 16 gage tie wire has a diameter of 0.051 in. American Wire Tie, Inc. supplies straight wire in this gage with preformed loops on each end. Typically, it is made from soft, annealed wire that is pliable enough to work with yet tough. When using bent wire, it must be bought in varying sizes to accommodate varying bar sizes. This machine shall join rebar and welded wire mesh by tying intersections with wire.

4.2.1 Saddle tie

The tying tool must be able to execute saddle ties at the intersection of two perpendicularly placed bars. The machine must be able to loop the tie wires under the bottom bar on each side of the top bar and over the top bar on either side of the bottom bar, as shown in **Figure 1.**

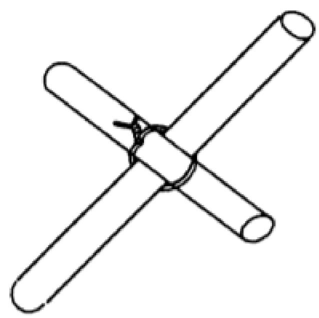


Figure 1- Saddle Tie for Rebar Intersections[2]

4.2.2 Simple (Snap) tie

The rebar tying machine must be able to execute simple ties for the overlapping welded wire mesh sheets. This type of tie requires wrapping the tie wire around the corners of wire mesh overlap and twisting the ends together at the top.

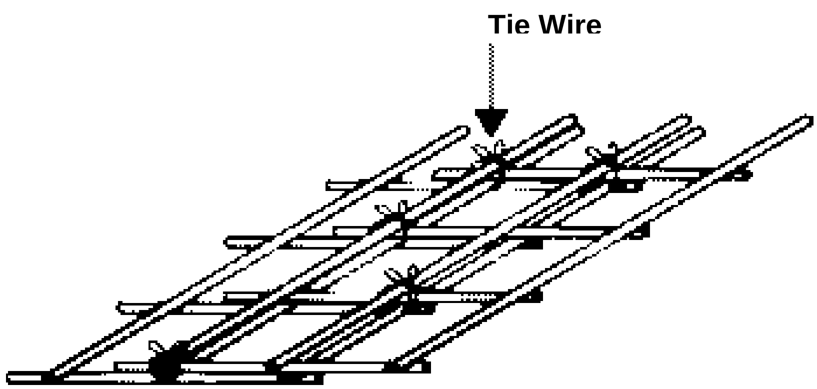


Figure 2- Simple Tie for wire mesh overlap

The required placement for simple ties on overlapping wire mesh is:

- One tie at each corner of the overlapping welded wire sheets
- At least one tie at the center of the overlap
-

With at least **2 squares** of overlap on the welded wire mesh sheets

4.2.3 Tie wire

The following forms of tie wire are acceptable for the automated rebar tying device:

- Premanufactured staple ties (**Figure 3).**
- Continuous wire spool

The tie wire material must be tough yet pliable enough to manipulate around the bars or welded wire mesh. Acceptable coatings for tire wire are nylon, epoxy, or vinyl[2].

4.2.3.1 Staple ties

Staple ties are pre-formed into bent configurations and can be purchased in strips (**Figure 3**). This form of tie wire can be useful to an automated rebar tying machine with a stapling mechanism. One factor that must be considered is the size of these wires. Staple ties can come in a variety of gages and lengths. However, the wire size must be appropriate for the size of bars or mesh being tied. The wire must be long enough to securely create a tight tie around the intersections. However, it must be short enough to not get in the way and take up too much space. The required staple tie length (L) is presented in **Table 1**.

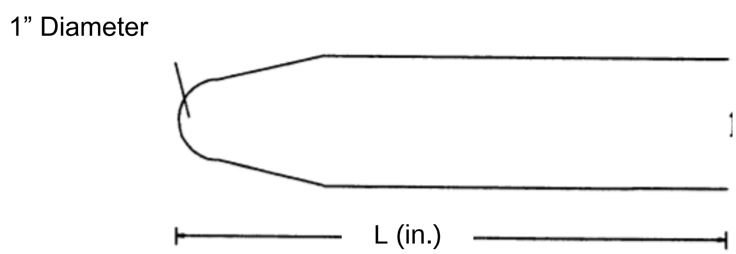


Figure 3a- Staple Tie Geometry

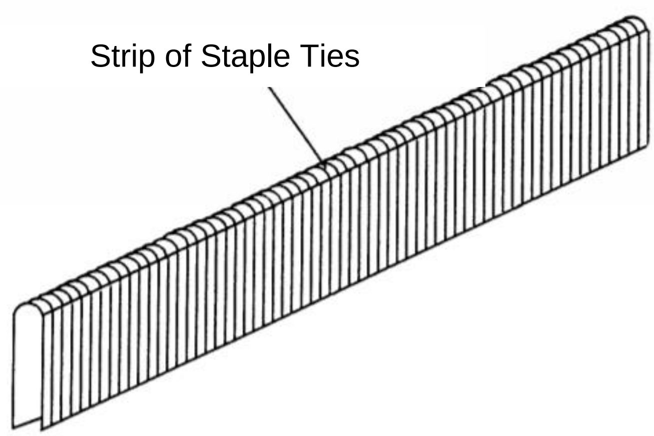


Figure 3b- Strip of Staple Tie

Table 1- Rebar Staple Tie Lengths[3]

	#2 ¼”	#3 3/8”	#4 ½”	#5 5/8”	#6 ¾”	#7 7/8”	#8 1”	#9 1 1/8”	#10 1 ¼”
#2 ¼”	3 ½”	4”	4 ½”	5”	5 1/2”	6 ½ ”	7”	7”	7 ½ ”
#3 ¾ ”	4”	4 ½ ”	5”	5”	5 ½ “	6 ½ ”	7”	7”	7 ½ ”
#4 ½”	4 ½”	5”	5”	5 ½”	6”	6 ½ ”	7 ½ ”	7 ½”	8”
#5 5/8”	5”	5”	5 ½ ”	6”	6 ½ ”	7”	8”	8”	8 ½ ”
#6 ¾”	5 ½ ”	5 ½ ”	6”	6 ½ ”	6 ½ ”	7 ½ ”	8”	8 ½”	8 ½”
#7 7/8”	6 ½ ”	6 ½ ”	6 ½ ”	7”	7 ½ ”	7 ½ ”	8 ½ ”	9”	9 ½ ”
#8 1”	7”	7”	7 ½ ”	8”	8”	8 ½ ”	9”	9 ½”	10”
#9 1 1/8”	7”	7”	7 ½ ”	8”	8 ½ ”	9”	9 ½ ”	10”	10 ½ ”
#10 1 ¼”	7 ½ ”	7 ½ ”	8”	8 ½ ”	8 ½ ”	9 ½ ”	10”	10 ½ ”	10 ½ ”

[a] See Figure 3a for illustration of staple tie length

4.2.3.2 Continuous wire spool

Tie wire in the form of a continuous spool is acceptable for an automated rebar tie machine. The machine must be able to cut the wire to appropriate lengths for different sized bars. These required lengths are twice the lengths specified in Table 1.

5 Degrees of freedom

The tying arm of the machine must be capable of traversing the x, y, and z dimensions. i.e. the machine must be able to execute ties along a planar surface and at various depths on a precast element, as a precast element may include multiple layers of welded wire mesh. Figure 4 illustrates these degrees of freedom. The datum for the z direction is the surface of the concrete deck, and the datum for the x-y plane is in the lower-left corner of the deck.

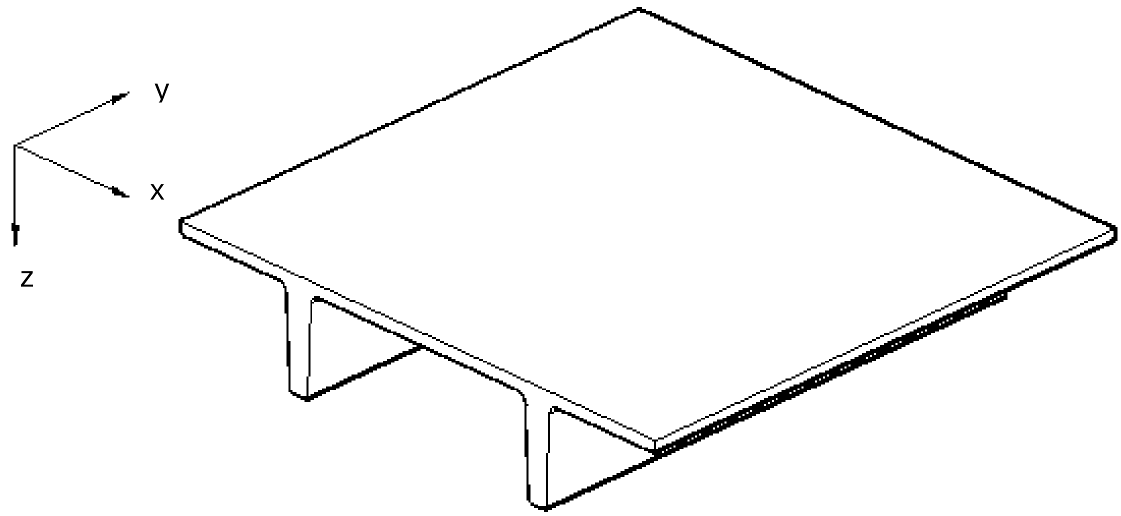


Figure 4- Degrees of freedom

6 Interference Constraints

6.1 Bar interference

To loop the tie wire around the bars, an automated rebar tying machine must reach past the bars to execute a strong, tight tie. The tool may experience some interference with adjacent bars or lower layers of bars beneath the work surface. The required minimum clearance between layers of bars is 1 inch[4]. Therefore, the automated rebar tying mechanism must be able to operate within 1 vertical inch of the rebar intersection.

6.2 Welded wire mesh interference

To loop the tie wire around the corners of overlapping welded wire mesh sheets, an automated rebar tying machine must reach around the welded wire intersection to execute a strong, tight tie. The tool may experience some interference with the adjacent longitudinal or transverse wire (see Annex A.1) or lower layers of welded wire mesh beneath the work surface. The required minimum clearance between layers of mesh is 1 inch. In addition, the smallest mesh square size typically used in double tee products is 4x4 inches. Therefore, the automated rebar tying mechanism must be able to operate within four inches of the welded wire intersection in the x and y directions.

7 Span

The required span that the automated rebar tying device must traverse in each direction is dictated by the typical dimensions and code requirements of double tee products. The span details the minimum and maximum range of motion that the machine must be able to operate in. **Figure 4** illustrated the directions of the various criteria outlined in this section.

7.1 Span in the x-y direction

The automated rebar tying machine must be able to accommodate the typical range of double tee product sizes. It must be able to traverse a minimum length of 58 ft and maximum length of 61 ft for typical double tee products in the x-direction. In the y-direction, the minimum distance the device must travel is 10 ft and the maximum distance is 13 ft.

7.2 Span in the z-direction

The minimum distance the rebar tying device must traverse in the z-direction is dictated by the maximum vertical location of welded wire mesh and in the concrete deck. Typical double tee decks range from 2 in. to 4 in. thick. Mesh intersections can occur from as little as 1 in. below the surface to 3 in. below the surface. Rebar tying is typically only required within the deck and not necessary for prestressed and nonprestressed reinforcement within the webs of a precast element.

8 Controls

The automatic rebar tying machine shall not be calibrated by CAD/CAM data or pre-plotting. Instead, the machine process visual data of rebar intersections and wire mesh overlap through *machine vision.* The process is as follows:

8.1 Machine Vision Process[1]

1 Acquire a suitable image.

There are a wide variety of imaging methods used in machine vision applications. The most common methods are color and grayscale versions of area scan imaging, which is simply taking a photo and processing the image all at once. This application of machine vision requires 3D profiling capabilities, where the z-dimension of the image is coded into the value of each pixel of the image. The specifications of a three-dimensional profiling system are outlined in patent US5193120A.

2 Find the object of interest.

To find the object of interest, the machine must distinguish the object of interest and everything else within the field of view. There are a variety of methods for object finding. However, for this application, the machine shall apply *template matching.* The template matching tool shall be “trained” to recognize reinforcement bar intersections and overlapping wire mesh. During operation, the machine searches the field of view for a close match to the rebar intersection it “learned”. When the degree of match exceeds a minimum threshold, the object is “kept”.
The automated rebar tying machine must be able to distinguish between rebar intersections and overlapping welded wire mesh.

3 Determine the position and orientation of the intersection.

Once the object of interest is identified, its position and orientation must be determined. For a rebar intersection, the x and y coordinates along the precast bed are located as well as the depth of the intersection into the deck (z coordinate). A template-matching tool could supply position data for the intersection it identifies.

4 Translate the information to the coordinate system of the machine.

The optical system and the robot have their own coordinate location system. To communicate to the robot, the optical system must translate its coordinate data to the language of the robot. Small errors in the translation can be corrected with a simple addition or subtraction of a correction factor to the x, y, and z values.

5 Send the information to the controller.

Both interfaces have "layers" that must be matched between the two systems. The bottom layers contain the familiar general types, and the top layers are the format and sequence protocol for the data itself and its transfer.

6 The robot arm uses this information to move to the correct position and orientation to tie the rebar

The optical system (vision system) tells the robot controller where to go. It does not inform it how to get there, so the path of the robot arm must be clear to travel. A configuration with a robot-mounted camera may allow the vision to continuously operate, providing feedback for higher accuracy.

8.2 Power

The automatic rebar tying machine must be operated by electrical actuators. Since the rebar tying operation does not involve a large load and requires precise movement, electrical actuators are better suited for the operation than pneumatic or hydraulic mechanisms. The specific type of actuator can be either of the two choices:

- Step motor
- Servo motor

The chosen actuator must offer the level of precision specified in Section 6 (Interference Constraints).

9 Safety

The safety guidelines outlined in the following standards are required for the operation of the automated rebar tying system.

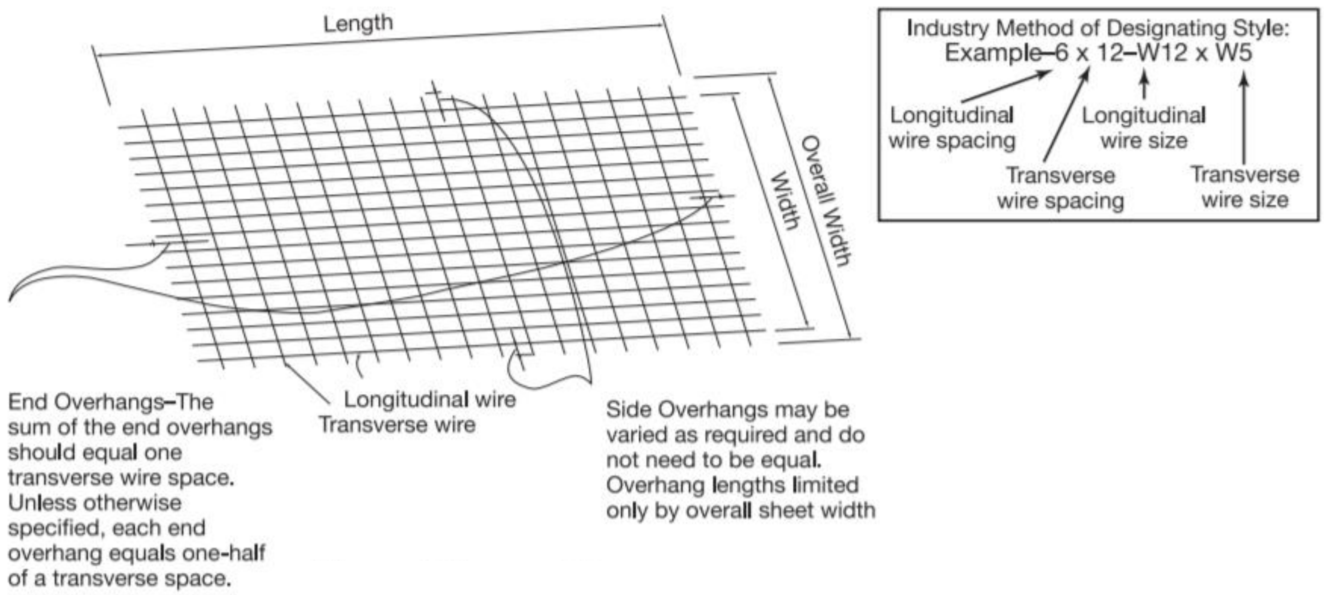
ISO 12100:2010(en), Safety of machinery — General principles for design — Risk assessment and risk reduction

IEC 60204-1:2005, *Safety of machinery — Electrical equipment of machines — Part 1: General requirements*

.

Annex A (informative) Welded Wire Fabric

A.1 Geometry and Nomenclature of Welded Wire Fabric[6]



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[1] Tureck, F. D. (2019, August 31). Machine Vision Fundamentals: How to Make Robots 'See'. Retrieved from https://www.techbriefs.com/component/content/article/tb/supplements/it/features/articles/10531

[2] Altobelli, F. R. (1991). *An innovative technology in concrete construction--semi-automated rebar tying* (Doctoral dissertation, Massachusetts Institute of Technology).

[3] Bar Tie Table for Various Rod Combinations. (n.d.). Retrieved from http://www.southernrebar.com/reference/rebar_bar_tie_table_for_various_rod_combinations.aspx

[4] The American Concrete Institute, ACI 318-83, Building Code Requirements for Reinforced Concrete, 1983.

[5] ACI Committee, & International Organization for Standardization. (2008). Building code requirements for structural concrete (ACI 318-08) and commentary. American Concrete Institute.

[6] “Manual of Standard Practice-Structural Welded Wire Reinforcement.” *Wire Reinforcement Institute*, Dec. 2016, wirereinforcementinstitute.org/.

APPENDIX C: Requirements Spreadsheet

Sr. No.	Requirement	Constraint/Criteria	Soure	Justification	Date of elicitation	Target Value
1	Must be able to execute a strong, tight tie around steel bars or welded wire mesh inersections	Constraint	(Inferred) Metromont	Prevent bars/welded wire fabric from moving during subsequent operations	2/15/2021	Shortest path travel around the bars
1a	Must be able to accommodate bar intersections and welded wire mesh	Constraint	Metromont	Two types of reinforcement in typical precast products	2/15/2021	
2	Must be able to traverse x, y, and z dimensions	Constraint	DT-510 Sizes (metromont)	Multiple layers of wire mesh must be tied	2/15/2021	
2a	Must accommodate: 58 ft minium and 61 ft maximum in x direction	Constraint	DT-510 Sizes (metromont)	Typical span for DT-510	2/15/2021	58 ft to 61 ft
2b	Must accommodate 10 ft. minimum an 13 ft. maximum in the y direction	Constraint	DT-510 Sizes (metromont	Typical span for DT-510	2/15/2021	10 ft to 13 ft
2c	Must accommodate depths from 1 inch to 3 inch in z direction		DT-510 Sizes (metromont)	Typical depths of welded wire mesh in concrete deck	2/15/2021	1 to 3 inches
3	Must be able to execute a Simple (snap) tie, and saddle tie configurations	Constraint		Two types of intersections in typical precast products for bars and wire mesh	2/15/2021	
4	Must able to operate within 1 vertical inch of the rebar intersection	Constraint	ACI Code	Minimum vertical spacing in concrete deck	2/15/2021	1 vertical inch
5	Must be able to operate within 4 inches of the welded wire intersection in the x and y directions	Constraint	Wire Reinforcement Institute	4x4 is smallest wire mesh square size	2/15/2021	4 horizontal inches
6	Must be able to autonomously navigate precast bed and identify and tie intersections	Criteria		High levels of product variety makes pre-calibration with CAD/CAM highly inefficient	2/15/2021	
7	Must be able to complete 1 tie in approximately 2 seconds	Criteria	Industry data	Industry average for union steelworkers and benchmark for similar equipment	2/15/2021	2 seconds

APPENDIX D: MATLAB Code for Mathematical Model

```
%%This function determines the linear speed in the x and y directions for
an
%%autonomous rebar tying machine based on a 8100 lb max total weight and
%%5500 Watt Power Input. Mechanical load, power, and mechanical and
%%electrical efficiencies are taken as inputs

%y-direction
F_y=4270.*[1 1 1 1 1 1 1 1]; %max wheel loading of 4720 N (960 lbs) per
wheel
nmech=0.8; %mechanical efficiency
nele=0.8;  %electrical efficiency
power_y=2000; %(Watts) Total power in y direction
power_yi= power_y/8 .*[1 1 1 1 1 1 1 1]; %(Watts) Power distributed across
8 wheels on rail screed
speed_y= (power_yi.*nmech.*nele)./F_y %(m/s) Linear speed in y direction
speed_y_en=speed_y.*3.28084; %(ft/s)Linear speed in y direction, English
units

%x-direction
F_x= (1470/4) .*[1 1 1 1]; %total tying module weight of 1470 N (330.5
lbs) divided between 4 wheels
nmech=0.8;%mechanical efficiency
nele=0.8; %electrical efficiency
power_x=1000; %(Watts) Total power in x direction
power_xi= power_x/4.*[1 1 1 1]; %(Watts) Power distributed across 4 wheels
carrying tie module
speed_x= (power_xi.*nmech.*nele)./F_x %(m/s) Linear speed in x direction
speed_x_en=speed_x.*3.28084 %(ft/s) Linear speed in x direction, English
units

%z-direction
%Assumed duration of 2 seconds to traverse 1 inch in the z-direction

%%Modeling for Total Time
t_tie=(2*86)/60 %tying time only (min). 2 seconds per tie, 86 total ties
x=50*6.5 %(ft) total distnce traversed by tying modulue in x direction to
travel to all tie locations
t_x=(x./speed_x_en(1))/60 %(min) total time spent traveling in the x
direction

y=60 %(ft) total distance traversed by the gantry frame in the y direction
to travel to all tie locations
t_y=(y./speed_y_en(1))/60 %(min) total time spent traveling in the y
direction

t_z= sum([2 2])/60 %(min) total time spend traveling in the z direction. 2
seconds to ascend 1 inch from end layer to midspan. 2 seconds to descend 1
inch from midspan to other end
t_total=t_tie+t_x+t_y+t_z
```