# An integrated framework to handle design, complexity, and controls challenges in industrial systems

by

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**ABSTRACT**

During the past few decades, there has been a significant increase in automation. Mechanical processes and operations are continuously being automated. Mechanical assemblies are no longer only mechanical, but also contain a large portion of electrical wires, connections, and controls signals. Therefore, while designing, modern mechatronics or an industrial system, the importance of electrical and control attributes cannot be ignored. Designing an industrial automation system requires the system designers to deal with a number of design, complexity, and controls challenges to ensure an efficient, productive and cost-effective system. These challenges include space (for better utilization of the available parts), electrical connections and wire harnesses (for better cable management), time (to assemble the parts along with their associated accessories), and cost. Furthermore, complexity is also an important challenge but often ignored when it comes to difficulties faced in manufacturing. Estimation of these challenges at an early design stage is difficult due to the limited availability of data but having an early estimate is helpful for system designers to make early design changes. However, limited information is available on the methods to reduce the number of parts in a control system, which is responsible for most of the aforementioned design challenges. The key to a good mechatronics system is the optimized combination of both mechanical and electrical. Therefore, while designing a mechatronics or an industrial system, controls complexity is equally important to consider along with mechanical. However, research available focuses only on the mechanical layer of the system leaving behind the electrical and controls side. This thesis provides an integrated framework to assist the system designers in early design stages; to reduce the number of electrical control parts, assembly time, and ultimately the cost. It further provides a metric to quantify controls complexity. The framework is composed of (1) an iterative design for electrical controls (DEC) methodology to reduce the number of electrical controls parts and for generating alternative electrical controls concepts, (2) a multi-attribute cost function for evaluating the cost of the concept. (3) A model to evaluate the controls complexity where controls complexity is defined as the degree to which individual wires/cables are prepared, assembled, installed, attached and the diversity in associated controls signals. (4) A control system strategy to reduce the complexity by incorporating the principles of Axiomatic Design. To demonstrate the application of the proposed framework a number of different industrial systems based on PLCs, sensors, motors, and industrial communication protocols are used. The application results show the productivity of the proposed framework for the system designers in handling design, complexity, and controls challenges.

## PREFACE

This thesis is the original work by Jawad Ul Haq. Chapter 2 and Chapter 3 of this thesis will be submitted to international journals. A version of Chapter 4 has been published in an international conference proceedings listed as below. The thesis is organized in paper format by following the paper-based thesis guideline. The numbered list represents the respective chapter of this thesis.

2. **Haq, J.,** Al-Hussein, M., and Qureshi, A.J., "Cost and assembly considerations in designing for electrical control systems." International Journal of Advanced Manufacturing Technology. (To be submitted)
3. **Haq, J.,** Al-Hussein, M., and Qureshi, A.J., "A complexity model for measuring controls complexity." International Journal of Computer Integrated Manufacturing. (To be submitted)
4. **Haq, J.,** Qureshi, A., and Al-Hussein, M. (2018). Design of a Saw Cutting Machine for Wood and Aluminum. In Proceedings of the 15th International Conference on Informatics in Control, Automation and Robotics - Volume 2: ICINCO, pages 456-464, ISBN: 978-989-758-321-6. DOI: 10.5220/0006909704560464

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**List of Abbreviations**

| | |
|---|---|
| AD | Axiomatic Design |
| CAs | Customer Attributes |
| CAD | Computer-aided Design |
| CNC | Computer Numerical Control |
| DEC | Design for Electrical Controls |
| DES | Discrete-event Simulation |
| DFA | Design for Assembly |
| DPs | Design Parameters |
| ESD | Emergency Shutdown |
| FRs | Functional Requirements |
| GUI | Graphical User Interface |
| HMI | Human Machine Interface |
| PVs | Process Variables |
| PLC | Programmable Logic Controller |
| SCM | Saw Cutting Machine |

# Chapter 1 Introduction

## 1.1 Background and motivation

Design is divided into three major stages of conceptual, embodiment, and detailed design (Pahl and Beitz 2013). Pisacane and Moore also agreed to the idea and divided the design into phases of conceptual, preliminary, detailed design, and fabrication and assembly (Pisacane and Moore 1998). Conceptual design is the first stage which is used to provide a description of the proposed design. This description is expressed in abstract thinking until a detailed design is started. Detailed design is the phase where design is further refined with the assistance of detailed 3D models and drawings. Both conceptual and detailed design are critical phases as most of the design features and specifications take shape in these two stages. There is a probability that a design idea is challenged during the conceptual stage and never reaches a detailed phase. However, if an idea passes the conceptual phase, it still doesn't assure that it will come to life without a detailed design phase where the design idea is further reviewed in greater details (Leavens, Baker and Ruby 1999).

Increasingly intensive global competition in manufacturing and changing consumer demand are resulting in a trend towards greater product variety and innovation, shorter product life-cycle, lower unit cost, higher product quality, and short lead-time (Bi and Zhang 2001). Therefore, the design is prone to changes and earlier these changes are identified easier they are to rectify. However, estimation at an early design stage is difficult due to the limited availability of data. Different design techniques and methods are available that assist the designers to improve or evaluate the design in early design stages.

For instance, Design for Assembly (DFA), Design for Manufacturing (DFM), Manufacturing Complexity Assessment Tool (MCAT), Axiomatic Design (AD).

We live in a world of advancement, where everything around is being automated from basic domestic appliances to sophisticated multi-axis industrial systems. This automation brings its own set of challenges in terms of cost, assembly, complexity, design, electrical wiring, control signals, etc. Therefore, while designing a modern industrial system, the automation challenges are equally important to consider as mechanical. However, most of the research available deals with the mechanical systems and limited information is available on systematic ways to assist the system designers in the early design stages to improve or evaluate the design from electrical and control point of view.

This thesis aims to investigate the available design and complexity models, challenges incurred due to automation, and propose methods and metrics to assist the system designers in evaluating and improving their electrical and control design concepts in the early design stages.

## 1.2 Research objectives

This research has the following objective:

*"The development of a framework that will help reduce the number of electrical control parts, calculate cost and measure controls complexity of given controls concept, thereby allowing the system designers to make early design decisions."*

The research is built on the following hypotheses:

1. Reducing the number of electrical control parts will reduce the assembly time and cost of a control system.
2. While designing a mechatronics or an industrial system, controls complexity is equally important to consider as mechanical complexity.
3. There exists a link between design, complexity, and controls in such a way that a good control system can assist reducing complexity and improving the design.

To validate hypotheses, the following research objectives are pursued:

1. Development of a methodology to calculate the cost of any given control concept and reduce the number of electrical control parts.
2. Development of a model to calculate the controls complexity.
3. Development of a control system strategy to reduce complexity by incorporating the principles of Axiomatic Design.

### 1.3 Organization of thesis

This thesis consists of five chapters. Chapter 1 elaborates on existing limitations, research motivation and objectives. Chapter 2 presents a methodology to reduce the number of electrical controls parts. The methodology is illustrated with case studies. Chapter 3 presents a complexity metric for assessing controls complexity. The metric is illustrated with case studies. Chapter 4 presents a control system solution to reduce complexity by incorporating the principles of Axiomatic Design. A brief introduction to each aforementioned chapter is shown in Figure 1.1. Finally, Chapter 5 provides conclusions and summarizes the research contributions, limitations, and future work potential.

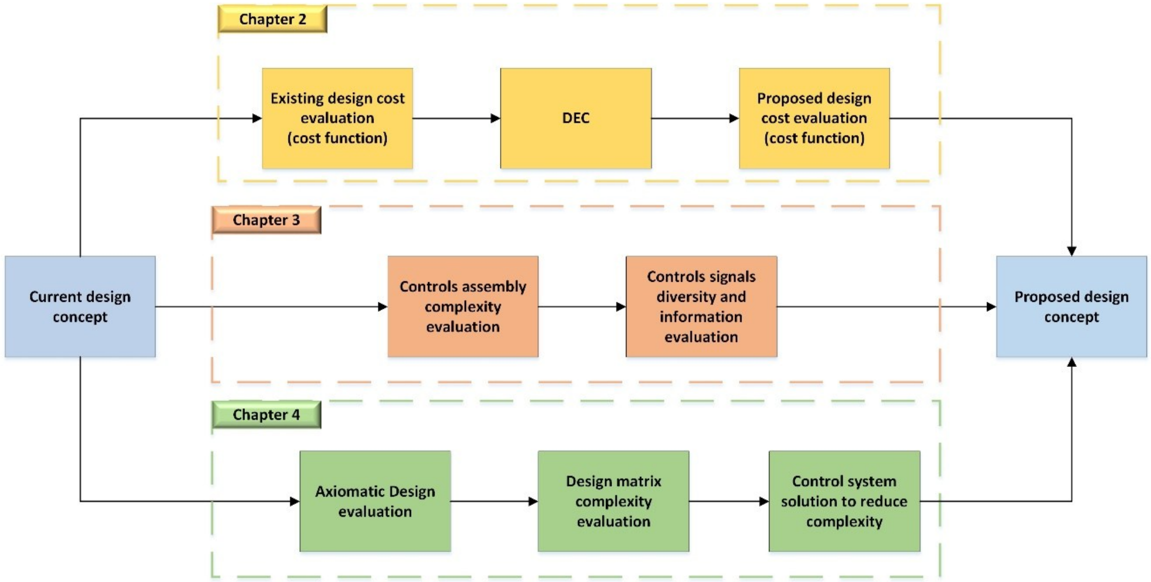



Figure 1.1 Thesis organization

## Chapter 2 Cost and assembly considerations in designing for electrical control systems[1]

This chapter presents a novel method based on the principles of Design for Assembly (DFA) to reduce the number of electrical control parts and better utilize space in the early design stage. This method is composed of a design for electrical controls (DEC) methodology for generating alternative electrical control concepts, and a cost function for evaluating the cost of the concept. The cost function calculates the total cost of a given concept, which includes part cost, wiring and connector cost, and associated assembly and labor cost. The chapter demonstrates the methodology through three case studies: a Programmable Logic Controller (PLC) based system; a sensor-based system; and a three-phase motor-based system. The application results show that the proposed approach is a useful tool for system designers to reduce the number of parts, assembly time for wiring, and ultimately the cost in the early design stages.

### 2.1 Introduction

Cost estimation at an early design stage is difficult due to the limited availability of data. However, having an early cost estimate is helpful for engineers to make design decisions (Freiman 2009). Molcho, Cristal and Shpitalni (2014) identified forty factors as governing part cost and proposed a cost estimator for designers. Savoretti et al. (2017) used the industrial survey approach to confirm the need for a tool for early cost estimation, which can support both the phase of the offer and the economic evaluation for placing a new

[1] The manuscript appearing as Chapter 2 of this thesis will be submitted to the International Journal of Advanced Manufacturing and Technology.

product in the market. Salmi et al. (2016) supported the early phase cost estimation, but with specific emphasis on assembly systems design and automation decision. Dewhurst and Boothroyd (1988) identified the need to estimate costs in the early design stages before the detailed design and without full knowledge of the manufacturing processing. Since cost estimation provides designers with valuable information, it must be quick and accurate. If the assumption is taken that efficient manufacturing will be carried out, then cost can be estimated without having any concern with the processes and tools used. In the early 1970s, Boothroyd, Dewhurt and Knight (2011), developed the idea that the number of parts in a mechanical assembly is directly related to the assembly time and cost. Based on this, a Design for Assembly (DFA) with emphasis on reducing the number of parts was proposed. Due to increased automation over the last few decades, the electrical wiring has emerged as one of the more complex tasks for mechatronics and electrical/electronic systems. It is a critical component of a designed system and can outweigh the amount of time it takes to assemble the mechanical part of the system. Keeping in mind the aforementioned concerns, Ong and Boothroyd (1991) proposed a method to calculate assembly times for electrical connections and wire harnesses. The assembly, in terms of electrical connections and wire harnesses, is divided into four stages: preparation, installation, securing, and attachment. Kang et al. (2008) state that design of modern control systems has become more complex and challenging due to an increasing number of elements and operation units. Recently, Tamayo et al. (2018) proposed a linear time complex algorithm for planning the control panel devices and wiring layouts that both embodies best practices and complements the computer-aided design of the control panel at the detailed design stages.

Conclusively, most of the research highlights the fact that an increase in the number of parts has complicated modern control panels with a significant amount of research emphasizing better utilization of the available space and parts. However, limited information is available on the methods to reduce the number of parts in a control system, which is responsible for the design challenges as shown in Figure 2.1. These challenges include space (for better utilization of the available parts) (Gao and Wang 2010), electrical connections and wire harnesses (for better cable management) (Agard and Tollenaere (2003), time (to assemble the parts along with their associated accessories) (Ong and Boothroyd 1991), and cost competitiveness (to remain relevant in the market) (Buckley, Pass and Prescott 1988).

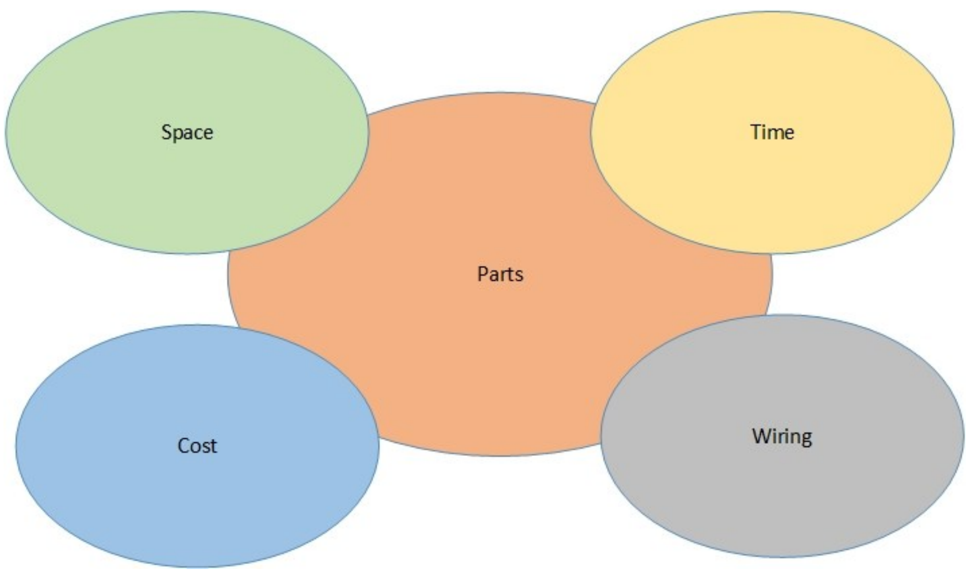



Figure 2.1 Design challenges

This chapter is organized as follows: Section 2.2 presents the methodology to address the design challenges, Section 2.3 describes the case studies and demonstrates the application of the proposed methodology, and Section 2.4 summarizes the research achievements.

### 2.2 Methodology

In order to aid the designers in dealing with the aforementioned challenges, a three-step methodology is proposed as shown in Figure 2.2. The first step consists of an estimation of the total cost of the system using a multi-attribute cost function. The second step includes the application of an iterative design for electrical controls (DEC) method that allows a designer to evaluate any given design concept with the emphasis on reducing the number of parts. The final step consists of calculating the total cost of the design proposed by the DEC.

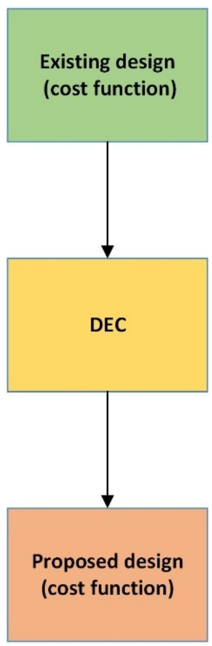



Figure 2.2 Three step methodology

#### 2.2.1 Cost function

Cost estimation holds an important role in an organization, business environment, product design, etc. Therefore, it is important to estimate cost as accurately as possible. It has a critical and sensitive role, overestimation and underestimation; both lead to wastage of resources. In this research, the cost is chosen as a decisive factor between two design concepts. Therefore, a multi-attribute cost function expressed in equation (2.1) is proposed to estimate the cost.

$$Cost = \sum_{p=1}^{n}(BE)_n + \sum_{m=1}^{k}(BW)_k * L_k + \sum_{o=1}^{q}(BT)_q + \sum_{l=1}^{u}(BC)_u + Assembly\ time\ (t) * Labor(\frac{\$}{t}) \tag{2.1}$$

where:

- BE: Base cost of electrical parts. (cost of parts, for instance, motor, PLC, etc.)
- n: Total number of electrical parts
- BW: Base cost of electrical wires. (cost of electrical wires, for instance, 14 AWG, 12 AWG, etc.)
- k: Total number of wires
- L: Length of wire (ft)
- BT: Base cost of tools. (wire strippers, soldering iron, harness jig, etc.)
- q: Total number of tools
- BC: Base cost of connector
- u: Number of connectors
- Assembly time: Time taken to prepare, install, secure and attach wires
- Labor: Cost of hiring an electrician

### 2.2.2 Assembly times for electrical connections and wire harnesses

Ong and Boothroyd (1991) proposed a methodology to estimate the assembly times for electrical connections and wire harnesses is divided into four stages, (1) preparation which includes, the time to manually pull each wire and then cut, once the wire is cut then it further needs the stripping of insulation and then tinning or soldering; (2) Installation which includes, the dressing of wires; (3) securing which includes, the clamping through cable ties or adhesive clamps and then labelling through stickers or markers; (4) attachment which is the final stage and includes the attachment of the each wire to its respective destination point. The attributes used to estimate the assembly times are given as:

- Manual pull and cut time: $4.3s + 0.6s/ft$
- Manual strip one end time: 7s
- Tinning one wire end time: 9s
- Dressing wire: $2.7s + 1.7 * L_w\ (ft)$
- Adhesive clamp: 14.3s
- Label with sticker: 10.0s
- Attachment terminal block time: 13.9s

### 2.2.3 Design for electrical controls (DEC)

The proposed design for electrical control method (DEC) is described by a sequence of twelve activities and decisions, as shown in the flow chart in Figure 2.3 below. It begins with the identification (1) of the electrical control parts. This is a bottoms-up approach in which all the parts after identification are sorted (2) on the basis of their respective voltage requirements (2). Once sorted, the next step is to inspect (3) each part for whether there is any voltage conversion (4) required in order to operate that part. If it is not required, then the part is not suspect (5), which means that part does not have the potential to be improved and without proceeding further with it, pick the next part in the list. Otherwise, proceed further and verify whether the voltage required by that specific part is unique (6), which further implies that if similar voltage required by that part does not exist in the system; If the part is suspect (10) i.e. the part has the potential for improvement, reselect (12) the part, which means discard the current part and find a replacement. However, if the voltage required by that specific part is not unique (6), implying that there is a similar voltage source available in the system, proceed further and check (7) if that voltage source has the capacity, meaning that wattages are available to accommodate that specific part; part is suspect (8); and merge (9) the part, which suggests to remove the part from its previous power source and connect it to the next power source already available in the system. However, if the voltage (7) source does not have capacity to power that specific part, increase (11) the capacity of that voltage source; and then merge (9) the part. The reselection of the part happens when (4), (6), (10) are satisfied. The part merges in the case of the flexible source when (4), (6), (7), (8) are met, and in the case of inflexible source when (4), (6), (7) are satisfied.

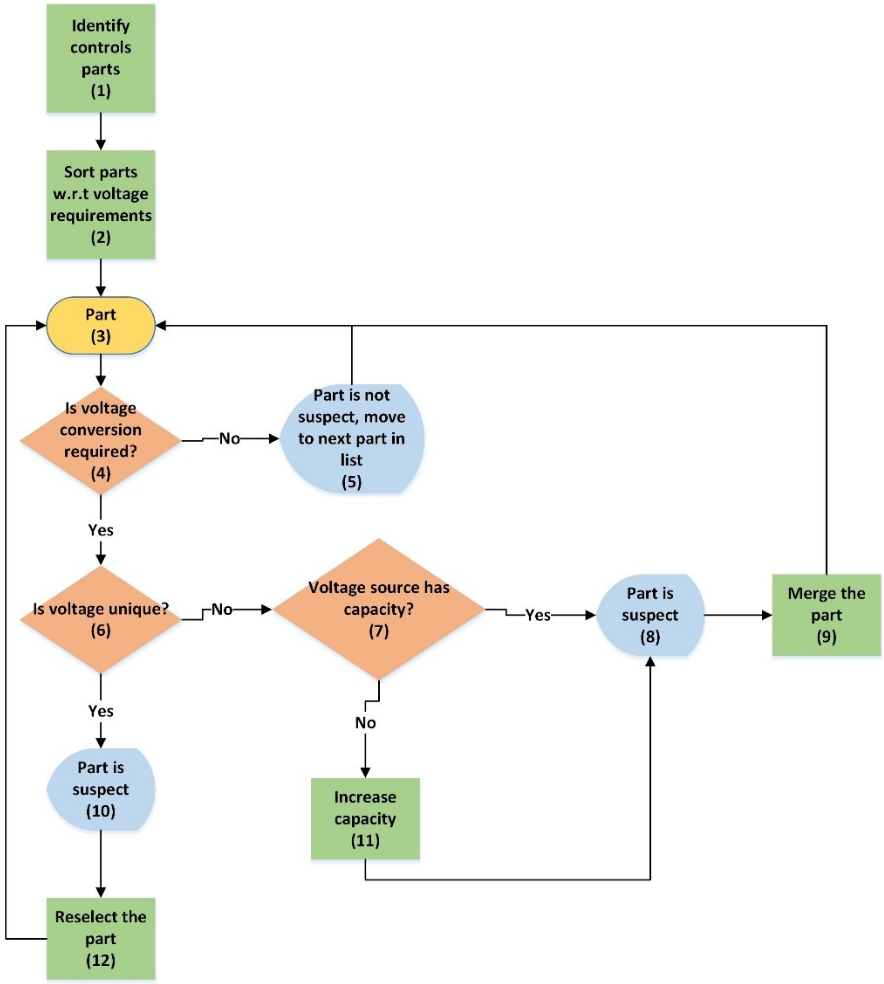



Figure 2.3 DEC methodology

## 2.3 Case Studies

PLCs, sensors and three-phase motors are vital building blocks of a modern industrial automation system. PLCs are efficient and reliable in applications involving sequential control and the synchronization of processes and auxiliary elements in the manufacturing, chemical, and process industries. Sensors detect the changes in the environment and communicate information to the programming unit. Three-phase motors are electromechanical systems and are widely used in industry. Three case studies are used to demonstrate the application of the proposed methodology: a PLC-based system is used to demonstrate the reselection concept, a sensor-based system is used to demonstrate the parts merging concept in case of flexible and inflexible sources, and a three-phase motor-based system is used to demonstrate that methodology can also be applied to multiphase AC systems. The cost of individual components used in the cost function are according to North American markets (Alis 2018).

### 2.3.1 PLC-based control system

A typical PLC-based control system, as shown in Figure 2.4, consists of a main AC voltage source to power the whole system, a secondary DC source to power the DC parts, and terminal blocks to provide solid and firm connections. The voltage specifications of the system are given, where the main AC source is 120 VAC, power supply converts 120 VAC to 24 VDC and PLC requires 24 VDC. The application of methodology is demonstrated in the sections that follow.

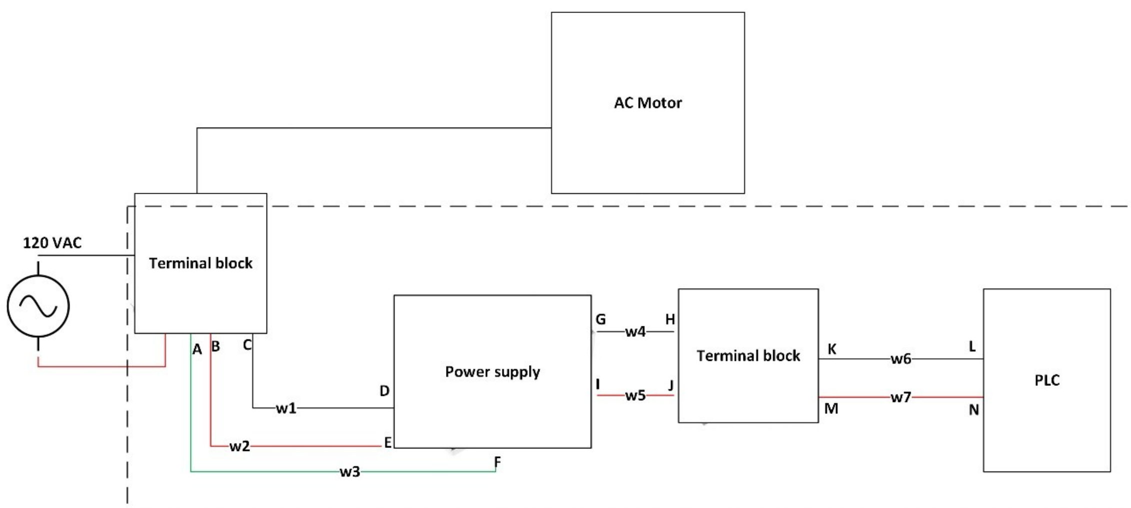



Figure 2.4 Wiring layout of a PLC-based control system

#### 2.3.1.1 Existing design cost evaluation

As per the three-step methodology shown in Figure 2.2, the first step is the cost estimation of the given design using cost function expressed in equation (2.1). This includes the cost of PLC, power supply, wires, wire stripper, soldering iron, soldering coil, terminal blocks and electrician.

$$Cost = (\$672 + \$93) + (3 * \$3.91 + 2 * \$2.35 + 2 * \$1.56) + (\$20 + \$9.61 + \$8.27) + (5 * \$78) + (0.179\ h) * (36.28\$/h)$$

$$Cost = \$1235.92$$

#### 2.3.1.2 Existing design assembly time evaluation

To estimate cost using cost function it is important to calculate the assembly times for electrical connections and wire harnesses. The values for the electrical connections and wire harnesses are calculated from the data given by (Ong and Boothroyd 1991). Table 2.1 enlists the total numbers of wires, length, connection type at the point of origin and destination. The wiring attributes for the current control system are illustrated in the Tables (2.2 – 2.5).

Table 2.1 Wire run list for current PLC-based control system

| *Wire* | *Length (ft)* | *From* | *Termination type* | *To* | *Termination type* |
|---|---|---|---|---|---|
| w1 flexible | 5 | C | terminal block | D | terminal block |
| w2 flexible | 5 | B | terminal block | E | terminal block |
| w3 flexible | 5 | A | terminal block | F | terminal block |
| w4 flexible | 3 | G | terminal block | H | terminal block |
| w5 flexible | 3 | I | terminal block | J | terminal block |
| w6 flexible | 2 | K | terminal block | L | terminal block |
| w7 flexible | 2 | M | terminal block | N | terminal block |

Table 2.2 Operation times for the preparation of wires

| *Wire* | *Length (ft)* | *Manual strip both ends (s)* | *Tinning wire both ends (s)* | *Manual pull and cut (s)* |
|---|---|---|---|---|
| w1 flexible | 5 | 14 | 18 | 7.3 |
| w2 flexible | 5 | 14 | 18 | 7.3 |
| w3 flexible | 5 | 14 | 18 | 7.3 |
| w4 flexible | 3 | 14 | 18 | 6.1 |
| w5 flexible | 3 | 14 | 18 | 6.1 |
| w6 flexible | 2 | 14 | 18 | 5.5 |
| w7 flexible | 2 | 14 | 18 | 5.5 |
| Total | | | | 269.1 |

Table 2.3 Operation times for the installation of wires

| *Wire* | *Length (ft)* | *Laying identical wires (s)* |
|---|---|---|
| w1 flexible | 5 | - |
| w2 flexible | 5 | - |
| w3 flexible | 5 | 11.2 |
| w4 flexible | 3 | - |
| w5 flexible | 3 | 7.8 |
| w6 flexible | 2 | - |
| w7 flexible | 2 | 6.1 |
| Total | | 25.1 |

Table 2.4 Operation times for securing of the wires

| *Wire* | *Length (ft)* | *Adhesive clamp (s)* | *Label with sticker (s)* |
|---|---|---|---|
| w1 flexible | 5 | - | 10 |
| w2 flexible | 5 | - | 10 |
| w3 flexible | 5 | 42.9 | 10 |
| w4 flexible | 3 | - | 10 |
| w5 flexible | 3 | 28.6 | 10 |
| w6 flexible | 2 | - | 10 |
| w7 flexible | 2 | 14.3 | 10 |
| Total | | | 155.8 |

Table 2.5 Operation times for the attachment of the wires

| *Wire* | *Length (ft)* | *Terminal block both ends (s)* |
|---|---|---|
| w1 flexible | 5 | 27.8 |
| w2 flexible | 5 | 27.8 |
| w3 flexible | 5 | 27.8 |
| w4 flexible | 3 | 27.8 |
| w5 flexible | 3 | 27.8 |
| w6 flexible | 2 | 27.8 |
| w7 flexible | 2 | 27.8 |
| Total | | 194.6 |

#### 2.3.1.2 DEC

As illustrated in the previous sections, the number of parts is directly related to the cost and the assembly time. If the number of parts is reduced, it will also reduce the cost and the assembly time. The first step includes sorting the parts in ascending order with respect to voltage requirements. The PLC requires 24 VDC, and AC motor requires 120 VAC respectively. PLC will be examined first as this is bottoms up approach. In order for PLC to operate a 24 VDC power supply is required. The purpose of this power supply is to convert 120 VAC to 24 VDC. This 24 VDC is also unique as no similar voltage exists in the control system under examination. This shows that PLC is a suspect part and reselection is suggested by DEC. The next step is to move onto the next part in the list which is AC motor. This part does not require any voltage conversion which indicates that part is not a suspect and does not have the potential for further improvement. The demonstration of the DEC methodology in order to reduce the number of parts is illustrated in Table 2.6 below.

Table 2.6 DEC methodology application PLC-based system

| *Part* | *Voltage conversion* | *Voltage unique* | *Voltage source has capacity* | *Increase capacity* | *Part suspect* | *Reselect the part* | *Merge the part* |
|---|---|---|---|---|---|---|---|
| PLC | ✓ | ✓ | ✓ | × | ✓ | ✓ | × |
| Motor | × | × | × | × | × | × | × |

Upon applying the DEC, the PLC is identified as a potential part for improvement and reselection is suggested. Instead of using a DC powered PLC, a 120 VAC powered PLC is proposed. The proposed control system is shown in Figure 2.5.

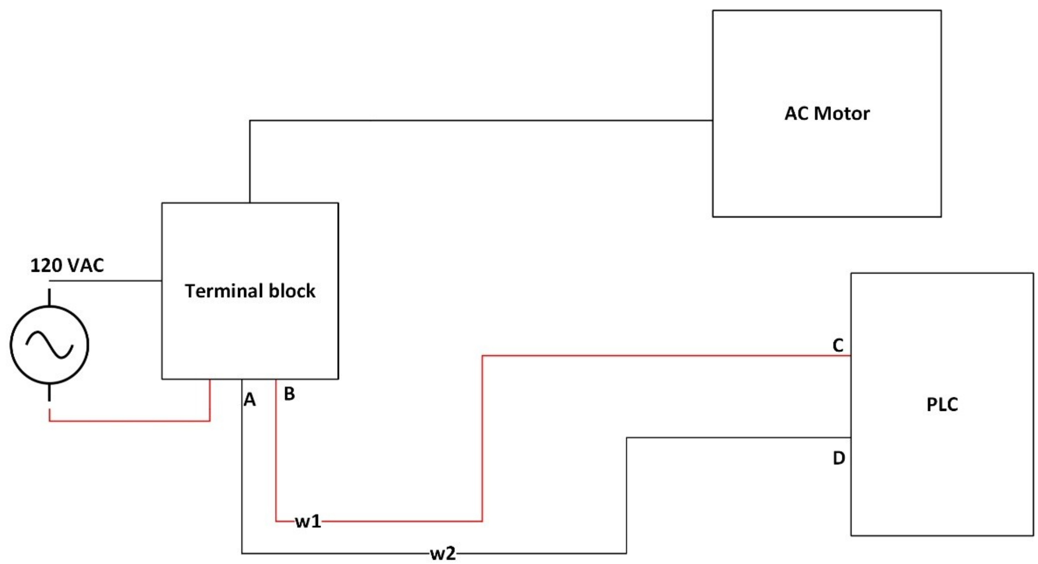



Figure 2.5 Proposed control system, PLC

#### 2.3.1.3 Proposed design cost and assembly time evaluation

The final step towards three step methodology is to evaluate the cost of the design proposed by the DEC using equation (2.1). This includes the cost of PLC, wires, tools, assembly times for electrical connections and wire harnesses of the proposed control system and electrician wage.

$$Cost = (\$373) + (2 * \$3.91) + (\$20 + \$9.61 + \$8.27 + \$17) + (2 * \$78) + (0.073166\, h) * (36.28\$/h)$$

$$Cost = \$594.35$$

#### 2.3.1.4 Discussion

The application of the proposed DEC methodology has resulted in significant improvements in terms of assembly time, number of parts and ultimately the cost. DEC removed a power supply, five wires, and their respective connections. As illustrated in

Figure 2.6 and Table 2.7, the comparison between current and proposed controls systems, shows the assembly time has been reduced from 10.74 to 4.39 min, and the cost has been reduced from $1235.92 to $594.35. There has been an improvement of 59.12% in assembly time and 51.91% in cost respectively.

Table 2.7 Assembly times for the current and proposed PLC-based controls systems

| | *Preparation* | *Installation* | *Securing* | *Attachment* | *Total (s)* | *Total (min)* |
|---|---|---|---|---|---|---|
| Current | 269.1 | 25.1 | 155.8 | 194.6 | 644.6 | 10.74 |
| Proposed | 78.6 | 11.2 | 62.9 | 111.2 | 263.9 | 4.39 |

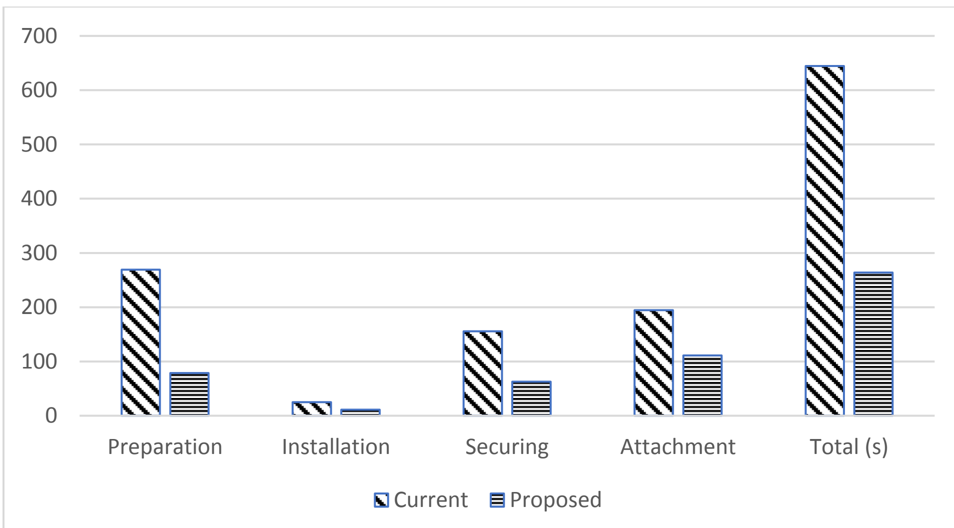



Figure 2.6 Assembly times for current and proposed controls system, PLC

### 2.3.2 Sensor-based control system

A typical sensor-based control system, as shown in Figure 2.7, consists of a main AC voltage source to power the whole system, two secondary DC sources to power the DC parts, and terminal blocks to provide solid and firm connections. The voltage specifications of the system are as follows: main AC source is 120 VAC, power supply 1 (flexible source) converts 120 VAC to 24 VDC, and power supply 2 converts 120 VAC to 12 VDC. The primary objective of this case study is to demonstrate part merging and the flexible source concept of the DEC methodology.

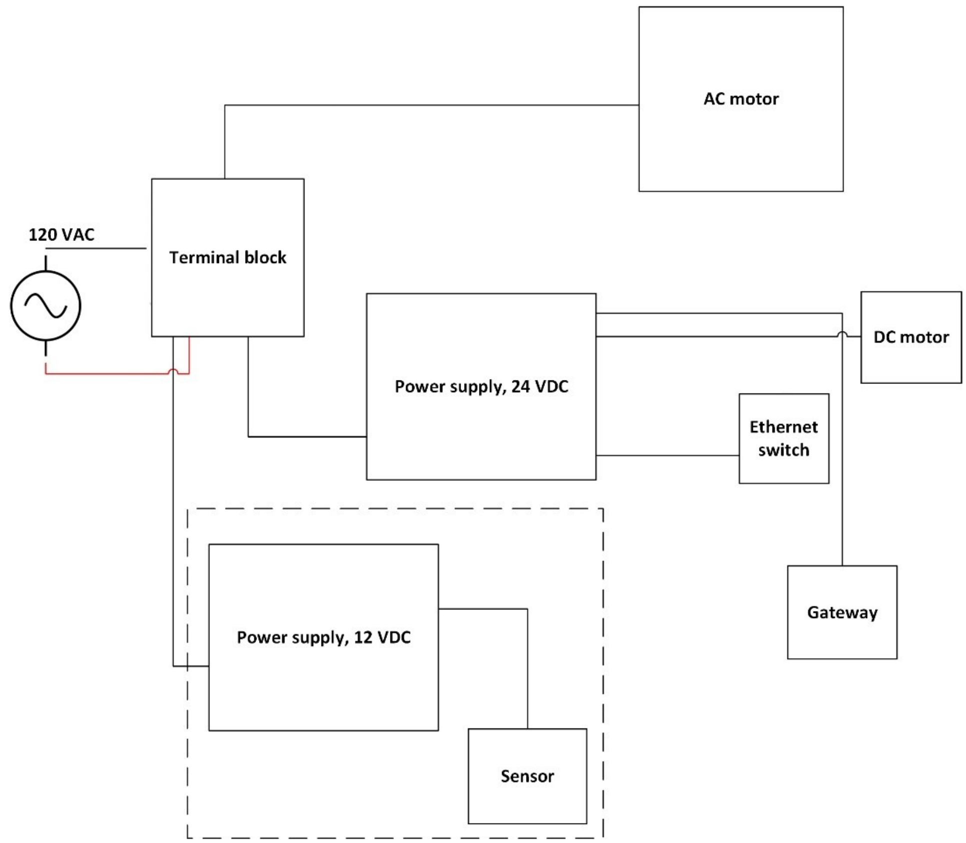



Figure 2.7 Current control system, sensor (flexible source)

#### 2.3.2.1 Existing design cost and assembly time evaluation

Cost of the given design is calculated as $604.99 using the cost function expressed in equation (2.1). This includes the cost of power supply, wires, wire stripper, soldering iron, soldering coil, terminal blocks and electrician. The assembly time for the given design is calculated as 11.52 min.

#### 2.3.2.2 DEC

The sensor requires 12 VDC, gateway, Ethernet switch and DC motor requires 24 VDC and AC motor requires 120 VAC respectively. As DEC is a bottom-up approach, sensor has the least voltage and will be investigated for potential improvement on priority basis. The 12 VDC required to operate sensor is unique as no similar voltage exists in the control system under examination. The first iteration of the DEC methodology as illustrated in Table 2.8 has suggested the reselection. Instead of using a 12 VDC sensor, a 24 VDC sensor is proposed.

Table 2.8 DEC methodology first iteration sensor-based system

| *Part* | *Voltage conversion* | *Voltage unique* | *Voltage source has capacity* | *Increase capacity* | *Part suspect* | *Reselect the part* | *Merge the part* |
|---|---|---|---|---|---|---|---|
| Sensor | ✓ | ✓ | × | × | ✓ | ✓ | × |

Once the part is reselected, the same part will go through second iteration illustrated in Table 2.9. This time 24 VDC requires to operate newly proposed sensor is not unique as a 24 VDC power supply already exists in the system. The next step as per DEC methodology is to check that the power supply 1 is flexible. This shows that it has enough power to accommodate the newly proposed sensor.

Table 2.9 DEC methodology second iteration sensor-based system

| *Part* | *Voltage conversion* | *Voltage unique* | *Voltage source has capacity* | *Increase capacity* | *Part suspect* | *Reselect the part* | *Merge the part* |
|---|---|---|---|---|---|---|---|
| Sensor | ✓ | × | ✓ | × | ✓ | × | ✓ |

Once all these conditions are satisfied, the power supply 2 can be removed from the system and sensor can be merged into power supply 1. The control system proposed by the DEC is shown in Figure 2.8.

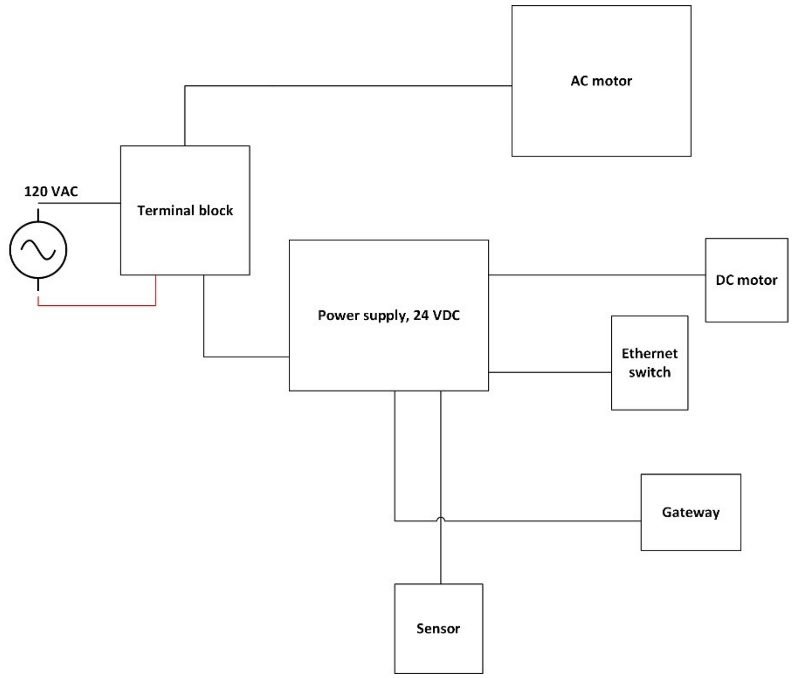



Figure 2.8 Proposed control system, sensor (flexible source)

### 2.3.2.3 Proposed design cost and assembly time evaluation

The cost of the proposed design is calculated as $244.29 using cost function expressed in equation (2.1). This includes the cost of power supply, wires, wire stripper, soldering iron, soldering coil, terminal block and electrician. The assembly time for the proposed design is calculated as 3.63 min.

### 2.3.2.4 Discussion

The application of the proposed DEC methodology has resulted in significant improvements in terms of assembly time, number of parts and ultimately the cost. As illustrated in Figure 2.9 and Table 2.10, the comparison between current and proposed controls systems, shows the assembly time has been reduced from 11.52 min to 3.63 min, and the cost has been reduced from \$604.99 to \$244.29. There has been an improvement of 68.48% in assembly time and 59.62% in the cost respectively.

Table 2.10 Assembly times for the current and proposed sensor-based systems

| | *Preparation* | *Installation* | *Securing* | *Attachment* | *Total (s)* | *Total (min)* |
|---|---|---|---|---|---|---|
| Current | 226.1 | 42.1 | 256.7 | 166.8 | 691.7 | 11.52 |
| Proposed | 32 | 23.1 | 135.2 | 27.8 | 218.1 | 3.63 |

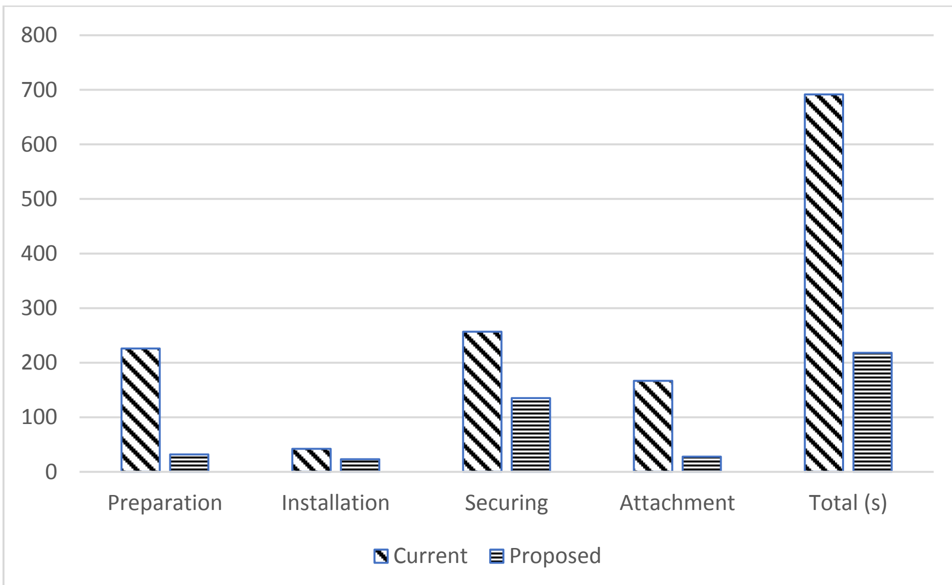



Figure 2.9 Assembly times for the current and proposed controls systems, sensor (flexible source)

### 2.3.3 Sensor-based system – inflexible source

In order to demonstrate the DEC concept of inflexible source, the control system shown in Figure 2.10 is used. The voltage specifications of the system are as follows: the main AC source is 120 VAC, power supply 1 (inflexible source) converts 120 VAC to 24 VDC, and power supply 2 converts 120 VAC to 12 VDC. It is assumed that power supply 1, which has a capacity of 60W, is already exhausted due to excessive load and there is no room for any other part to be merged.

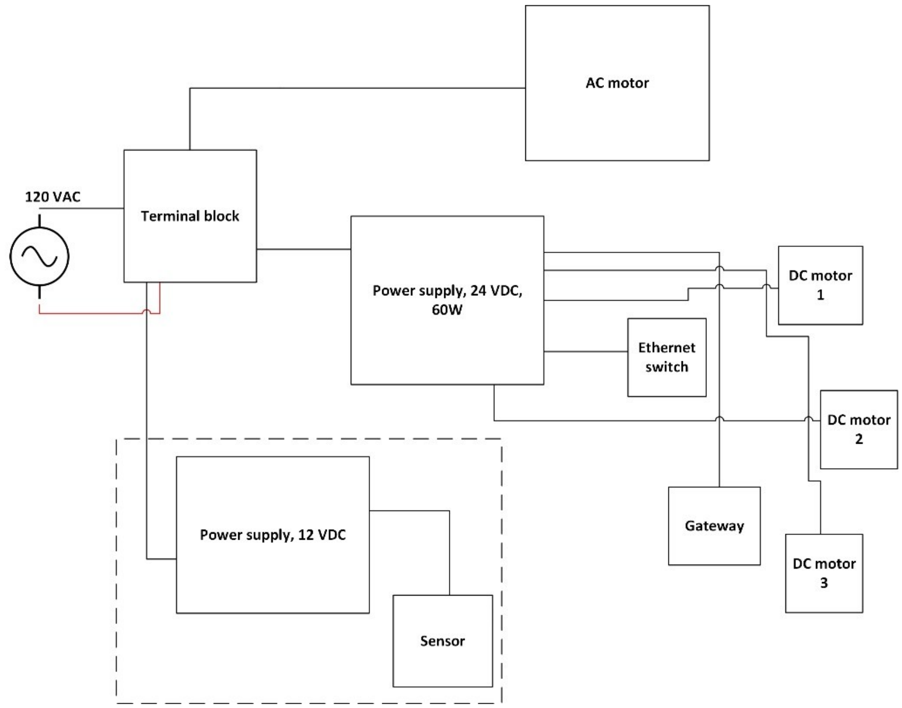


Figure 2.10 Current control system, sensor (inflexible source)

### 2.3.3.1 DEC

The first iteration of the DEC methodology reaches the same conclusion as illustrated above in Table 2.8. Since there is no change in low voltage parts in the system. However, once the part is reselected, the second iteration of the DEC methodology, as shown below in Table 2.11, suggests the merging of the part (sensor), but after increasing the capacity due to the fact that the source (power supply 1) with which it is going to merge is already exhausted and has not enough power available to accommodate the newly proposed sensor. The proposed control system as per the DEC is shown in Figure 2.11. Instead of using two separate power supplies, a single power supply having a capacity of 100W is proposed.

Table 2.11 DEC methodology second iteration (inflexible source)

| *Part* | *Voltage conversion* | *Voltage unique* | *Voltage source has capacity* | *Increase capacity* | *Part suspect* | *Reselect the part* | *Merge the part* |
|---|---|---|---|---|---|---|---|
| Sensor | ✓ | × | × | ✓ | ✓ | × | ✓ |

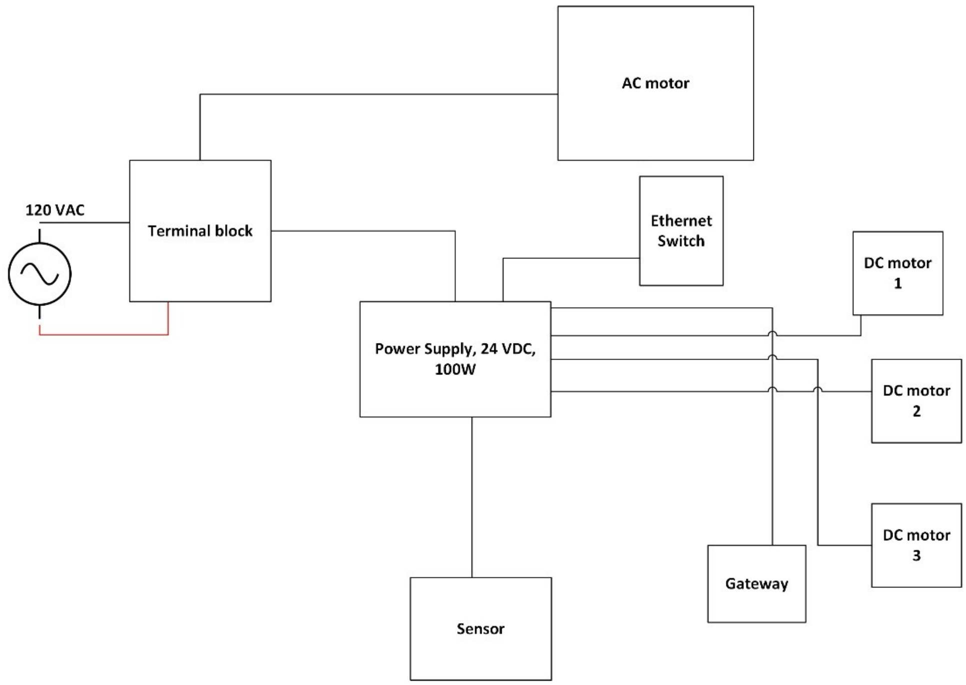



Figure 2.11 Proposed control system with increased capacity, sensor (inflexible source)

### 2.3.4 Motor-based system

Motors usually come in two different types—single or three-phase. One of the solutions in order to run a three-phase motor using single phase power is through phase converters. A typical motor-based control system is shown in Figure 2.12 where the single phase is being converted into three-phase. Although it's a cost-effective solution, the quality of power generated by these phase converters is not ideal and may reduce the life of the motor. A three-phase motor-based system is used to demonstrate that the DEC methodology can also be applied to multiphase AC systems. As per the given conditions, if only single phase power is available, it might be impossible to replace a three-phase motor with a single phase motor having the same speed, torque and horsepower specifications and the use of a phase converter would be mandatory.

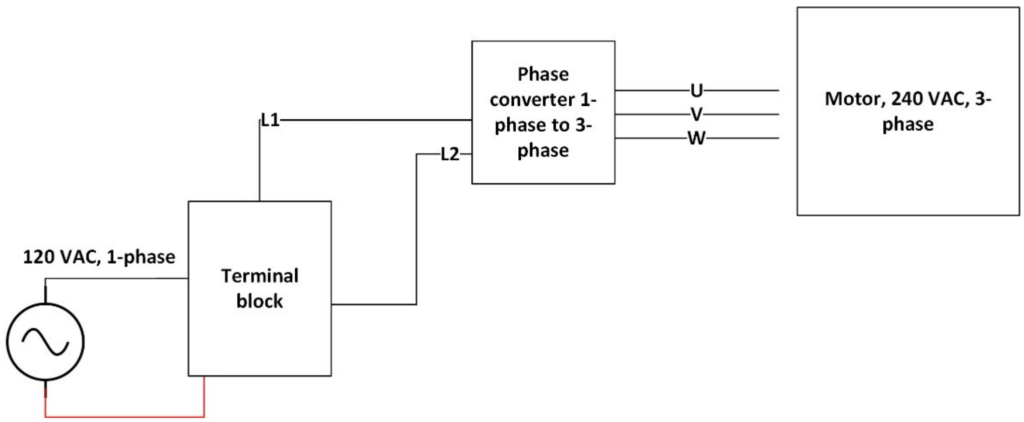



Figure 2.12 Current control system, multiphase

### 2.3.4.1 Existing design cost and assembly time evaluation

Cost of the given design is calculated as \$1305.15 using the cost function expressed in equation (2.1). This includes the cost of AC motor, phase converter, wires, wire stripper, soldering iron, soldering coil, terminal blocks and electrician. The assembly time for the given design is calculated as 7.83 min.

$$Cost = (\$564 + \$502) + (2 * \$9.43 + 3 * \$1.56) + (\$20 + \$9.61 + \$8.27 + \$17) + (2 * \$78) + (0.1305\ h) * (36.28\$/h)$$

$$Cost = \$1305.15$$

### 2.3.4.2 DEC

The application of the DEC methodology on the existing design is illustrated in Table 2.12. The application results suggest the merging of the part.

Table 2.12 DEC methodology application motor-based system

| *Part* | *Voltage conversion* | *Voltage unique* | *Voltage source has capacity* | *Increase capacity* | *Part suspect* | *Reselect the part* | *Merge the part* |
|---|---|---|---|---|---|---|---|
| Motor | ✓ | × | ✓ | × | ✓ | × | ✓ |

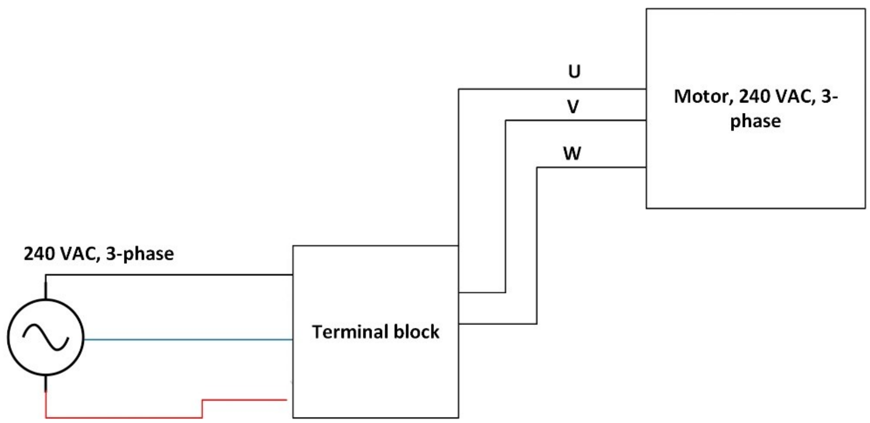



Figure 2.13 Proposed control system, multiphase

### 2.3.4.3 Proposed design cost and assembly time evaluation

The cost of the proposed design is calculated as \$745.90 using cost function expressed in equation (2.1). This includes the cost of AC motor, wires, wire stripper, soldering iron, soldering coil, terminal blocks and electrician. The assembly time for the proposed design is calculated as 4.94 min.

$$Cost = (\$502) + (3 * \$9.43) + (\$20 + \$9.61 + \$8.27 + \$17) + (2 * \$78) + (0.1305\ h) * (36.28\$/h)$$

$$Cost = \$745.90$$

### 2.3.4.4 Discussion

The application of the proposed DEC methodology has removed a phase converter and two wires along with their accessories. As illustrated in Table 2.13 and Figure 2.14, the comparison between current and proposed controls systems, shows the assembly time has reduced from 7.83 min to 4.94 min, and the cost has been reduced from $1305.15 to $745.90. There has been an improvement of 36.90% in assembly time and 42.84% in the cost.

Table 2.13 Assembly time for current and proposed motor-based controls systems

| | *Preparation* | *Installation* | *Securing* | *Attachment* | *Total (s)* | *Total (min)* |
|---|---|---|---|---|---|---|
| Current | 127.5 | 53 | 150.1 | 139 | 469.6 | 7.83 |
| Proposed | 103.5 | 53.4 | 55.8 | 83.4 | 296.1 | 4.94 |

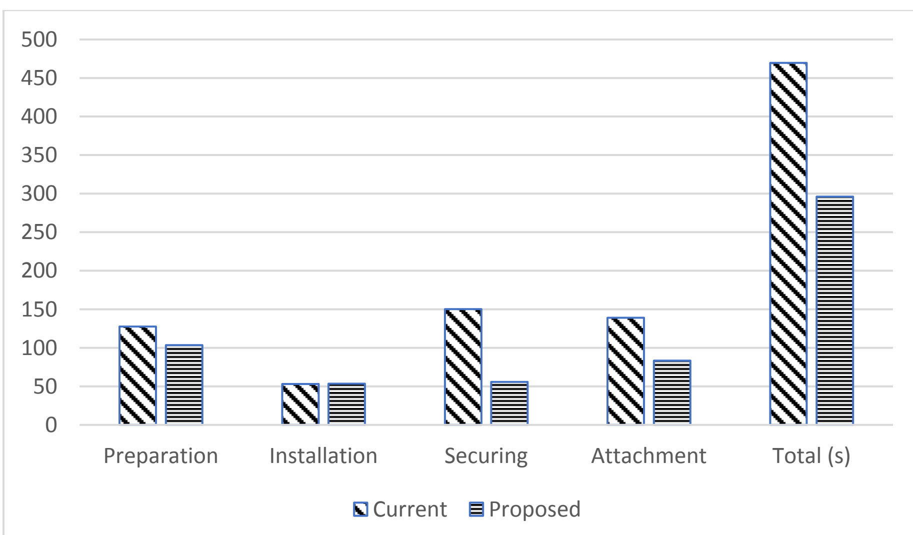



Figure 2.14 Assembly time for current and proposed controls system, multiphase

## 2.4 Conclusion

Due to increased automation over the last few decades, control engineers are required to adopt new strategies to improve efficiencies, increase productivity, and reduce costs. Space utilization is one key aspect that challenges the control engineers to reduce the size and make a compact control system. Electrical wiring is another challenge, and, if not designed properly, can result in failures and wastage of resources. Apart from the aforementioned challenges, the amount of time required to assemble the newly designed controls system is also vitally important. However, the most crucial factor in a competitive market is cost. The earlier these challenges are addressed, the easier it gets for the designers to rectify. This chapter presents a novel method based on two approaches: 1) a multi-attribute cost function that allows a designer to calculate the cost of any given control concept taking into consideration the cost of parts, wires, tools, assembly, and labor, and 2) an iterative DEC methodology to reduce the number of electrical control parts. A Programmable Logic Controller (PLC) based system, a sensor-based system, and a three-phase motor-based system are used to demonstrate the different possible scenarios and application diversity of the proposed approach. The assembly time for the PLC-based system has reduced from 10.74 min to 4.39 and cost from \$1235.92 to \$594.35; assembly time for the sensor-based system has reduced from 11.52 min to 3.63 min and cost from \$604.99 to \$244.29; and assembly time for the multiphase AC system has reduced from 7.83 min to 4.94 min and cost from \$1305.1 to \$745.90. The successful application indicates that the proposed methodology is a useful tool for system designers to reduce the number of parts, the assembly time for wiring, and ultimately the cost in the early design stages.

## Chapter 3 Complexity model for measuring controls complexity[2]

This chapter presents a new model for measuring controls complexity by incorporating the principles of assembly complexity model, information content, and assembly attributes for electrical connections and wire harnesses. Controls complexity is defined as the degree to which individual wires/cables are prepared, assembled, installed, and attached and amount of diversity in controls signals. The model takes into account the complexity of individual wires using indices that are added to assess overall controls system complexity. To demonstrate, a sub-assembly in a semi-automatic machine is used with three different controls alternatives: pneumatics, bipolar stepper, and Ethernet-based stepper. The results vindicate that proposed model is a productive tool in early design stages, to compare and select potential best-suited controls system in terms of complexity.

### 3.1 Introduction

Cost, materials, manufacturing and assembly processes play a vital role in producing a quality product. The challenge is to keep the cost minimum which demands detailed knowledge of design, assembly, manufacturing, materials, processes and the complex nature of interaction among them. An increase in demand combined with growing needs has made the manufacturing industry much more competitive in terms of cost and simpler products. Assembly attributes account for the majority of production time and, most importantly, the cost. Design for Assembly (DFA) provides a systematic procedure for analyzing a proposed design from the assembly point of view. This procedure results in simpler

[2] The manuscript appearing as Chapter 3 of this thesis will be submitted to International Journal of Computer Integrated Manufacturing.

products that take less time to assemble. Apart from assembly time and cost, Steger (2007) sees complexity as an important factor contributing to difficulties faced in manufacturing. Mitchell (2009) explains the difficulty in understanding complexity because of different solutions and explanations for what constitutes complexity. Complexity has been proposed by many researchers in terms of size, entropy, information content, thermodynamic and information required to construct, computational capacity, statistical complexity, as well as others. ElMaraghy, Tomiyama and Monostori (2012) state that within last decades, complexity has increased continuously in many industries. Schuh, Arnoscht and Rudolf (2010) see complexity as one of the biggest challenges that manufacturing companies have to face. The breakthrough in modern electronics and control units have increased the automation at domestic and industrial scale. Alphonsus and Abdullah (2016) state that due to a significant increase in need of automation, a control system is required to be easily programmable, flexible, reliable, robust and cost effective. Therefore, it is equally important to consider controls complexity along with mechanical while designing a mechatronics system. Most of the available research focuses on mechanical assemblies when it comes to complexity. However, limited information is available on a systematic approach to assess the complexity of wiring and associated controls in early design stages. This leads to an important conclusion that there is a need of a metric for a designer to be aware of the complexity he is going to introduce in the system by making certain controls related choices.

### 3.1.1 Design for Assembly

Nof et al. (1997) divides the assembly tasks into two basic categories of parts mating and parts joining. In the first category, different parts are aligned with each other. In the second category, after aligning, the parts are held together through fastening. The economic significance of the assembly tasks is such that it accounts for more than 50% of total production time and 20% of the total unit production cost. According to Jung and Billatos (1993), 85% of a product's manufacturing cost is determined before even starting the manufacturing process. Boothroyd, Dewhurst and Knight (2011) began research on Design for Manufacture (DFM) and Design for Assembly (DFA) methodology. The major goal of DFA is to reduce the cost by reducing the number of parts. During DFA analysis, production feasibility should not affect the idea generation, since this will discourage possible search and creativity. Components that can be combined but are hard to produce can be reanalyzed at a later stage for an alternate production method. Pan and Smith (2006) studied the impact of assembly direction reorientations on assembly time. A robot assembly and human operator assembly were used to demonstrate that more assembly direction reorientations result in longer assembly time. Miles (1990) showed the significance of time at which the various design tools and techniques are used with respect to the design process. It was found that DFA and DFM bring additional benefits to a multidisciplinary design team when used with the appropriate training and support (Miles 1990). Mo et al. (1999) stated that the combination of DFA expert system and CAD systems puts more requirements on the assembly model. In order to satisfy the requirements of such systems, a DFA-oriented assembly relation model is presented, which is composed of function, geometry, and connection relation models. Booker, Swift and Brown (2005) described the need for an approach focusing problems related to assembly variability in the early design process. Hsu and Lin (1998) presented a DFA-based redesign approach (DBPRA) that combines assembly functional presentation (AFP) and a problem recommendation driven mechanism (PRDM). The redesign approach assists in the product modification process and without compromising important functions it also makes the existing design better. Moultrie and Maier (2014) presented a new tool that is designed to communicate critical design messages in a structured, concise and compelling way that is suitable for use in a team setting.

### 3.1.2 Complexity

"The purpose of good design is seen as the elimination of the unforeseen, the unexpected and the unintended, not as the consideration of the unforeseeable, the unthinkable and the unknown. There is a strong tendency to control or limit complexity instead of embracing it" (Braha, Minai and Bar-yam 2006). Suh (1999) draws a distinction between complex and complicated systems. The behavior of complicated systems is well understood; however, the same cannot be said in the case of complex systems. Biggiero (2001) describes complexity as arising due to lack of knowledge of the system under study. According to Mitchell (2009), complexity is difficult to understand as many researchers have proposed. Aside from the difficulty inherent in defining the complexity, the other difficult thing is its quantification. Warfield (1999) developed twenty laws of complexity in order to quantify and evaluate complexity. According to ElMaraghy, Kuzgunkaya and Urbanic (2005), there are three basic approaches to measure complexity: entropy/information content, heuristic, and hybrid. ElMaraghy and Urbanic (2003) developed a rapid Manufacturing Complexity Assessment Tool (MCAT) for the modelling of manufacturing system complexity, where the model is based on three core elements: total quantity of information, diversity of information, and the information content. They further divide the manufacturing complexity into product complexity (Deif and ElMaraghy 2006), process complexity (EIMaraghy and Urbanic 2004), and operational complexity (Tomiyama et al. 2007). The increased competitiveness has made machines multi-disciplinary and has given rise to two different types of complexity: complexity by design and the intrinsic complexity of multi-disciplinarity. These two types of complexities not only affect the product development processes but also result in design failures. Suh (1999) defines the complexity as a measure of uncertainty in achieving Functional Requirements (FRs) and is related to information axiom, which is defined in terms of the probability of success of achieving FRs. The complexity is divided into two main classes, time-independent and time-dependent, which may be further divided into real, imaginary, combinatorial, and periodic complexities. Frey, Jahangir and Engelhardt (2000) state that if more than one design satisfying independence axiom are available, then choose the one with less information content. Samy and Elmaraghy (2010) developed a complexity model incorporating information content and DFA principles. The model is used to assess the assembly complexity of individual parts using an index for measuring the complexity, and then the individual parts are used to measure total product assembly complexity.

The complexity models to assess the mechanical assembly are discussed in the following sections:

#### 3.1.2.1 Manufacturing systems complexity

The original model proposed by Elmaraghy and Urbanic (2003) for the manufacturing systems complexity is given in equation (3.1). The complexity is represented by complexity index and is a function of the information entropy, the diversity ratio, and the relative complexity coefficient. The perception of complexity changes with the environment in which it is being perceived. Therefore a ranking system was used where low, medium, and high effort levels correspond to factor levels 0, 0.5 and 1. The scale is not limited to 0-1, a 1-10 scale was also proposed with the final difficulty factor value normalized by the maximum value of the scale.

$$C_{part} = \left[\frac{n}{N} + CI_{part}\right] \left[\log_2(N+1)\right] \quad (3.1)$$

where:

- Cpart : is part complexity
- N: is the total quantity of information
- n: is the quantity of unique information
- CIpart: is the part complexity index

The model was originally proposed to measure the complexity of the machining process. However, it is unable to take into account various parts handling and insertion attributes, to measure product assembly complexity.

#### 3.1.2.2 Assembly complexity model

Samy and Elmaraghy (2010) proposed a model for measuring product assembly complexity, which is defined in equation (3.2). The original model expressed in equation (3.1) was further modified on the principles of DFA to incorporate various parts handling and insertion attributes.

$$C_{product} = \left[\frac{n_p}{N_p} + CI_{product}\right]\left[\log_2\left(N_p + 1\right)\right] + \left[\frac{n_s}{N_s}\right]\left[\log_2(N_s + 1)\right] \quad (3.2)$$

where:

- $C_{product}$: product assembly complexity
- $N_p$: total number of parts
- $N_S$: total number of fasteners
- $n_p$: number of unique parts
- $n_s$: number of unique fasteners

The model was originally proposed to measure product assembly complexity. However, it is unable to take into account the assembly attributes for electrical connections, wire harnesses, and associated controls signals, to measure controls complexity.

### 3.2 Methodology

The assembly complexity model expressed in equation (3.2) is therefore modified to consider the aforementioned attributes to propose a controls complexity model expressed in equation (3.3). The model is defined as the degree to which individual wires have physical attributes that require effort; (i) preparation, (ii) installation, (iii) securing and (iv) attachment as per the principles of electrical connections and wire harnesses given by Ong and Boothroyd (1991). The model further takes into account the effect of different controls signals. The relative complexity factors for these physical attributes are calculated from the data given in Ong and Boothroyd (1991) and after normalization expressed in Tables 3.1, 3.2, 3.3, 3.4, and 3.5 respectively. In order to calculate the system complexity (equation 3.3), the average difficulty factors expressed in (equations 3.4-3.8) for each individual wire are calculated. Based on average difficulty factors, the weighted average value of each individual wire is calculated using equation (3.9), which is further used to calculate the system complexity index expressed in equation (3.10). The equations (3.3-3.10) are adapted and modified from (Samy and Elmaraghy 2010).

$$C_{system} = \left[\frac{n_w}{N_w} + CI_{system}\right] [\log_2(N_w + 1)] + \left[\frac{n_c}{N_c}\right] [\log_2(N_c + 1)] \quad (3.3)$$

where:

- $C_{system}$: system controls complexity
- $N_w$: total number of wires
- $N_c$: total number of controls signals
- $n_w$: number of unique wires
- $n_c$: number of unique controls signals

$$C_p = \frac{\sum_1^J C_{p,f}}{J} \quad (3.4)$$

where:

- $C_p$: average preparation complexity factor
- $C_{p,f}$: relative preparation complexity factor

- J: number of preparation attributes of each wire

$$C_i = \frac{\sum_1^K C_{i,f}}{K} \tag{3.5}$$

where:

- $C_i$: average installation complexity factor
- $C_{i,f}$: relative installation complexity factor
- K: number of installation attributes of each wire

$$C_s = \frac{\sum_1^L C_{s,f}}{L} \tag{3.6}$$

where:

- $C_s$: average securing complexity factor
- $C_{s,f}$: relative securing complexity factor
- L: number of securing attributes of each wire

$$C_a = \frac{\sum_1^M C_{a,f}}{M} \tag{3.7}$$

where:

- $C_a$: average attachment complexity factor
- $C_{a,f}$: relative attachment complexity factor
- M: number of installation attributes of each wire

$$C_{pc} = \frac{\sum_1^N C_{pc,f}}{N} \tag{3.8}$$

where:

- $C_a$: average connector preparation complexity factor

- $C_{a,f}$: relative connector preparation complexity factor
- N: number of connector preparation attributes of each wire

$$C_{wire} = \frac{C_p \sum_1^J C_{p,f} + C_i \sum_1^K C_{i,f} + C_s \sum_1^L C_{s,f} + C_a \sum_1^M C_{a,f} + C_{pc} \sum_1^N C_{pc,f}}{\sum_1^J C_{p,f} + \sum_1^K C_{i,f} + \sum_s^L C_{s,f} + \sum_1^M C_{a,f} + \sum_1^N C_{pc,f}} \tag{3.9}$$

where:

- $C_{wire}$: weighted average value of the wire complexity factor

$$CI_{system} = \sum_{p=1}^{n} x_w C_{wire} \tag{3.10}$$

where:

- $CI_{systemt}$: controls system complexity index
- $x_w$: percentage of the $x_{th}$ dissimilar wires
- n: number of unique wires

Table 3.1 illustrates the preparation attributes, for instance, cutting, stripping, tinning, and cramping for the single and multi-conductor wires. These attributes are carried out either manually, with the assistance of machine/tool or the combination of both. The effort to perform each of the attribute is calculated and expressed as complexity factor. The tables (3.1-3.5) are adapted and modified from (Ong and Boothroyd 1991).

Table 3.1 Preparation attributes complexity factor, $C_{p,f}$

| | Wire cutting operation | | Wire stripping | | Tinning wire | | Crimping terminal | |
|---|---|---|---|---|---|---|---|---|
| Single wire | Manual pull and cut | *0.6 | Manual | 0.7 | Soldering iron | Solder pot | Manual | Semi auto |
| | Machine pull and cut | ^0.51 | Semi auto | 0.51 | 0.79 | 0.71 | 1.02 | 0.51 |
| Multi conductor wire | Manual pull and cut | *0.65 | Manual | 2 | 1.21 | 0.71 | 1.67 | 0.65 |
| | | | Semi-auto | 1.72 | | | | |
| | Per additional wire | | Manual | 0.65 | 1.07 | 0.65 | 1.3 | 0.79 |
| | | | Semi-auto | 0.51 | 0.93 | 0.51 | 1.16 | 0.65 |
| | Machine pull and cut | ^0.51 | Manual | 1.91 | 1.21 | 0.71 | 1.67 | 0.65 |
| | | | Semi-auto | 1.63 | | | | |
| | Per additional wire | | Manual | 0.65 | 1.07 | 0.65 | 1.3 | 0.79 |
| | | | Semi-auto | 0.51 | 0.93 | 0.51 | 1.16 | 0.65 |

- *0.4 per foot for each additional foot
- ^0.5 per foot for each additional foot

Connectors provide a firm connection between the wires and their destination point. Table 3.2 illustrates the connectors attributes and the effort to attach connectors is calculated and expressed as complexity factor.

Table 3.2 Connectors attributes complexity factor, $C_{pc,f}$

| Operation | Manual/Machine | Description | $C_{pc,f}$ |
|---|---|---|---|
| Crimping contact and inserting into connector | Manual crimping | Base time for one contact | 0.59 |
| | | Additional time per contact | 0.8 |
| | Machine crimping | Base time for one contact | 0.47 |
| | | Additional time per contact | 0.26 |
| Filling solder cup and soldering contact | | Base time for one contact | 0.57 |
| | | Additional time per contact | 0.46 |
| Insulation displacing (discrete wire) | | Base time for first pair of contacts | 0.45 |
| | | Time per additional pair | 0.1 |
| Mass termination (flat cable) | | Manual press | 0.7 |
| | | Automatic machine | 0.4 |
| Coaxial connector (includes cutting and stripping cable) | | | 2 |

Once the wires are prepared, it is important to dress and route the wires properly. Table 3.3 illustrates the installation attributes, for instance, point to point, the wiring on chassis, and laying wires onto harness jig. The effort associated with each attribute is calculated and expressed as complexity factor.

Table 3.3 Installation attributes complexity factor, $C_{i,f}$

| Operation | | | Basic* | Per additional* |
|---|---|---|---|---|
| Point to point | Direct wiring | | 0.52 | 0.34 |
| Wiring on chassis | U-channel | | 0.51 | 0.48 |
| Laying flat cable | | | 0.69 | 0.45 |
| Laying wires onto harness jig | Number of wires to the same breakout | 1 | 0.87 | 0.26 |
| | | 2 | 1.10 | 0.37 |
| | | 3 | 1.32 | 0.48 |
| | | 4 | 1.55 | 0.58 |
| | | 5 | 1.77 | 0.69 |
| | | 6 | 2.00 | 0.80 |
| | | Per additional wire | 0.50 | 0.13 |
| Laying cable connector (one end) onto harness jig | Number of wires to the same breakout | 1 | 0.80 | 0.23 |
| | | 2 | 0.92 | 0.32 |
| | | 3 | 1.04 | 0.40 |
| | | 4 | 1.17 | 0.48 |
| | | 5 | 1.29 | 0.56 |
| | | 6 | 1.41 | 0.64 |
| | | Per additional wire | 0.40 | 0.10 |

Basic*: Complexity factor for one foot of wire or cable or less

Per additional*: Complexity factor per additional foot of wire or cable

For protection it is important to secure the wires properly once they are installed. Table 3.4 illustrates the securing attributes, for instance, lacing, taping, cable ties, shrinking tube, etc. The effort associated with securing attributes is calculated and expressed as complexity factor.

Table 3.5 illustrates the attachment attributes, for instance, screw fastening, fork lug, install only, etc. for bare wire, wire terminal, circular connector, and rectangular connector. The effort associated with attachment attributes is calculated and expressed as complexity factor.

Table 3.4 Securing attributes complexity factor, $C_{s,f}$

| Operation | | $C_{s,f}$ |
|---|---|---|
| Spot-tying onto cable and cutting with scissors | | 1.23 |
| Tying strap onto cable and cutting with tool | | 1.07 |
| Lacing operation | First stich | 1.42 |
| | Per additional stich | 0.8 |
| Taping operation | First inch | 1.03 |
| | Per additional inch | 0.72 |
| Inserting into tube or sleeve | First inch | 0.55 |
| | Per additional inch | 0.1 |
| Shrinking tube with heat gun | First inch | 0.4 |
| | Per additional inch | 0.49 |
| Installing cable clamp | Adhesive clamp | 0.7 |
| | Screw-down type | 2 |
| Labelling wire or cable | Sticker | 0.85 |
| | Marker | 1.07 |

Table 3.5 Attachment attributes complexity factor, $C_{a,f}$

| Type | Operation | Connection | Ca,f |
|---|---|---|---|
| Bare wire | Attaching bare end | Terminal block | 1.15 |
| | | Screw fastening | 1.54 |
| | | Screw and nut fastening | 2.00 |
| | Soldering bare end | Wire not secured | 1.40 |
| | | Wire secured | 1.75 |
| Wire terminal | Wire wrapping | | 0.89 |
| | Quick disconnect terminal | | 0.41 |
| | Terminal block fastening | Fork lug | 0.86 |
| | | Ring lug | 1.51 |
| | Screw fastening of terminal | | 1.15 |
| | Screw and nut fastening of terminal | | 1.63 |
| Circular connector | Install only | | 0.40 |
| | Bayonet | | 0.40 |
| | Friction | | 0.49 |
| | Screw thread | | 0.78 |
| Rectangular connector | Install only | | 0.48 |
| | Latch or snap on | | 0.58 |
| | Spring clip | | 0.69 |
| | Screw (2x) | | 1.58 |

### 3.3 Case Study

A mechatronics subassembly (dragging jaw) in a semi-automatic machine shown in Figure 3.1 is used to demonstrate the application of the proposed model. The wood framing machine is designed to support the growth of panelized construction in North America's building construction sector and consists of two sets of dragging jaws and four modular stations: feeding, nailing, cutting, and drilling on each side. The feeding table, or table A, assists the operator in loading the frames, and the dragging table, or table B, is used to pull the frame with the help of a mechanical assembly called dragging jaw after each operation of the nail, cut or drill. The control panel contains all the electrical components, such as programmable logic controller (PLC), communication devices, and circuit breakers.

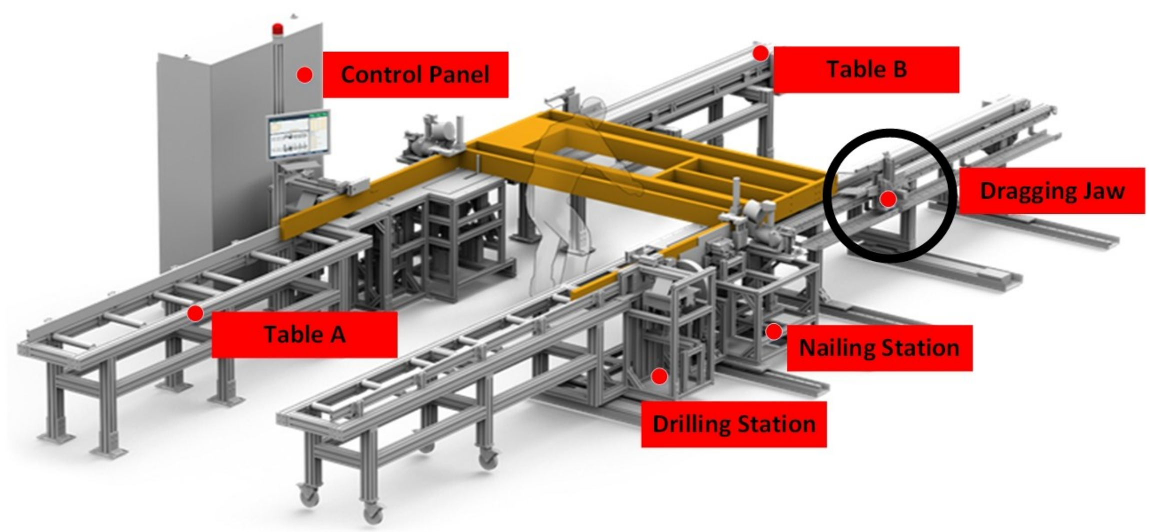



Figure 3.1 Wood framing machine

#### 3.3.1 Computer-aided design

The CAD model of the dragging jaw in the wood wall framing machine, shown in Figure 3.2 was developed in SOLIDWORKS, a solid modelling computer-aided design tool that runs on a computer. The dragging jaw assembly is driven along the rack using DC stepper motor, which is mounted horizontally on the rack and pinion drive mechanism. All dragging jaw parts are mounted on the back plate, carry all dragging jaw parts on the front side and the linear blocks on the back side. Bottom claw and top claw are mounted on top and bottom mounting brackets respectively. The mounting brackets are connected to top and bottom claws through aluminum profiles, T-nuts and screws. Pneumatic actuators are attached to mounting brackets through foot mounts. Both actuators have their rods mounted onto an angle bracket called bottom bracket. The top and bottom claws are attached to separate pneumatic actuators that are controlled independently through solenoid valves triggered by means of a PLC. In order to clamp the wood, both the pneumatic actuators are extended and make room for the incoming wood piece. Once the wood is between the top and bottom claws, the solenoid valves are triggered again to clamp the wood from top and bottom. Once the wood is clamped, it is then pulled by means of a motor.

### 3.3.2 Fabricated assembly

The fabricated assembly of dragging jaw is shown in Figure 3.3. In order to guide the air into actuators, red and blue transparent pipes are used. The pneumatic pipes are connected to the air compressor and their respective solenoid valves are further connected to PLC inside the control panel.

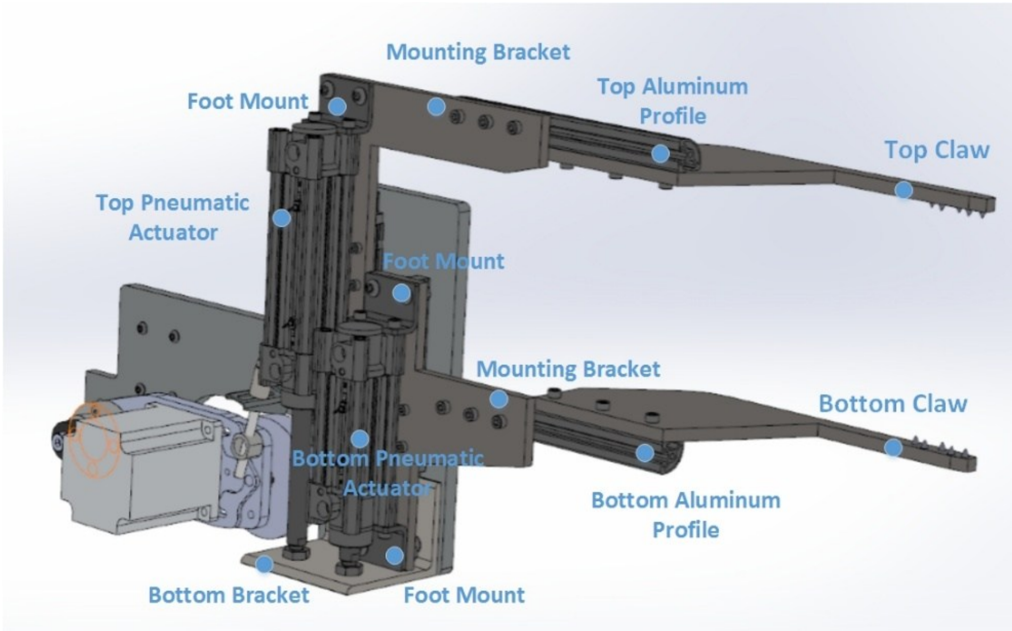



Figure 3.2 Current dragging jaw CAD model

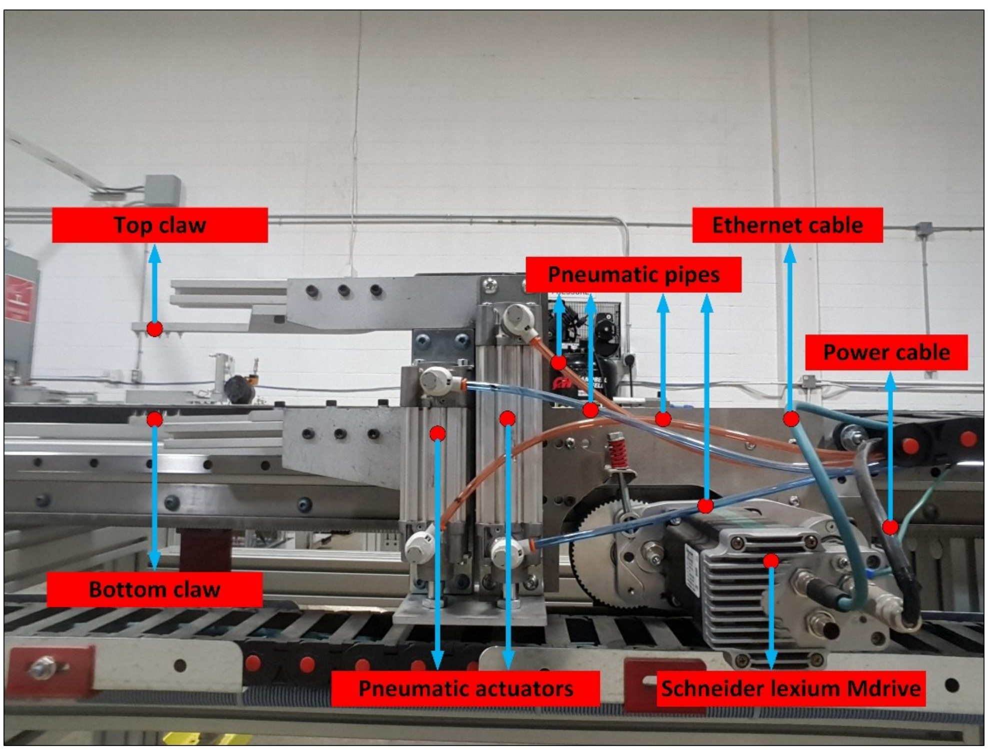



Figure 3.3 Dragging jaw fabricated assembly

## 3.4 Proposed complexity model application approach

The approach used to demonstrate the application of the proposed complexity model is divided into two main steps shown in Figure 3.4. In the first step, the current design is examined on the principles of DFA to determine design efficiency, calculate assembly times for mechanical parts and electrical connections and wire harnesses. The application of DFA resulted in proposing a simpler design with a lesser number of mechanical parts. The DFA analysis does optimization of the design more in terms of mechanical parts. In the second step, the proposed design is evaluated in terms of design efficiency and assembly time. However, in automation to achieve the same task, different controls alternatives with different communication protocols are available. Therefore, it is important for the designer to have a metric to know in the early design stages that how much complexity he is going to add into the system by selecting specific controls. For instance, the case study presented has pneumatic actuators to achieve actuation. The same actuation can be achieved by the bipolar stepper and Ethernet-based stepper. However, the control system attributes change significantly from pneumatics to Ethernet-based controls. Therefore, the controls complexity is evaluated along with mechanical attributes and the effect of assembly time is also tracked.

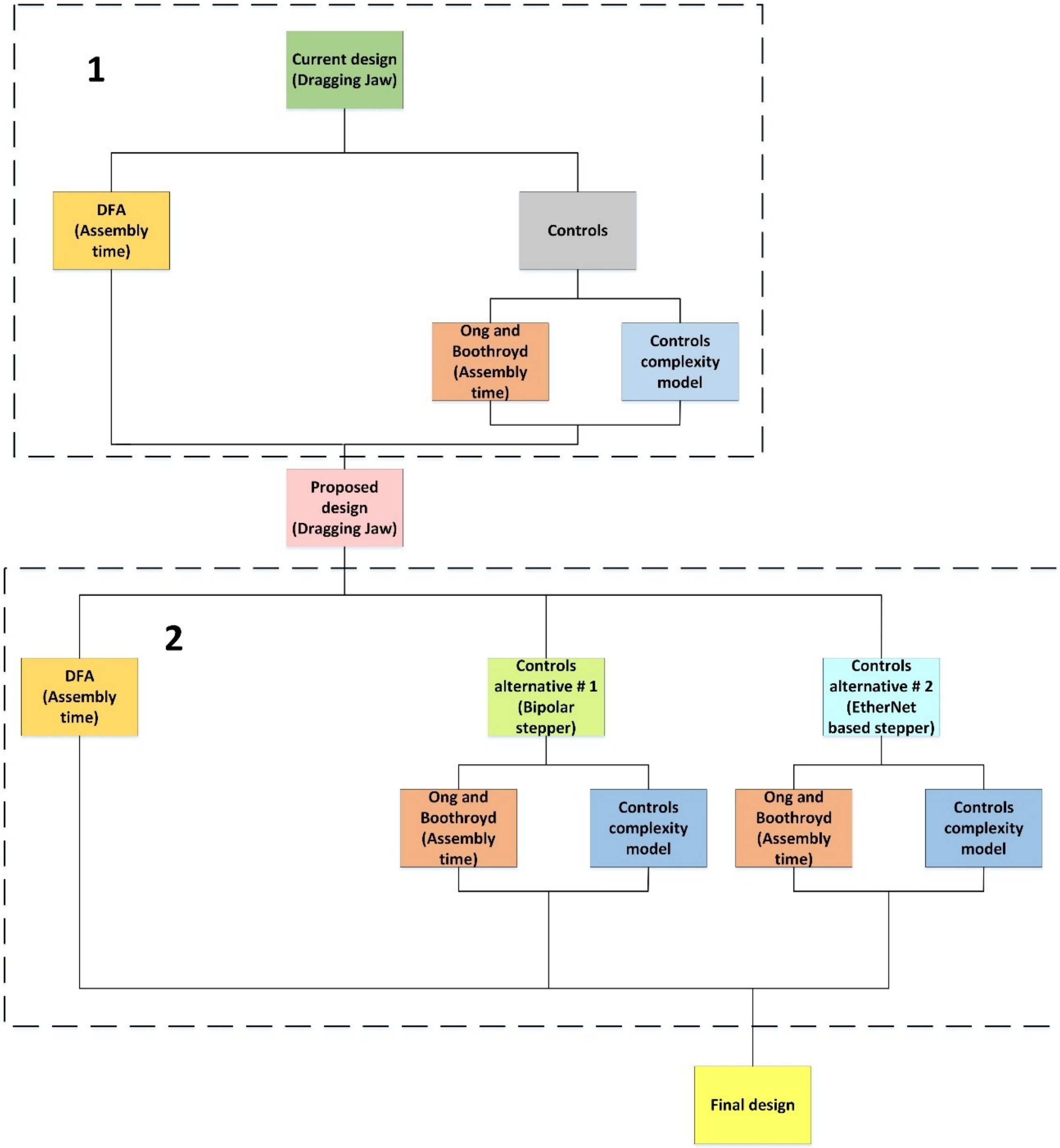



Figure 3.4 Bird's-eye view of strategy to demonstrate application of proposed model

### 3.5 Design for assembly evaluation

DFA methodology provides three criteria against which each part must be examined as it is added to the product during assembly.

- Should the component move or be able to move in relation to the preceding component in the assembly?
- Are there fundamental reasons for the components being made of a different material?
- Should the component be fitted or removed separately because otherwise assembly or disassembly of other components would be impossible?

If the answer to all the aforementioned questions come out to be negative, then it means that the specific component has the potential to be integrated with another component. Each assembly operation is divided into handling and insertion, and the corresponding time and two digit code numbers (Boothroyd, Dewhurst and Knight 2011).

### 3.5.1 Current dragging jaw assembly

Boothroyd, Dewhurst and Knight (2011) proposed DFA method is applied to the current dragging jaw assembly to calculate assembly time and design efficiency. The break down of the assembly is illustrated in Table 3.6:

where:

- Alpha: Maximum angle the part must be rotated perpendicular to the axis of insertion to repeat its orientation.
- Beta: Maximum angle part must be rotated about the axis of insertion to repeat its orientation.
- The total angle of symmetry: Alpha + Beta
- Handling time: Time required to grasp and orient

- Insertion time: Time required to insert
- Total operation time: Sum of handling and insertion time multiplied by the number of items

Table 3.6 DFA analysis of current dragging jaw

| *Part* | *Usage* | *Alpha* | *Beta* | *A+B* | *Handling code* | *Handling time (s)* | *Insertion code* | *Insertion time (s)* | *Total time (s)* |
|---|---|---|---|---|---|---|---|---|---|
| Linear rail | 2 | 180 | 180 | 360 | 10 | 1.50 | 06 | 5.50 | 14.00 |
| Bottom bracket | 1 | 360 | 360 | 720 | 30 | 1.95 | 06 | 5.50 | 7.45 |
| Foot mounts | 4 | 360 | 360 | 720 | 30 | 1.95 | 06 | 5.50 | 29.80 |
| Pneumatic actuator | 2 | 360 | 90 | 450 | 10 | 1.50 | 06 | 5.50 | 14.00 |
| Mounting bracket | 2 | 360 | 360 | 720 | 91 | 3.00 | 30 | 2.00 | 10.00 |
| Aluminum profile | 2 | 360 | 360 | 720 | 30 | 1.95 | 06 | 5.50 | 14.90 |
| Claw | 2 | 360 | 360 | 720 | 91 | 3.00 | 06 | 5.50 | 17.00 |
| Linear bearing | 2 | 360 | 360 | 720 | 30 | 1.95 | 06 | 5.50 | 14.90 |
| M8x1.25x30 bolt bottom bracket | 2 | 360 | 0 | 360 | 10 | 1.50 | 38 | 6.00 | 15.00 |
| M8x1.25x16 bolt bottom bracket | 2 | 360 | 0 | 360 | 10 | 1.50 | 38 | 6.00 | 15.00 |
| M5x0.8x20 bolt linear bearing | 8 | 360 | 0 | 360 | 10 | 1.50 | 38 | 6.00 | 60.00 |
| M4x0.7x25 bolt linear rail | 6 | 360 | 0 | 360 | 10 | 1.50 | 38 | 6.00 | 45.00 |
| M8x1.25x20 bolt foot mount | 8 | 360 | 0 | 360 | 10 | 1.50 | 38 | 6.00 | 60.00 |
| Bolts for T Nut | 12 | 360 | 0 | 360 | 10 | 1.50 | 38 | 6.00 | 90.00 |
| Pneumatic actuator bolt | 8 | 360 | 0 | 360 | 10 | 1.50 | 38 | 6.00 | 60.00 |
| Pneumatic actuator rods Nut | 4 | 180 | 0 | 180 | 01 | 1.43 | 00 | 1.50 | 11.72 |
| T Nut | 12 | 360 | 180 | 540 | 20 | 1.80 | 00 | 1.50 | 39.60 |
| M8x1.25x30 Nut bottom bracket | 2 | 180 | 0 | 180 | 01 | 1.43 | 00 | 1.50 | 5.86 |
| M8x1.25x16 Nut bottom bracket | 2 | 180 | 0 | 180 | 01 | 1.43 | 01 | 1.50 | 5.86 |
| M5x0.8x20 Nut linear bearing | 8 | 180 | 0 | 180 | 02 | 1.88 | 02 | 1.50 | 27.04 |
| M4x0.7x25 Nut linear rail | 6 | 180 | 0 | 180 | 02 | 1.88 | 03 | 1.50 | 20.28 |
| M8x1.25x20 Nut foot mount | 8 | 180 | 0 | 180 | 01 | 1.43 | 04 | 1.50 | 23.44 |
| Total | 105 | | | | | | | | 600.8 |

### 3.5.2 Proposed dragging jaw assembly

Once the current assembly is assessed, it is concluded that the following changes will result in a design that is more efficient and requires less assembly time.

- In Figure 3.2, it can be seen that the claws are connected to their respective mounting brackets through aluminum profiles. A total of twenty-four fasteners are used to connect the claws, aluminum profiles, and mounting brackets. This not only increases the assembly time but also the cost. In order to make the design more efficient, it is proposed to weld the claws with mounting brackets; it will help get rid of twenty-four fasteners and two aluminum profiles, which will decrease the assembly time significantly.

- In Figure 3.2, it can be seen that both claws move up and down independently through two pneumatic actuators. The pneumatic actuators are attached to the base plate through linear rails and bearings. A total of twenty-eight fasteners are used for this connection. The pneumatic actuators are attached to mounting brackets through four-foot mounts and a total of sixteen fasteners. The pneumatic actuator rods are connected to the bottom bracket through a total of four fasteners. In order to clamp the wood, the relative motion of both claws is not required. If the bottom claw is fixed and the top claw is allowed to move the clamping action can still be achieved. This will help remove a complete pneumatic actuator, linear rail, bearing and the respective fasteners, which will reduce the assembly time and ultimately the cost. The proposed dragging jaw assembly is illustrated in Figure 3.5 and the breakdown is illustrated in Table 3.7

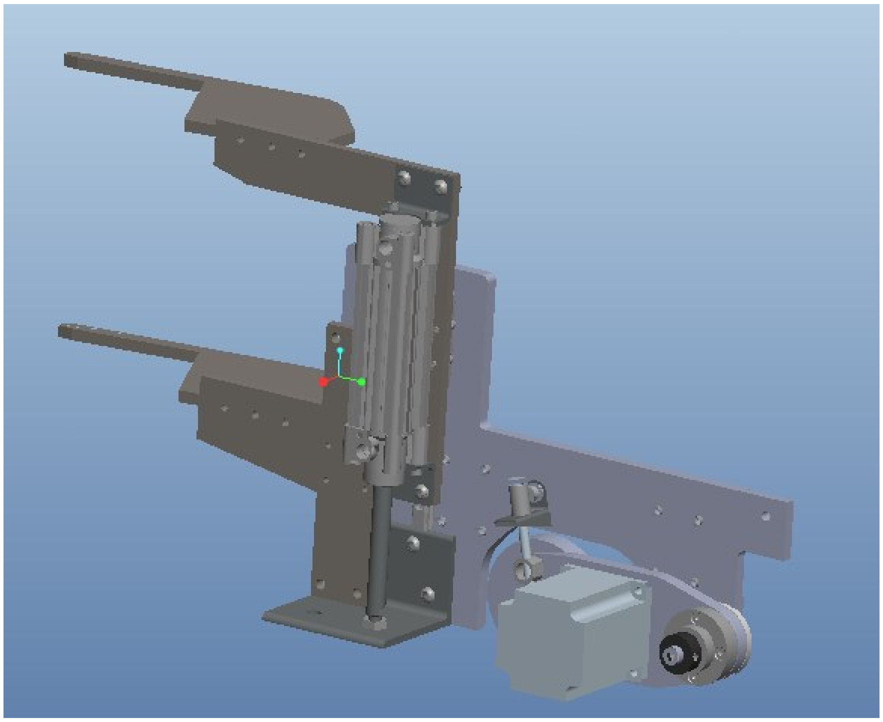


Figure 3.5 Proposed dragging jaw assembly

Table 3.7 DFA analysis of proposed dragging jaw

| *Part* | *Usage* | *Alpha* | *Beta* | *A+B* | *Handling code* | *Handling time (s)* | *Insertion code* | *Insertion time (s)* | *Total time (s)* |
|---|---|---|---|---|---|---|---|---|---|
| Linear rail | 1 | 180 | 180 | 360 | 10 | 1.50 | 06 | 5.50 | 7.00 |
| Bottom bracket | 1 | 360 | 360 | 720 | 30 | 1.95 | 06 | 5.50 | 7.45 |
| Foot mounts | 2 | 360 | 360 | 720 | 30 | 1.95 | 06 | 5.50 | 14.90 |
| Pneumatic actuator | 1 | 360 | 90 | 450 | 10 | 1.50 | 06 | 5.50 | 7.00 |
| Mounting bracket | 2 | 360 | 360 | 720 | 91 | 3.00 | 30 | 2.00 | 10.00 |
| Linear bearing | 1 | 360 | 360 | 720 | 30 | 1.95 | 06 | 5.50 | 7.45 |
| Claw | 2 | 360 | 360 | 720 | 91 | 3.00 | 94 | 7.00 | 20.00 |
| M8x1.25x30 bolt bottom bracket | 2 | 360 | 0 | 360 | 10 | 1.50 | 38 | 6.00 | 15.00 |
| M8x1.25x16 bolt bottom bracket | 2 | 360 | 0 | 360 | 10 | 1.50 | 38 | 6.00 | 15.00 |
| M5x0.8x20 bolt linear bearing | 4 | 360 | 0 | 360 | 10 | 1.50 | 38 | 6.00 | 30.00 |
| M4x0.7x25 bolt linear rail | 3 | 360 | 0 | 360 | 10 | 1.50 | 38 | 6.00 | 22.50 |
| M8x1.25x20 bolt foot mount | 4 | 360 | 0 | 360 | 10 | 1.50 | 38 | 6.00 | 30.00 |
| Pneumatic actuator bolt | 4 | 360 | 0 | 360 | 10 | 1.50 | 38 | 6.00 | 30.00 |
| Pneumatic actuator rods Nuts | 2 | 180 | 0 | 180 | 01 | 1.43 | 00 | 1.50 | 5.86 |
| M8x1.25x30 Nut bottom bracket | 2 | 180 | 0 | 180 | 01 | 1.43 | 00 | 1.50 | 5.86 |
| M8x1.25x16 Nut bottom bracket | 2 | 180 | 0 | 180 | 01 | 1.43 | 01 | 1.50 | 5.86 |
| M5x0.8x20 Nut linear bearing | 4 | 180 | 0 | 180 | 02 | 1.88 | 02 | 1.50 | 13.52 |
| M4x0.7x25 Nut linear rail | 3 | 180 | 0 | 180 | 02 | 1.88 | 03 | 1.50 | 10.14 |
| M8x1.25x20 Nut foot mount | 4 | 180 | 0 | 180 | 01 | 1.43 | 04 | 1.50 | 11.72 |
| Total | 46 | | | | | | | | 269.3 |

### 3.5.3 Discussion

The main portion of assembly time for both the assemblies is attributed to the fasteners, which indicates there is potential to improve the assembly time by reducing the number of fasteners. The total angle of symmetry for the main parts in both assemblies is greater than 360. The maximum total assembly time is associated with foot mounts. The design efficiency and assembly time, as illustrated in Table 3.6 for the current assembly, is calculated to be 4.0 % and 10.0 minutes respectively. The design efficiency and assembly time, as illustrated in Table 3.7 for the proposed assembly, comes out to be 7.8 % and 4.49 minutes respectively. The design efficiency is almost doubled and assembly time has been reduced by half. The number of parts has been reduced from 105 to 46. The comparison between the assemblies is summarized in Figure 3.6.

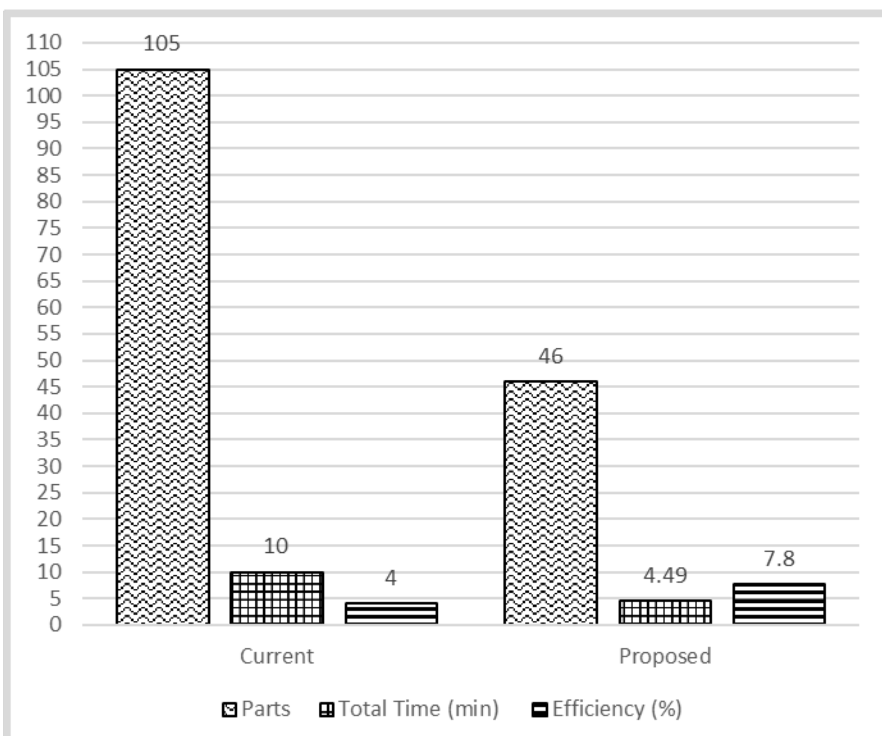



Figure 3.6 Comparison between current and proposed assemblies

### 3.6 Assembly time evaluation of controls

The key to a good mechatronics system is the optimized combination of both mechanical and electrical. Therefore, it is important to consider the electrical wiring and controls while creating the physical layer of a mechatronics system. Otherwise, even though the system is optimized from a mechanical point of view, the electrical wiring and controls have the potential to increase the assembly time of whole system. To demonstrate, assembly times for the current and proposed dragging jaw are calculated using the method given by Ong and Boothroyd (1991). The assembly attributes for electrical connections and wire harnesses are divided into four stages given as follows (Ong and Boothroyd 1991):

- Wire preparation: includes the measuring, cutting and stripping of wires, the crimping of terminals and lugs onto wires, and the fixing of wires and cables to connectors.
- Installation: includes the laying of wires and cable-connector assemblies.
- Securing: includes the tying of wires together.
- Attachment: includes the attachment of the wire ends to their termination point.

#### 3.6.1 Current dragging jaw control system

The controls of the current dragging jaw assembly consist of four single conductor wires which are labelled as w1, w2, w3, and w4 respectively, as shown in Figure 3.7, and the associated wire run list is illustrated in Table 3.8. These wires need to be manually cut and stripped from both ends so the conductors can be attached to the respective connection point. Once the wires are stripped, the next step is to tin them. After tinning, the wires are soldered with the wires on the solenoid valve. These wires can be tied using cable ties and contoured through a U-channel or cable tray to the control panel where the ends of the wires are connected to the output module. The output module is used to send a 24 VDC signal to turn on/off the valve. Each solenoid valve has one inlet for the air from the air compressor and two outlets for the pneumatic actuator. The pneumatic pipes labelled as p1, p2, p3, p4, p5, and p6 are treated as electrical wires that carry air and need to be cut, properly installed and secured.

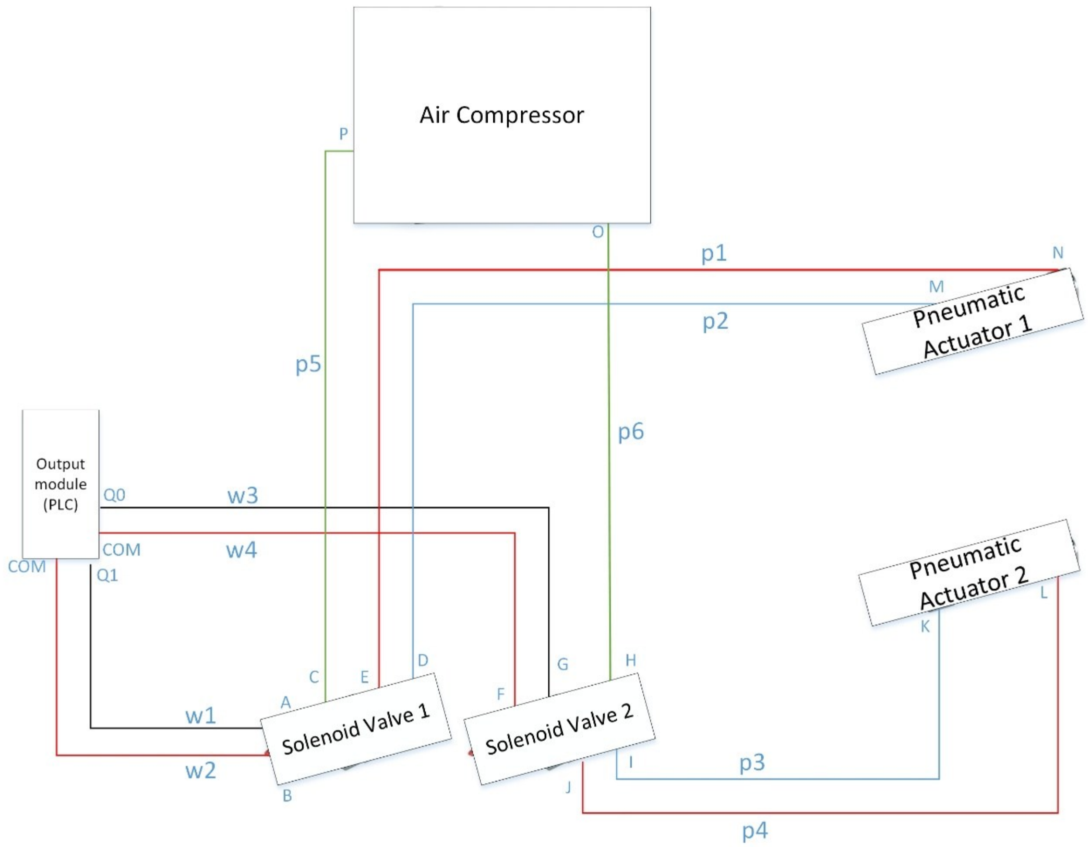



Figure 3.7 Current wiring layout for dragging jaw

Table 3.8 Wire run list for current dragging jaw

| *Wire* | *Length (ft)* | *From* | *Termination type* | *To* | *Termination type* |
|---|---|---|---|---|---|
| w1 flexible | 12 | A | tin and solder | Q1 | tin and terminal block |
| w2 flexible | 12 | B | tin and solder | COM | tin and terminal block |
| w3 flexible | 12 | G | tin and solder | Q0 | tin and terminal block |
| w4 flexible | 12 | F | tin and solder | COM | tin and terminal block |
| p1 flexible | 16 | E | friction | N | friction |
| p2 flexible | 16 | D | friction | M | friction |
| p3 flexible | 16 | I | friction | K | friction |
| p4 flexible | 16 | J | friction | L | friction |
| p5 flexible | 12 | C | friction | P | friction |
| p6 flexible | 12 | H | friction | O | friction |

The evaluation of the assembly times for the current dragging jaw is illustrated in Tables (3.9-3.11). It includes the time required to cut, strip, tin, solder, secure, and attach wires. In the case of pneumatic pipes, there is no need to strip, tin, and solder. The time will be taken only to pull the pipe to the desired length and then cut.

Table 3.9 Preparation time for current dragging jaw

| *Wire* | *Manual pull and cut (s)* | *Manual stripping both ends (s)* | *Tinning wire – soldering iron both ends (s)* | *Total (s)* |
|---|---|---|---|---|
| w1 flexible | 11.5 | 14 | 18 | 43.5 |
| w2 flexible | 11.5 | 14 | 18 | 43.5 |
| w3 flexible | 11.5 | 14 | 18 | 43.5 |
| w4 flexible | 11.5 | 14 | 18 | 43.5 |
| p1 flexible | 13.9 | - | - | 13.9 |
| p2 flexible | 13.9 | - | - | 13.9 |
| p3 flexible | 13.9 | - | - | 13.9 |
| p4 flexible | 13.9 | - | - | 13.9 |
| p5 flexible | 11.5 | - | - | 11.5 |
| p6 flexible | 11.5 | - | - | 11.5 |
| Total | | | | 252.6 |

Table 3.10 Installation and securing time for current dragging jaw

| *Wire* | *Dressing time (s)* | *Total (s)* | *Securing time (s)* | *Total (s)* |
|---|---|---|---|---|
| w1 flexible | - | - | - | - |
| w2 flexible | - | - | - | - |
| w3 flexible | - | - | - | - |
| w4 flexible | 23.1 | 23.1 | 14.4 | 86.4 |
| p1 flexible | - | - | - | - |
| p2 flexible | - | - | - | - |
| p3 flexible | - | - | - | - |
| p4 flexible | 29.9 | 20.9 | 14.4 | 57.6 |
| p5 flexible | - | - | - | - |
| p6 flexible | 23.1 | 23.1 | 14.4 | 86.4 |
| Total | - | 67.1 | - | 230.4 |

Table 3.11 Attachment time for current dragging jaw

| *Wire* | *Terminal block (s)* | *Soldering (s)* | *Friction one end(s)* | *Friction other end(s)* |
|---|---|---|---|---|
| w1 flexible | 13.9 | 8.5 | - | - |
| w2 flexible | 13.9 | 8.5 | - | - |
| w3 flexible | 13.9 | 8.5 | - | - |
| w4 flexible | 13.9 | 8.5 | - | - |
| p1 flexible | - | - | 6.7 | 6.7 |
| p2 flexible | - | - | 6.7 | 6.7 |
| p3 flexible | - | - | 6.7 | 6.7 |
| p4 flexible | - | - | 6.7 | 6.7 |
| p5 flexible | - | - | 6.7 | 6.7 |
| p6 flexible | - | - | 6.7 | 6.7 |
| Total | - | - | - | 170 |

### 3.6.2 Proposed dragging jaw controls system

The application of DFA on existing dragging jaw assembly resulted in getting rid of many parts. The removal of parts also removed the associated electrical connections, wires and controls signals from the assembly. For instance, instead of controlling two pneumatic actuators, only one is left in the proposed assembly shown in Figure 3.8. However, the control architecture remains same where a solenoid valve triggers upon receiving a signal from the output module. The number of wires has been reduced to half as illustrated in Table 3.12.

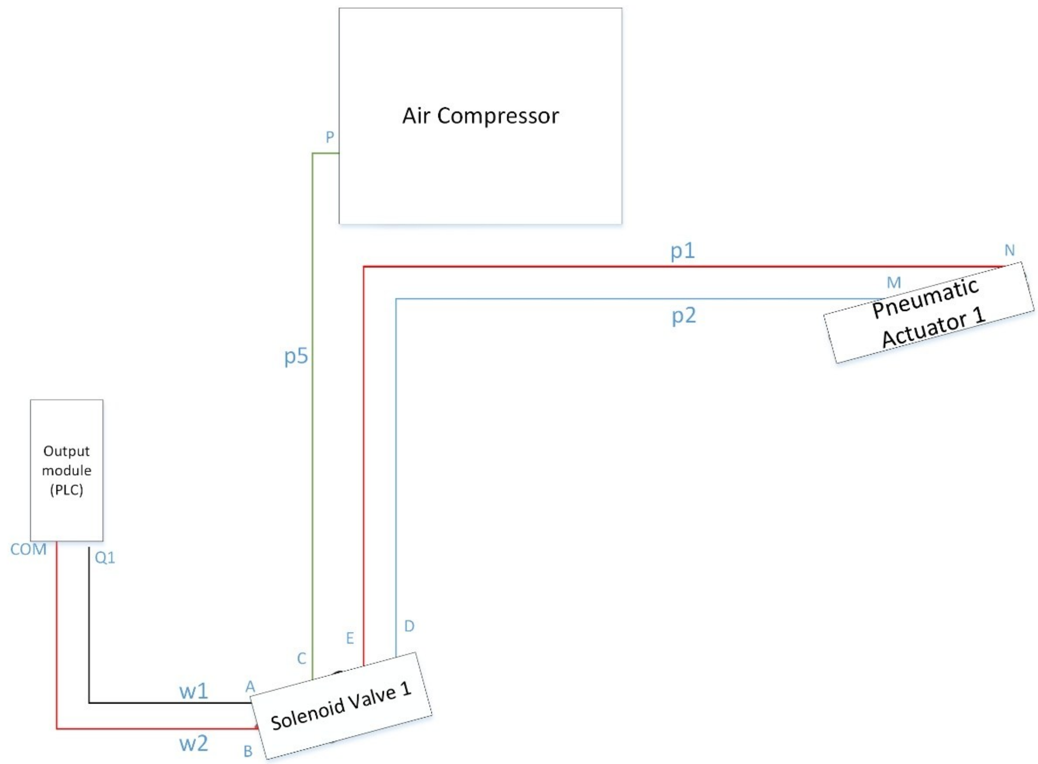



Figure 3.8 Wiring layout for proposed dragging jaw

Table 3.12 Wire run list for proposed dragging jaw

| *Wire* | *Length (ft)* | *From* | *Termination type* | *To* | *Termination type* |
|---|---|---|---|---|---|
| w1 flexible | 12 | A | tin and solder | Q1 | tin and terminal block |
| w2 flexible | 12 | B | tin and solder | COM | tin and terminal block |
| p1 flexible | 16 | E | friction | N | friction |
| p2 flexible | 16 | D | friction | M | friction |
| p5 flexible | 12 | C | friction | P | friction |

### 3.6.3 Discussion

Mechanical aside, the application of DFA resulted in significant improvements on the electrical side in terms of wiring attributes. In the proposed dragging jaw assembly, there has been reduction of one solenoid valve, one pneumatic actuator, three pneumatic pipes, and two electrical wires. The total assembly time has been reduced from 12 min to 7 min.

Table 3.13 Assembly times for current and proposed dragging jaw

| | *Preparation* | *Installation* | *Securing* | *Attachment* | *Total (s)* | *Total (min)* |
|---|---|---|---|---|---|---|
| Current | 326.8 | 67.1 | 230.4 | 95.8 | 720.1 | 12.00 |
| Proposed | 163.4 | 67.1 | 144 | 47.9 | 422.4 | 7.04 |

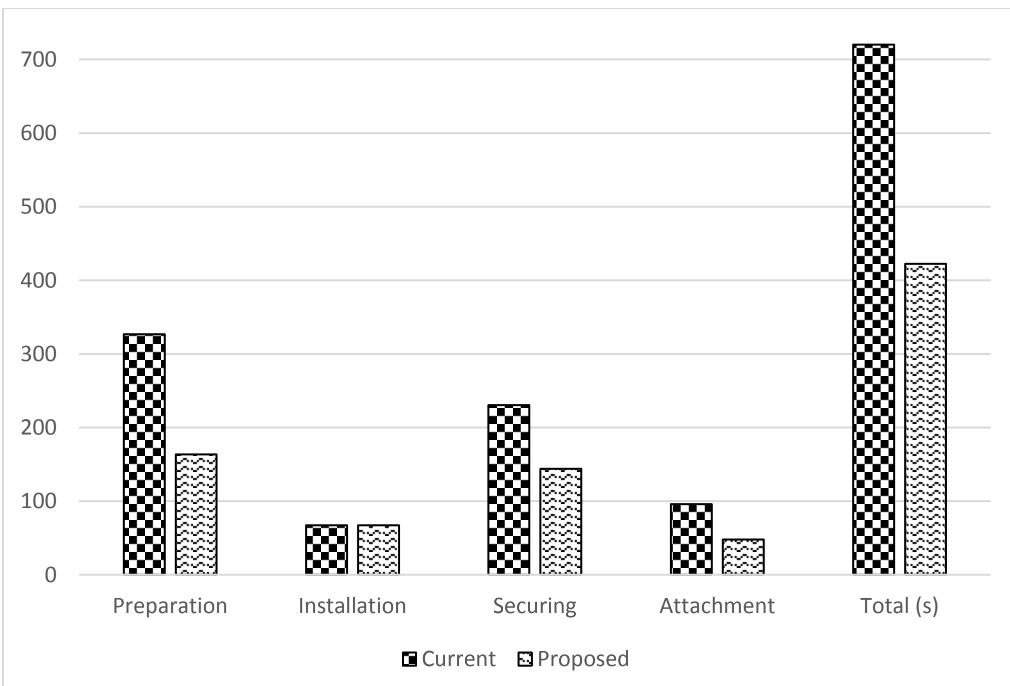



Figure 3.9 Wiring attributes current and proposed design

## 3.7 Controls complexity evaluation

The application of the DFA method as demonstrated in the previous section has resulted in significant improvement in assembly times. However, there is more potential in terms of diversity and information content when it comes to the controls system. Furthermore, multiple controls alternatives are available to achieve the same actuation, and each controls alternative brings different power and communication protocols. Therefore, it is of great interest to devise a systematic model to capture not only the assembly attributes but also the complexity of associated controls signals. The proposed model should aid the designers in comparing different controls alternatives and choosing the one best suited for their system in the early stages of design. The application of the proposed controls complexity model is demonstrated as follows.

### 3.7.1 Current dragging jaw controls complexity evaluation

The controls complexity is based on the complexity factors illustrated in Tables (3.1-3.5) and complexity equations (3.3-3.10). The average complexity factors for preparation, installation, securing, and attachment are calculated using equations (3.4-3.7). The complexity factor for each wire operation is calculated using Tables (3.1-3.5). The detailed evaluation of the controls complexity is illustrated in Tables (3.14-3.19).

Table 3.14 Preparation complexity attributes current dragging jaw

| *Wire* | *Number* | *Wire Cut* | *Manual Strip* | *Tin Wire* | *J* | *Sum* | *Cp* | *Sum . Cp* |
|---|---|---|---|---|---|---|---|---|
| w1 flexible | 4 | 5 | 1.4 | 1.58 | 3 | 7.98 | 2.66 | 21.22 |
| p1 flexible | 4 | 6.6 | 0 | 0 | 1 | 6.6 | 6.6 | 43.56 |
| p5 flexible | 2 | 5 | 0 | 0 | 1 | 5 | 5 | 25 |

Table 3.15 Installation complexity attributes current dragging jaw

| *Wire* | *Number* | *U-channel* | *K* | *Sum* | *Ci* | *Sum . Ci* |
|---|---|---|---|---|---|---|
| w1 flexible | 4 | 6.27 | 1 | 6.27 | 6.27 | 9.82 |
| p1 flexible | 4 | 8.19 | 1 | 8.19 | 8.19 | 16.7 |
| p5 flexible | 2 | 6.27 | 1 | 6.27 | 6.27 | 19.65 |

Table 3.16 Securing complexity attributes current dragging jaw

| *Wire* | *Number* | *Strap onto cable* | *L* | *Sum* | *Cs* | *Sum . Cs* |
|---|---|---|---|---|---|---|
| w1 flexible | 4 | 1.07 | 1 | 1.07 | 1.07 | 0.28 |
| p1 flexible | 4 | 1.07 | 1 | 1.07 | 1.07 | 0.28 |
| p5 flexible | 2 | 1.07 | 1 | 1;07 | 1.07 | 0.57 |

Table 3.17 Installation complexity attributes current dragging jaw

| *Wire* | *Number* | *Terminal block One End* | *Solder at other end* | *M* | *Sum* | *Ca* | *Sum . Ca* |
|---|---|---|---|---|---|---|---|
| w1 flexible | 4 | 1.15 | 0.61 | 2 | 1.76 | 0.88 | 1.5488 |
| p1 flexible | 4 | 0.49 | 0.49 | 2 | 0.98 | 0.49 | 0.4802 |
| p5 flexible | 2 | 0.49 | 0.49 | 2 | 0.98 | 0.49 | 0.4802 |

Table 3.18 Controls complexity index calculation current dragging jaw

| *Wire* | *Number* | $C_{wire}$ | $x_w$ | $CI_{wire} = x_p . C_{wire}$ |
|---|---|---|---|---|
| w1 | 4 | 1.92 | 0.4 | 0.770 |
| p1 | 4 | 5.29 | 0.4 | 2.116 |
| p5 | 2 | 3.43 | 0.2 | 0.686 |
| $CI_{system}$ | | | | 3.57 |

Table 3.19 Total and unique controls signals current dragging jaw

| *Signals* | $N_c$ | $n_c$ |
|---|---|---|
| Solenoid valve 1: 24V | 1 | - |
| Solenoid valve 1: 0V | 1 | - |
| Solenoid valve 2: 24V | 1 | 1 |
| Solenoid valve 2: 0V | 1 | 1 |
| Total | 4 | 2 |

The controls complexity of the whole system is calculated using the equation (3.3). There is a total of ten wires out of which three are unique. The installation and securing attributes values are divided by number of respective wires. The controls system complexity index takes into account the percentage of each dissimilar wire and the weighted average value of each wire. The complexity index is calculated as 3.57 using equation (3.10). A typical solenoid valve requires a positive and negative electrical polarity to operate. Therefore, a total of four electrical polarities are required in order to operate two solenoid valves.

$$C_{system} = \left[\frac{3}{10} + 3.57\right] [\log_2(10+1)] + \left[\frac{2}{4}\right] [\log_2(4+1)]$$

$$C_{system} = 14.55$$

### 3.7.2 Proposed dragging jaw controls complexity evaluation

The proposed controls system is shown in Figure 3.8. There is a significant reduction in the number of wires. However, the type of wires and the associated assembly operations are same. The detailed evaluation of the control complexity for the proposed dragging jaw is illustrated in Tables (3.20-3.24).

Table 3.20 Preparation complexity attributes proposed dragging jaw

| *Wire* | *Number* | *Wire Cut* | *Manual Strip* | *Tin Wire* | *J* | *Sum* | *Cp* | *Sum . Cp* |
|---|---|---|---|---|---|---|---|---|
| w1 flexible | 2 | 5 | 1.4 | 1.58 | 3 | 7.98 | 2.66 | 21.23 |
| p1 flexible | 2 | 6.6 | 0 | 0 | 1 | 6.6 | 6.6 | 43.56 |
| p5 flexible | 1 | 5 | 0 | 0 | 1 | 5 | 5 | 25 |

Table 3.21 Installation complexity attributes proposed dragging jaw

| *Wire* | *Number* | *U-channel* | *K* | *Sum* | *Ci* | *Sum . Ci* |
|---|---|---|---|---|---|---|
| w1 flexible | 2 | 6.27 | 1 | 6.27 | 6.27 | 19.65 |
| p1 flexible | 2 | 8.19 | 1 | 8.19 | 8.19 | 33.54 |
| p5 flexible | 1 | 6.27 | 1 | 6.27 | 6.27 | 39.31 |

Table 3.22 Securing complexity attributes proposed dragging jaw

| *Wire* | *Number* | *Strap onto cable* | *L* | *Sum* | *Cs* | *Sum . Cs* |
|---|---|---|---|---|---|---|
| w1 flexible | 2 | 1.07 | 1 | 1.07 | 1.07 | 0.57 |
| p1 flexible | 2 | 1.07 | 1 | 1.07 | 1.07 | 0.57 |
| p5 flexible | 1 | 0 | 0 | 0 | 0 | 0 |

Table 3.23 Attachment complexity attributes proposed dragging jaw

| *Wire* | *Number* | *Terminal block One End* | *Solder at other end* | *M* | *Sum* | *Ca* | *Sum* **.** *Ca* |
|---|---|---|---|---|---|---|---|
| w1 flexible | 2 | 1.15 | 0.61 | 2 | 1.76 | 0.88 | 1.55 |
| p1 flexible | 2 | 0.49 | 0.49 | 2 | 0.98 | 0.49 | 0.48 |
| p5 flexible | 1 | 0.49 | 0.49 | 2 | 0.98 | 0.49 | 0.48 |

Table 3.24 Controls complexity index calculation proposed dragging jaw

| *Wire* | *Number* | $C_{wire}$ | $x_w$ | $CI_{wire} = x_w \cdot C_{wire}$ |
|---|---|---|---|---|
| w1 | 2 | 2.52 | 0.4 | 1.01 |
| p1 | 2 | 4.64 | 0.4 | 1.86 |
| p5 | 1 | 5.29 | 0.2 | 1.06 |
| $CI_{system}$ | | | | 3.92 |

The controls complexity of the whole system is calculated using the equation (3.3). The complexity index is calculated as 3.92 using equation (3.10). A total of two electrical polarities are required as there is only one solenoid valve, and both the polarities are unique.

$$C_{system} = \left[\frac{3}{5} + 3.92\right] [\log_2(5+1)] + \left[\frac{2}{2}\right] [\log_2(2+1)]$$

$$C_{system} = 13.27$$

### 3.7.3 Discussion

The Figure 3.10 summarizes the assembly times for mechanical parts, electrical wiring and controls complexity of current and proposed design. There is no significant difference in controls complexity due to similar nature of wiring and associated controls signals. The assembly time for electrical connections and wire harnesses is greater than assembly time of mechanical parts in both current and proposed design. However, controls complexity is directly related to assembly time.

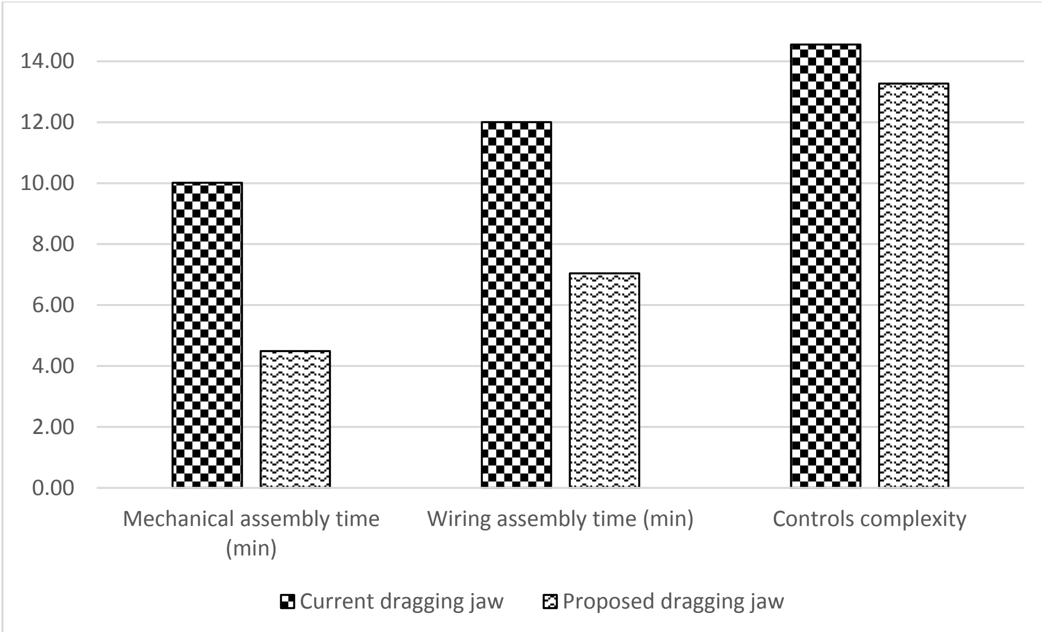



Figure 3.10 Comparison between current and proposed design

### 3.8 Controls alternatives

Typically, pneumatic actuators have been used for light loads and only for travel between two positions. Each end of the travel is controlled by mechanical limits or hard stops. The primary objective of these actuators is to provide actuation between two set points. Pneumatic systems may have maintenance issues due to impurities in the pressure and return lines. Electromechanical actuators, however, offer greater strength with more precise movement and motion control. This precise movement and motion control bring additional wires, connections and require further knowledge of associated controls signals. The proposed complexity model will assist the designer to compare different controls choices available. For instance, actuation between two set points can be achieved through a pneumatics-based control, conventional bipolar stepper and Ethernet-based stepper. However, each of the aforementioned controls solution bring different controls challenges in terms of wiring, connections, harnesses, and controls signals. The designer should have a metric to foresee these challenges in the early design stages. This is demonstrated in the following sections:

### 3.8.1 Bipolar stepper motor – controls alternative #1

Stepper motors are DC motors and are widely used in many industrial applications. These motors are best suited in applications where precision and discrete motion is required. Instead of using a pneumatic actuator, it would be of great interest to see how the controls complexity of the system will change if a bipolar stepper motor is used. The wiring layout for a bipolar stepper motor is shown in Figure 3.11.

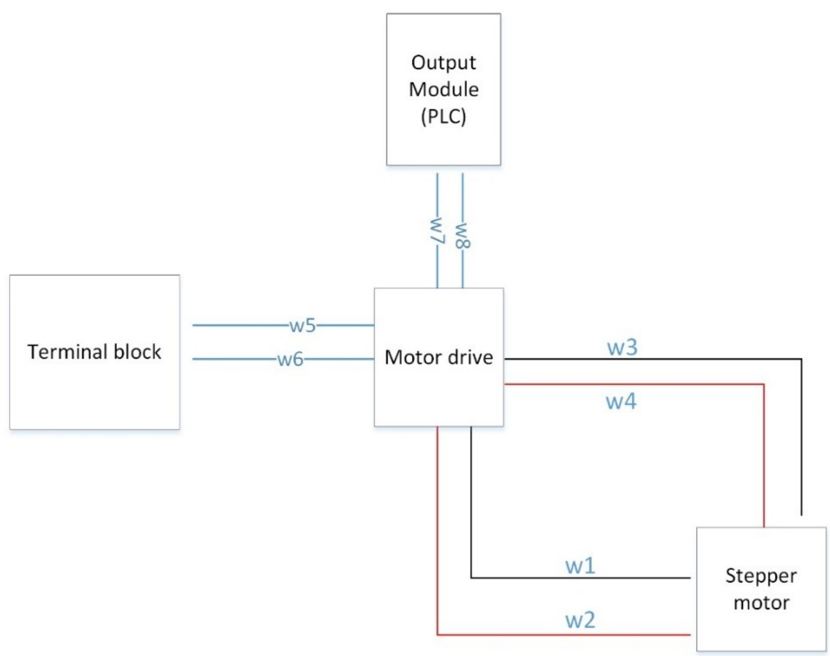



Figure 3.11 Wiring layout of a bipolar stepper motor

Table 3.25 illustrates the wire run list that contains information about all wires in a controls system, for instance, type, length, and connectors. Table 3.26 illustrates total and unique controls signals associated with a bipolar stepper motor and its drive. For instance, pulse, direction, motor phases, and power.

Table 3.25 Wire run list for bipolar stepper

| *Wire* | *Length (ft)* | *From* | *Termination type* | *To* | *Termination type* |
|---|---|---|---|---|---|
| w1 flexible | 24 | A | tin and solder | B | tin and terminal block |
| w2 flexible | 24 | C | tin and solder | D | tin and terminal block |
| w3 flexible | 24 | E | tin and solder | F | tin and terminal block |
| w4 flexible | 24 | G | tin and solder | H | tin and terminal block |
| w5 flexible | 2 | I | tin and terminal block | J | tin and terminal block |
| w6 flexible | 2 | K | tin and terminal block | L | tin and terminal block |
| w7 flexible | 1 | M | tin and terminal block | N | tin and terminal block |
| w8 flexible | 1 | O | tin and terminal block | P | tin and terminal block |

Table 3.26 Total and unique controls signals bipolar stepper

| *Signals* | $N_c$ | $n_c$ |
|---|---|---|
| Pulse | 1 | 1 |
| Direction | 1 | 1 |
| Enable | 1 | 1 |
| Motor phase A+ | 1 | - |
| Motor phase A- | 1 | - |
| Motor phase B+ | 1 | - |
| Motor phase B- | 1 | - |
| 48V | 1 | 1 |
| 0V | 1 | 1 |
| Total | 9 | 5 |

The controls complexity of the whole system is calculated using the equation (3.3). There is a total of eight wires out of which three are unique. The complexity index is calculated as 5.33 using equation (3.10). There is a total of eight controls signals out of which five are unique. The power source used to power the stepper drive is the same source which appears across different motor phases. There is a significant increase in the complexity. The increase in complexity is resulted due to the assembly attributes of wires and the increased information content of associated controls signals.

$$C_{system} = \left[\frac{3}{8} + 5.33\right] [\log_2(8+1)] + \left[\frac{5}{9}\right] [\log_2(9+1)]$$

$$C_{system} = 19.93$$

### 3.8.2 Schneider Lexium Mdrive - controls alternative #2

Although bipolar steppers are cost-effective, they introduced a significant increase in controls complexity. Ethernet/IP architecture is effective in reducing the number of wires where a single cable can carry multiple signals. Apart from better cable management, it also provides better communication and flexibility in terms of remote monitoring. An alternative to bipolar steppers would be to use a costly Schneider Lexium Mdrive Ethernet -based stepper. The wiring layout is shown in Figure 3.12. It is assumed that the cables are premade, which reduces the assembly time significantly; however, the controls signals diversity has increased.

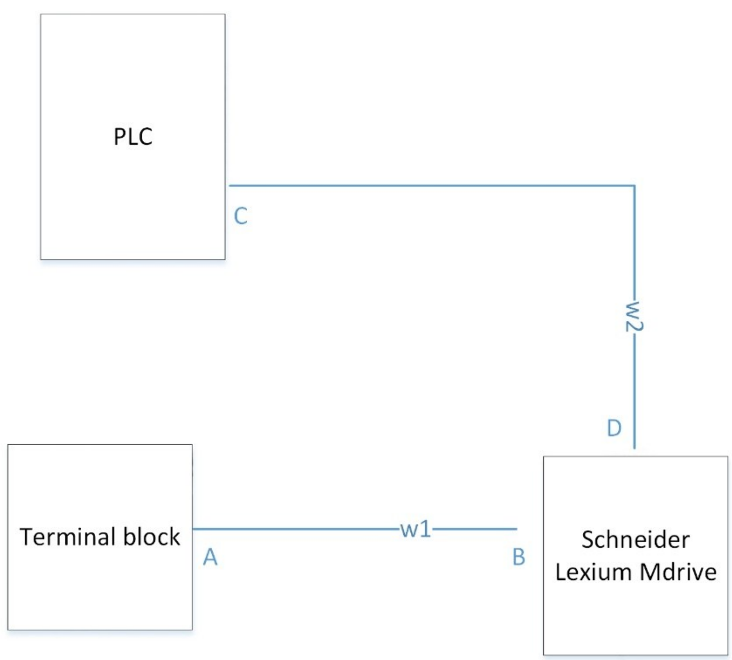



Figure 3.12 Wiring layout of a Schneider lexium Mdrive

Table 3.27 shows the wire run list for an Ethernet-based stepper and Table 3.28 illustrates the associated controls signals. The individual wires and controls signals are carried through a coated multi-conductor cable. One cable is used to transmit power which further carries two conductors for opposite electrical polarities. The second cable is used to transmit and receive controls signals between the control unit and the stepper drive. This cable has four conductors that further carries four different controls signals.

Table 3.27 Wire run list for lexium Mdrive

| *Wire* | *Length (ft)* | *No of conductors* | *From* | *Termination type* | *To* | *Termination type* |
|---|---|---|---|---|---|---|
| w1 multi-conductor | 24 | 2 | A | terminal block | B | M12 |
| w2 multi-conductor | 24 | 4 | C | RJ45 | D | M12 |

Table 3.28 Total and unique controls signals Ethernet-based stepper

| *Signals* | $N_c$ | $n_c$ |
|---|---|---|
| TX- | 1 | 1 |
| TX- | 1 | 1 |
| RX- | 1 | 1 |
| RX+ | 1 | 1 |
| 48V | 1 | 1 |
| 0V | 1 | 1 |
| Total | 6 | 6 |

Multiconductor cables and special connectors, for instance, M12 and RJ45 are required for the proposed controls alternative. Furthermore, the controls signals are also diverse in nature but still, there is a significant decrease in the overall complexity due to the assumption that cables are premade. However, the information content and diversity in controls signals is maximum for Ethernet-based stepper solution.

$$C_{system} = \left[\frac{2}{2} + 3.23\right] [\log_2(2+1)] + \left[\frac{6}{6}\right] [\log_2(6+1)]$$

$$C_{system} = 9.51$$

### 3.9 Discussion

The results show that controls complexity is directly related to assembly times as shown in Figure 3.13. The assembly times for bipolar stepper and current pneumatic-based controls are almost the same due to more or less the same number of wires and associated connections. However, the least assembly time is for Schneider Mdrive due to only two cables and which are premade. The preparation time is taken to strip one end of the multi-conductor cable for power and then attach it to terminal blocks inside the control panel. The conductors inside the cables are already coated with strong insulation and need no further securing and labeling as the individual wires required in case of a bipolar stepper

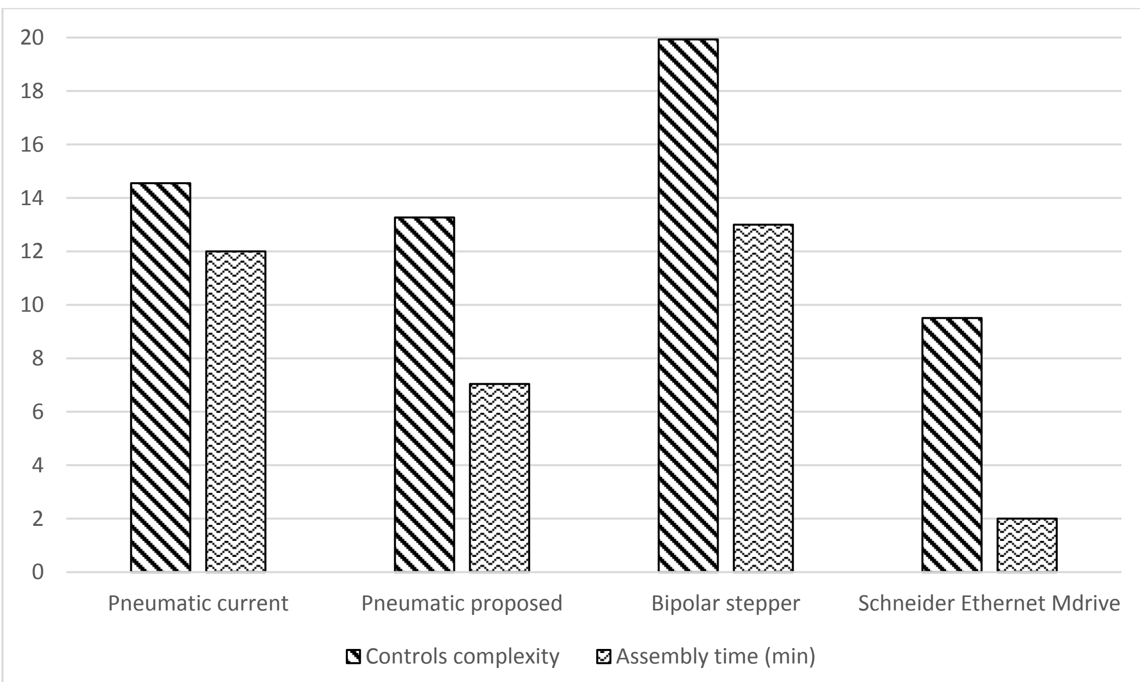



Figure 3.13 Controls complexity and assembly time comparison of studied controls solutions

The controls complexity is divided into two halves as shown in Figure 3.14. The first half takes into account the assembly attributes for electrical connections and wire harnesses and the second half includes the diversity and information content of associated controls signals. It can be seen that the overall controls complexity is least for Schneider Ethernet Mdrive. However, the complexity of the associated controls signals is maximum. The interesting results are reported in pneumatic-based controls. Although the assembly complexity is reduced in case of proposed pneumatic-based controls, but the diversity and information content of associated controls signals are increased.

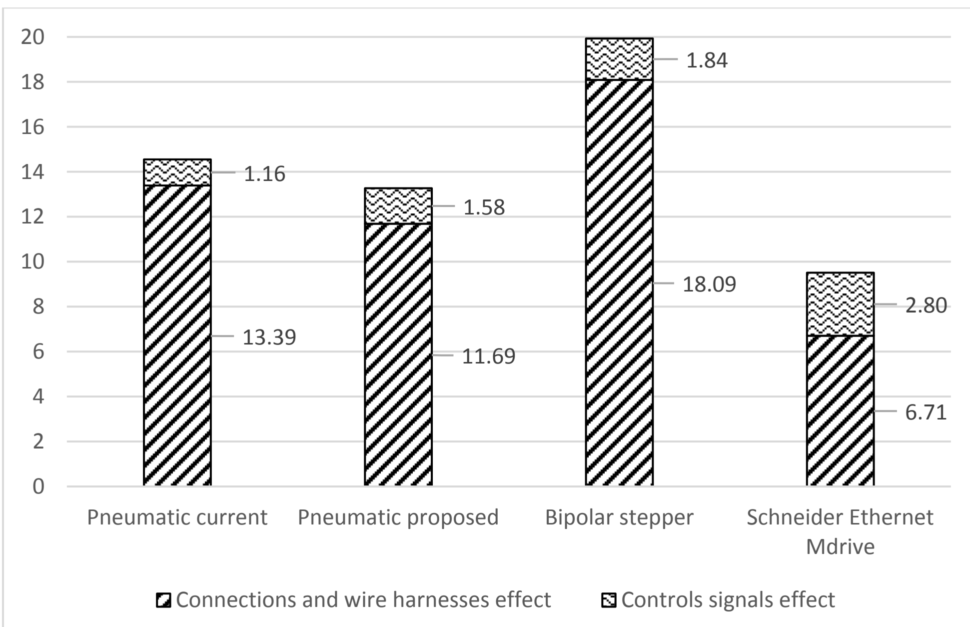



Figure 3.14 Controls complexity breakdown

### 3.10 Conclusion

The need for automation has increased significantly over the last few decades. The automation introduces complex electric wiring, connections, and controls signals in modern mechatronics systems. Complexity is considered an important factor contributing to difficulties faced in manufacturing. Therefore, while designing a system, controls complexity is equally important to consider along with mechanical. This paper presents a new model for measuring controls complexity by incorporating the principles of assembly complexity model, information content, and assembly attributes for electrical connections and wire harnesses. Controls complexity is defined as the degree to which individual wires/cables are prepared, assembled, installed, attached and the diversity in the controls signals. To demonstrate the application of the proposed model, a sub-assembly in a semi-automatic machine is used with three different controls alternatives: pneumatics, bipolar stepper, and Ethernet-based stepper. The results show; (i) the importance of electrical wiring through calculation of assembly times for both mechanical parts and electrical connections and wire harnesses. It further vindicates that the time required to assemble wires can outweigh the time required to assemble mechanical parts, (ii) the assembly time for electrical connections and wire harnesses is directly related to controls complexity, and (iii) the information content and diversity in controls signals increase as the nature of controls system changes from basic controls in case of pneumatics to a conventional stepper and then further to a more sophisticated Ethernet-based stepper. Hence, the proposed model is a productive tool for the designers in the early stages of design, to be aware of complexity they are going to introduce in the system by making certain controls decisions.

## Chapter 4 A study to investigate the effect of control system on design and complexity, using a saw cutting machine as a case study[3]

This chapter presents a study to investigate the link between design, complexity, and controls shown in Figure 4.1. It further aims to improve the design and reduce complexity in the early design stages through a control system implementation. To demonstrate, a concept of a saw cutting machine (SCM) is presented using Axiomatic Design (AD) to ensure design objectives such as safety, user comfort, usage on a domestic scale and capability to cut wood and aluminum. In the presented case study, the mapping from Customer Attributes (CAs) to Functional Requirements (FRs) and then respective Design Parameters (DPs) resulted in a coupled design. A complete controls system strategy is devised to reduce the complexity by uncoupling the design.

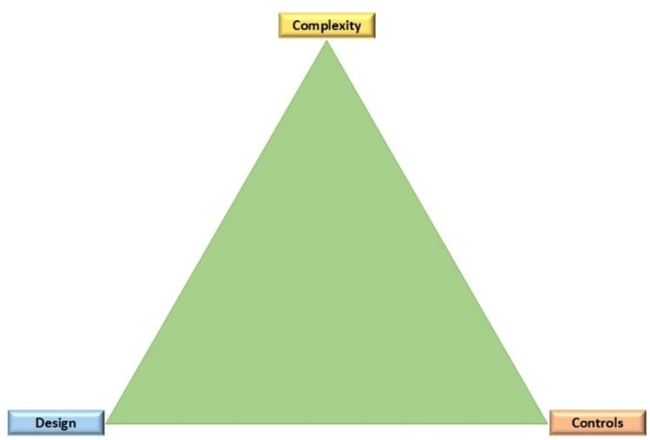



Figure 4.1 Complexity, design and controls triangle

[3] The Chapter 4 of this thesis is an extension of my work which has been published in the proceedings of International Conference on Informatics in Control, Automation, and Robotics (ICINCO), Porto, Portugal

## 4.1 Introduction

Forest products are a major contributor to the Canadian economy. In 2013, production in the forestry sector contributed $19.8 billion to the economy. In a global context, Canada has the world's largest forest product trade balance. The aluminum industry is another important sector of Canada's economy, with aluminum products export valued at $10.8 billion in 2016, an increase of $211 over 2015; (Canada ranks third in aluminum production in the world after China, and Russia) (Canada, 2013). The motivation for the development of the saw cutting machine (SCM) described in this chapter arose out of a broader research initiative at the University of Alberta (Canada) to develop a semi-automated wood framing machine (Figure 3.1) and a semi-automated light-gauge steel framing machine (Figure 4.2). The primary objective of both machine development projects is to support the growth of panelized construction in North America's building construction sector. The structures of both machines consist of aluminum extrusions that need to be cut in different lengths and angles. The lab has to outsource the cutting to third-party companies, resulting in increased costs and delays of the machine development program. In order to overcome the aforementioned challenges, the research team began investigating SCM solutions with the design objectives of (1) the ability to cut both wood and aluminum, (2) versatility to be deployed in a lab or domestic scale without three-phase industrial power supply or complex pneumatics, (3) safety mechanisms to enable safe use, and (4) capable of angled cutting started and resulted in a design discussed in the following sections.


Figure 4.2 Steel framing machine

Table saws are associated with more injuries than any other type of woodworking tool. Shields, Wilkins and Smith (2011) estimate that 565,670 table-saw related injuries were treated in the United States during the period 1990‑2007. Injuries to fingers/thumbs were the most common overall (86%–486,181 of 565,670). Chung and Shauver (2013) discuss SawStop, a technology designed to stop the saw blade when contact is made with skin, resulting in a small cut rather than a serious laceration or amputation. A few disadvantages associated with SawStop, though, are that the force required to quickly stop the saw blade damages the blade and brake beyond repair such that they must be replaced each time the brake is triggered; furthermore, the brake cartridges are blade-specific; there are no brakes available for some specialty blades; and brakes can only be used when cutting nonconductive materials. Graham and Chang (2015) provide a quantitative estimate of the economic benefits of automatic protection systems that could be deployed in new table saw products. The general consensus among researchers is that the benefits of automatic protection are likely to outweigh the incremental costs of implementation significantly.

Schwaneberg et al. (2012) discussed the use of a LED-based sensor system to distinguish human skin from work pieces. In this context, it is thus of interest to investigate new technology to automate the process by designing a machine using a systematic method of design. Farid and Suh (2016) Axiomatic design is a design method introduced by Nam P. Suh. It consists of four domains: consumer, functional, physical, and process. These domains are interlinked in such a way that customer needs—referred to as customer attributes (CAs)—in the customer domain are transformed into functional requirements (FRs) in the functional domain. FRs, in turn, are satisfied by design parameters in the physical domain. Process variables (PVs) are determined from DPs in the same manner. Axiomatic design as described above has been used in many fields, such as software design (Suh and Do, 2000) and control system design (Lee, Suh and Oh, 2001). Negahban and Smith (2014) provide a comprehensive review of discrete-event simulation in which the discrete-event model of a system can be implemented using a computer. This simulation-based approach can aid in understanding the system under study in terms of cycle time, utilization of different resources, improvements in design, and production levels.

### 4.2 Methodology

In order to overcome design limitations in the existing designs and to come up with a new one, it is suggested to use a systematic design approach, for instance, Axiomatic Design. The benefits of using a systematic design approach are; (i) make the thinking process more creative, (ii) streamline the designer's direction, and (iii) provides a metric for the different designs to be compared. In a design process, conceptual and detailed designs are crucial design stages as they shape most of the design characteristics. Therefore, Axiomatic Design is used in the conceptual stage to systematically transform the CAs or design objectives into FRs and then respective DPs. The SCM is expected to meet the following design objectives; (i) capable of cutting both wood and aluminum, (ii) can be used at domestic scale, (iii) ensure safety and operator comfort, and (iv) can accommodate angled cutting. Computer Aided Design (CAD) model of the SCM is developed in SOLIDWORKS. Control system of the SCM is realized on Programmable Logic Controller (PLC) using Sequential Function Chart (SFC) which is one of the IEC 61131-3 languages. In order to estimate the performance of the machine, discrete-event modelling technique is used.

### 4.3 Axiomatic Design

Axiomatic Design (AD) proposed by Nam P. Suh in 1990 is a process design method. It consists mainly of axioms and theorems. The design process is governed by axioms, one is the independence axiom that keeps the independence of functional requirements (FRs), and the other is information axiom that deals with information content. Design process in Axiomatic Design is top-down, in which the initial concept is decomposed to design details. The relationship between FRs and DPs is given as (Suh 1998):

$$\{FRs\} = [A]\{DPs\} \tag{4.1}$$

FRs are a minimum set of independent requirements that completely characterize the functional needs of the product in the functional domain. Each FR is independent of every other FR at the time the FRs are created. [A] is defined as the design matrix. When [A] is the diagonal matrix, the design is called uncoupled design. When [A] is lower triangular matrix, the design is called decoupled and preferred in absence of uncoupled design, while all the other designs are called coupled (Figure 4.3). DPs are the physical variables in the physical domain that characterize the design that satisfies the specified FRs.

$$\begin{bmatrix} FR1 \\ FR2 \\ FR3 \\ FR4 \\ FR5 \end{bmatrix} = \begin{bmatrix} X & 0 & 0 & 0 & 0 \\ 0 & X & 0 & 0 & 0 \\ 0 & 0 & X & 0 & 0 \\ 0 & 0 & 0 & X & 0 \\ 0 & 0 & 0 & 0 & X \end{bmatrix} \begin{bmatrix} DP1 \\ DP2 \\ DP3 \\ DP4 \\ DP5 \end{bmatrix} ; \begin{bmatrix} FR1 \\ FR2 \\ FR3 \\ FR4 \\ FR5 \end{bmatrix} = \begin{bmatrix} X & 0 & 0 & 0 & 0 \\ X & X & 0 & 0 & 0 \\ X & X & X & 0 & 0 \\ X & X & X & X & 0 \\ X & X & X & X & X \end{bmatrix} \begin{bmatrix} DP1 \\ DP2 \\ DP3 \\ DP4 \\ DP5 \end{bmatrix} ; \begin{bmatrix} FR1 \\ FR2 \\ FR3 \\ FR4 \\ FR5 \end{bmatrix} = \begin{bmatrix} X & X & X & X & X \\ X & X & X & X & X \\ X & X & X & X & X \\ X & X & X & X & X \\ X & X & X & X & X \end{bmatrix} \begin{bmatrix} DP1 \\ DP2 \\ DP3 \\ DP4 \\ DP5 \end{bmatrix}$$

Figure 4.3 (a) uncoupled; (b) decoupled; (c) coupled

### 4.3.1 Complexity in perspective of AD

Complexity is defined by Suh (1999) as a measure of uncertainty in achieving functional requirements. The probabilistic definition of complexity is expressed as the success of achieving the Functional Requirements (FRs). Suh further divides the complexity into:

- Time independent real complexity
- Time independent imaginary complexity
- Time dependent combinatorial complexity
- Time dependent periodic complexity

Common area between the design range and the system range determines the probability of achieving a FR. This common area is called common range. Thus, the real complexity is related to the information content, which is defined in terms of the probability. Real complexity associated with a coupled design is greater than an uncoupled or decoupled designs that satisfy the same set of FRs. Existence of real complexity is independent of the satisfaction of independence axiom. Suh (1999) defines the information content in terms of probability of success of achieving the desired FRs as:

$$I = \sum_{i=1}^{n} log_2 \left(\frac{1}{P_i}\right) \qquad (4.2)$$

where:

- $P_i$ = probability of achieving $FR_i$
- n = total number of FRs

The conversion of a design from a coupled to an uncoupled or a decoupled design reduces the real complexity. In the case of uncoupled designs, the FRs are not affected by each other due to which information content can be minimized. Real complexity in case of a coupled design can be altered. However, all the FRs may change when one of the DPs is modified due to which significance of least information content for each FR has no value (Suh 1999).

### 4.3.2 SCM Axiomatic Design

The axiomatic design of SCM has three parts: CAs, FRs, and DPs. At the beginning of the design process, the needs of the customers (i.e., CAs) are taken into account in order to generate the FRs and then the DPs. The top-level design is given as follows:

CA: Wood and aluminum cutting capability, safety, user comfort, usage on a domestic scale, and angled cutting capability.

$FR_0$: Carry saw, motors, sensors (electrical components) inside a safe cabinet (mechanical)

$DP_0$: Programmable logic controller (PLC)-controlled saw cutting machine

After the top level design, FRs and DPs are decomposed and second level FRs and DPs are illustrated in Table 4.1.

Table 4.1 Second level design matrix

| FRs/DPs | 1 Cut wood | 2 Cut aluminum | 3 Stepper motors & HMI | 4 Single phase power supply & force controlled actuators | 5 Rotary table | 6 Sensors based mechanical assembly |
|---|---|---|---|---|---|---|
| 1 Need to cut wood | x | x | | | | |
| 2 Need to cut aluminum | x | x | | | | |
| 3 Facilitate operator | | | x | | | |
| 4 Industry power & pneumatics alternative | | | | x | | |
| 5 Angle cut | | | | | x | |
| 6 Safety | | | | | | x |

The FRs and DPs keep on decomposing until they take their final form. The $FR_{1-2}$ and $DP_{1-2}$ are of our interest as coupling is found and this coupling is restricting the existing design to cut both materials. Table 4.2 illustrates the coupling in low level $FR_{1-2}$ and $DP_{1-2}$.

Table 4.2 Low level design matrix

| FRs/DPs | 1 Cut wood | 2 Cut aluminum | 1.1 Cutting RPM | 1.2 Cutting feed speed |
|---|---|---|---|---|
| 1 Need to cut wood | x | | | |
| 1.1 Use cutting RPM | | | x | x |
| 1.2 Use feed speed | | | x | x |
| 2 Need to cut aluminum | | x | | |
| 2.1 Use cutting RPM | | | x | x |
| 2.2 Use feed speed | | | x | x |

The one obvious coupling which is not discussed for this case study is the type of saw. A universal saw is proposed to uncouple the design; although this will compromise the quality of the cut in the case of aluminum, it satisfies the design objectives and the purpose for which the machine is being designed.

$$Feed\ speed = \frac{RPM \times no\ of\ teeth \times Chip\ load}{12} \tag{4.3}$$

where:

- Feed speed: inches per minute
- RPM: revolutions per minute
- Chip load: inches

The initial design results in a coupled design as illustrated in Table 4.1 due to the fact that existing design is unable to provide feed speed and RPM expressed in (equation 4.3) for both materials. The first step towards uncoupling the initial design is permutation that resulted in a better design but still a coupled one (Table 4.3).

Feed speed and RPM have to be adjusted according to the material being cut. The Table 4.3 provides a key information about the limitations in our design, that FRs are greater than DPs. In order to meet the design objective of cutting both wood and aluminum and as per the AD principles, it is suggested to add more DPs to meet the design objectives and make the design matrix square (Table 4.4).

Table 4.3 Design matrix after permutation

| FRs/DPs | 1 Cut wood | 1.1 Cutting RPM | 1.2 Cutting feed speed | 2 Cut aluminum |
|---|---|---|---|---|
| 1 Need to cut wood | x | | | |
| 1.1 Use cutting RPM | | x | x | |
| 1.2 Use feed speed | | x | x | |
| 2 Need to cut aluminum | | | | x |
| 2.1 Use cutting RPM | | x | x | |
| 2.2 Use feed speed | | x | x | |

Table 4.4 Uncoupled design

| FRs/DPs | 1 Cut wood | 1.1 Cutting wood RPM | 1.2 Cutting wood feed speed | 2 Cut aluminum | 2.1 Cutting aluminium RPM | 2.2 Cutting aluminium feed speed |
|---|---|---|---|---|---|---|
| 1 Need to cut wood | x | | | | | |
| 1.1 Use cutting RPM | | x | | | | |
| 1.2 Use feed speed | | | x | | | |
| 2 Need to cut aluminum | | | | x | | |
| 2.1 Use cutting RPM | | | | | x | |
| 2.2 Use feed speed | | | | | | x |

A controls system solution is proposed to uncouple the design by setting the desired RPM and feed speed based on the material being cut. The lowest level decomposition of FRs and DPs is illustrated in Table 4.5.

Table 4.5 Detailed low level design matrix

| FRs/DPs | 1.1 Apply cutting wood RPM | 1.2 Apply cutting wood feed speed | 2.1 Apply cutting aluminum RPM | 2.2 Apply cutting aluminum feed speed | 3.1 Stepper motors | 3.2 Human Machine Interface | 4.1 Single phase power supply | 4.2 Force controlled actuators | 6.1 Safety enclosure | 6.2 Ultrasonic sensors |
|---|---|---|---|---|---|---|---|---|---|---|
| 1.1 Use cutting RPM | x | | | | | | | | | |
| 1.2 Use feed speed | | x | | | | | | | | |
| 2.1 Use cutting RPM | | | x | | | | | | | |
| 2.2 Use feed speed | | | | x | | | | | | |
| 3.1 Use automation | | | | | x | | | | | |
| 3.2 Ease interaction with machine | | | | | | x | | | | |
| 4.1 Use domestic power | | | | | | | x | | | |
| 4.2 Use pneumatic alternative | | | | | | | | x | | |
| 6.1 Incorporate safety measures against airborne debris | | | | | | | | | x | |
| 6.2 Make sure user is at a safe distance | | | | | | | | | | x |

Axiomatic Design systematically transformed the design objectives or customer needs into functional requirements in the functional domain. These FRs are equivalent to what a designer wants to achieve. Apart from this systematic transformation, application of AD also helped to identify the coupling in the existing design. Furthermore, it led to a detailed mechanical design and control system which are discussed in the following sections.

### 4.4 Mechanical design

The CAD model of the SCM as shown in Figure 4.4 and Figure 4.5 is developed in SOLIDWORKS, a solid modelling computer-aided design tool that runs on a computer. The machine design is flexible, it should be noted, with regard to the length of material to be cut. Depending on the length of the profile the table can be attached along with a motor-controlled length measurement unit, or the profile can be put directly on the main cutting station. The force-controlled actuators are used to clamp the piece firmly. A safety enclosure protects against any debris or particle hitting the operator while working, and the rotary table is used to achieve the cut angle.

1. Table
2. Cutting length measurement unit
3. Main cutting station
4. Force-controlled actuators
5. Safety enclosure
6. Rotary table

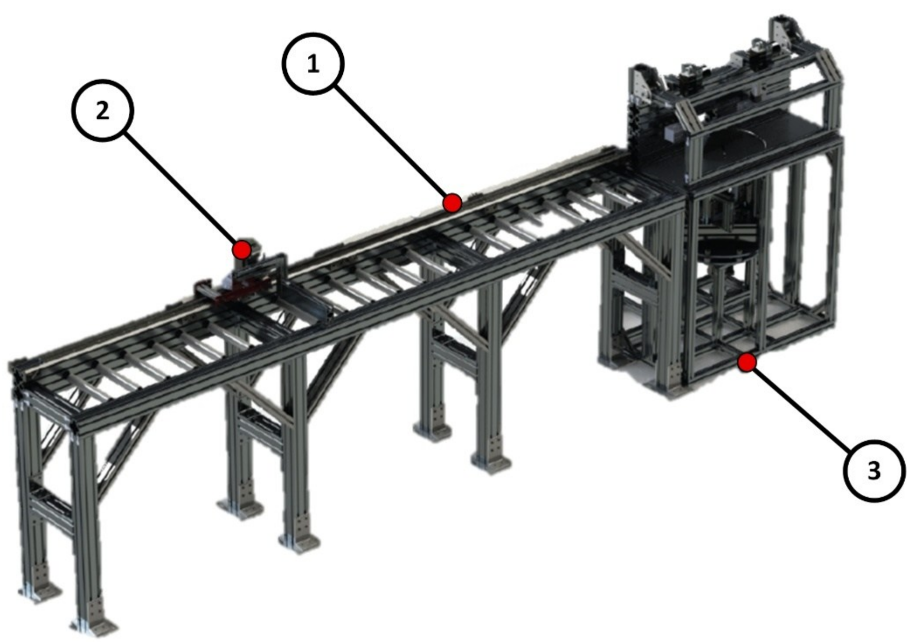



Figure 4.4 SCM CAD model

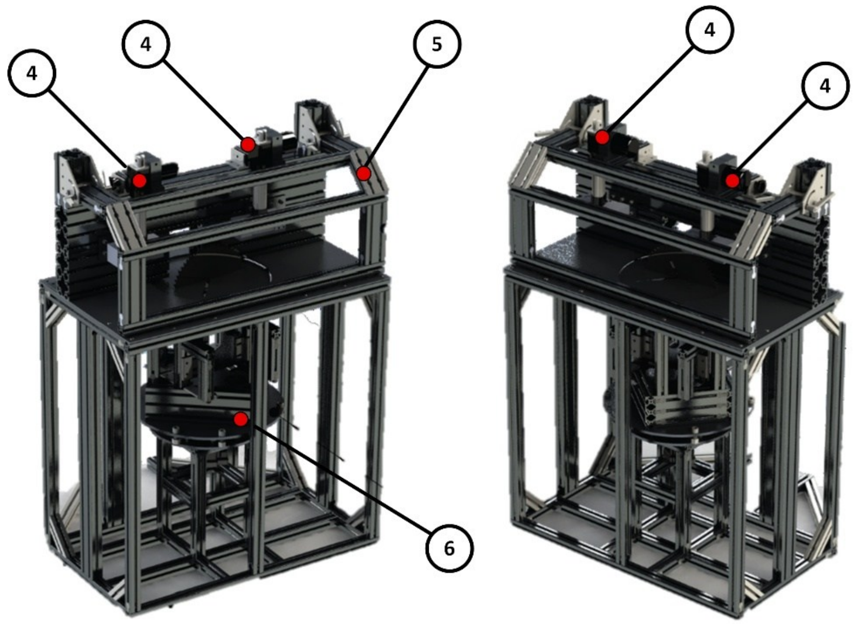



Figure 4.5 SCM main cutting station.

### 4.5 Control system

Machine control system is a collection of hardware and software, designed to coordinate the output of each individual component to achieve the desired machine functionality. A typical control system consists of; (i) reference input, (ii) a programmable logic unit or control unit, and (iii) output signals. The reference input is fed to a programmable logic unit or control unit which interprets the input according to the instructions programmed by the designer. The control unit then generates output signals to control the desired equipment, for instance, actuator, sensor, etc.

#### 4.5.1 Process Flow

The process as shown in Figure 4.6 starts with the manual loading of the wood/aluminum profile. A human–machine interface (HMI) is used to obtain the desired length and angle to be cut, followed by clamping in which load sensors are used to apply the required force to clamp the wood or aluminum being cut. The saw motor waits for the safety enclosure to come down and for the operator to move a safe distance away. The sequence of operations consists of (1) loading; (2) length and angle input; (3) clamping; (4) engagement of safety enclosure and sensors for operator's safety; and (5) engagement of saw motor and feed motor to cut material.

Loading is the manual operation in which the operator picks a profile and places it in the designated area of the machine. Once the loading is done, the next step is to input material and cut specifications. The HMI facilitates the interaction between the operator and the machine. The information is inputted to the machine by either of two methods. In the first method, a computer numerical control (CNC) file containing the complete information about the profile is uploaded, and the machine reads the file in a sequential manner to perform the operation.

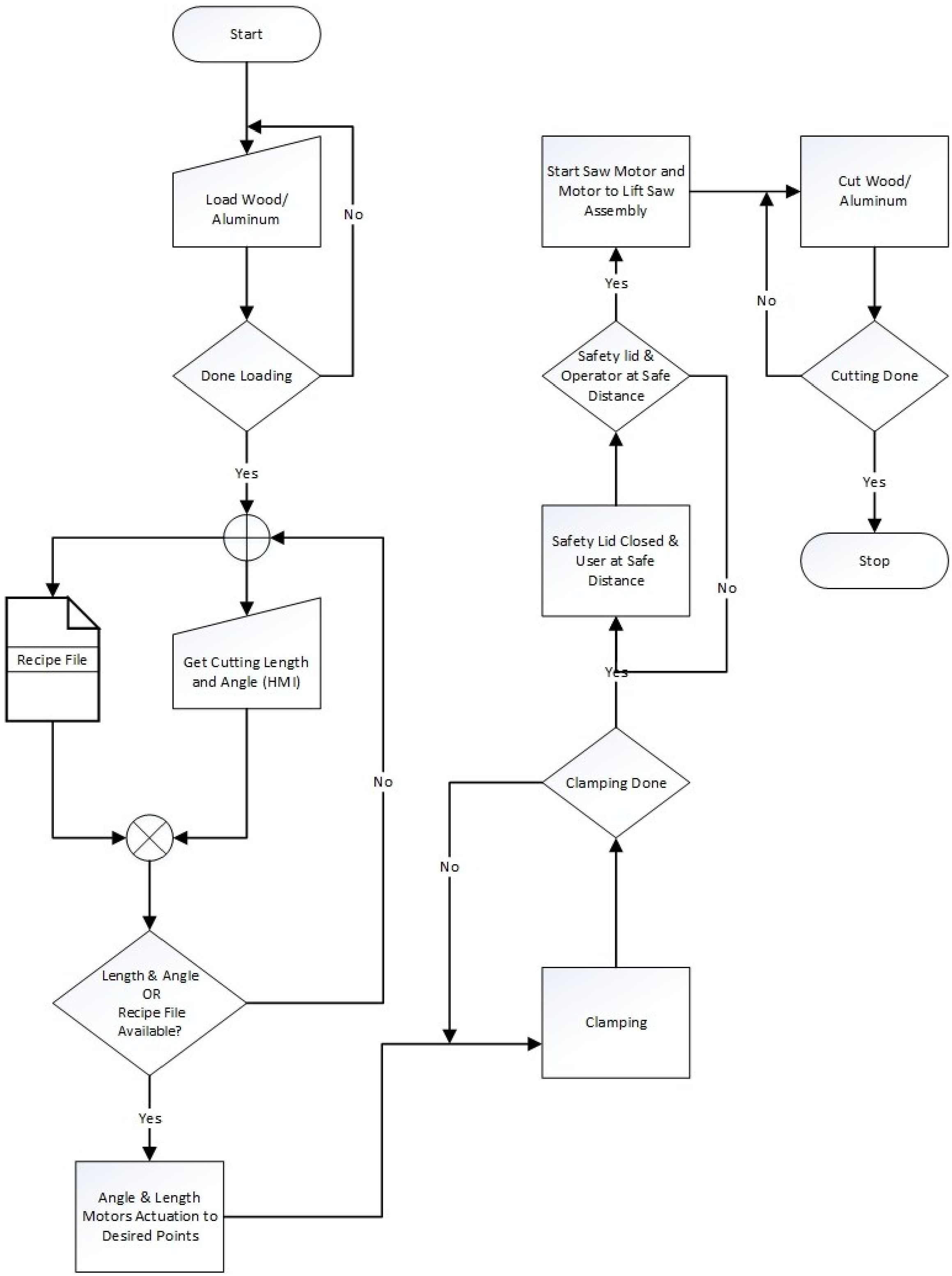



Figure 4.6 Basic process flow chart

The CNC file contains information such as the material, coordinates, and angle to cut. In the second method, the operator loads the profile and inputs the information manually. Once the operator has inputted the information, the machine executes safety measures before carrying out the cutting operation. It looks for a valid CNC file or coordinates to cut, ensures by means of ultrasonic sensors that the operator is at a safe distance, clamps the profile, and engages the safety enclosure. If all the conditions are met, then the PLC sends a command to the saw motor to engage and perform the cut. Apart from these safety checks, there are also emergency shutdown (ESD) push-buttons which can be used to halt the machine in case of any abnormal scenario. To clamp and to replace the pneumatic system, feedback force-controlled actuators are used. Based on the material selected, the actuators apply the right amount of force and the feed motor selects the desired feed speed to cut the material. Once the material is cut, it is unclamped in order for the operator to collect it.

### 4.5.2 Implementation of control system

Automation of the sequence of operation is realized by means of PLC as follows:

- Discrete inputs from proximity sensors for wood/aluminum detection.
- Discrete inputs from limit switches for safety and initial calibration.
- Analog inputs from load sensors to clamp wood/aluminum.
- Analog inputs from ultrasonic sensors for operator safety.
- Motor drive outputs to linear actuators for clamping.
- Motor drive outputs to cut wood/aluminum at desired angle and length.
- HMI to facilitate the automation process.

Once the hardware is known, next step is to select the software to make hardware operational. The PLC code is developed in SoMachine, while the HMI code is developed in Schneider Electric's Vijeo Designer. SoMachine is a software tool for developing, configuring, and commissioning the entire machine in a single software environment, including logic, motion control, and related network automation functions while Vijeo Designer is an HMI configuration software (Electric 2018b). IEC 6113-3 standard is a global standard for control programming that helps to improve software quality. Ladder programming has several drawbacks, including weak software structure and limited capacity to handle complex data structures (Plaza, Medrano and Blesa 2006). Jetley et al., (2013) discussed the comparison of graphical IEC 61131-3 programs, asserting that it is easier to trace the error with graphical languages as compared to textual.

#### 4.5.2.1 Implementation of code

The code for SCM is written in Sequential Function Chart (SFC), which is one of the IEC 61131-3 languages. Each block in SFC has three portions: entry, main body, and exit conditions. The program flows through these portions in a sequential manner. The flow between blocks is governed by transitions, which are conditions the satisfaction of which drives the flow of the program on to the next block as shown in Figure 4.7.

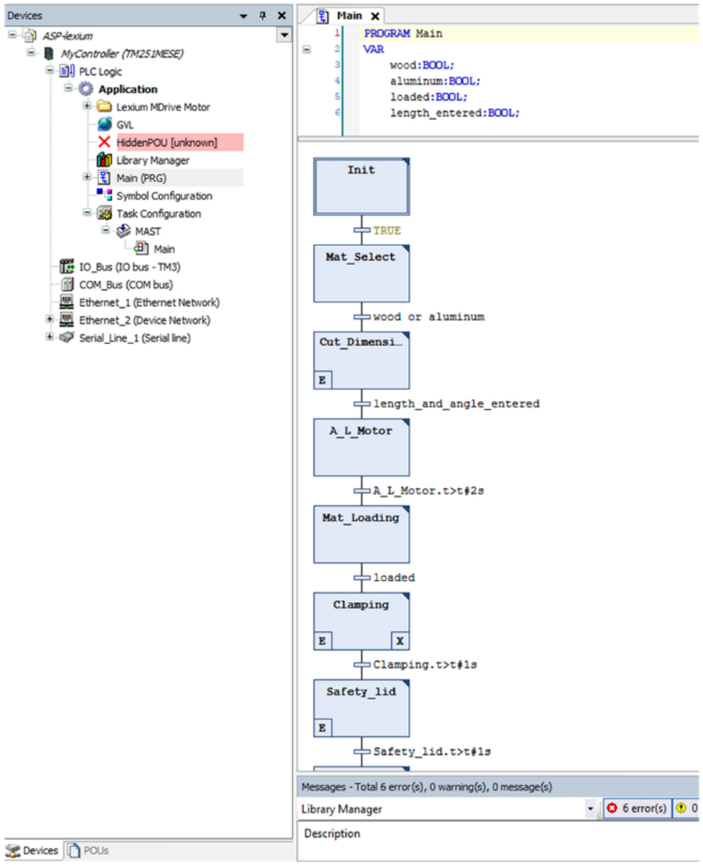



Figure 4.7 SCM code in SoMachine.

### 4.5.2.2 Implementation of HMI

Vijeo Designer provides great flexibility in designing graphical user interfaces (GUIs), where the nature of the operator's interaction with the machine dictates the design of the HMI. A well designed HMI aids the operator in understanding the previous, ongoing, and future tasks. It provides great advantages in terms of providing a user-friendly interface even for users without a relevant technical background, in which warnings and emergency situations can be communicated more efficiently by using bright colors to attract the operator's attention, and a single button can be assigned multiple tasks providing more flexibility in terms of coding. The GUI implementation in Vijeo Designer is shown in Figure 4.8 and Figure 4.9.

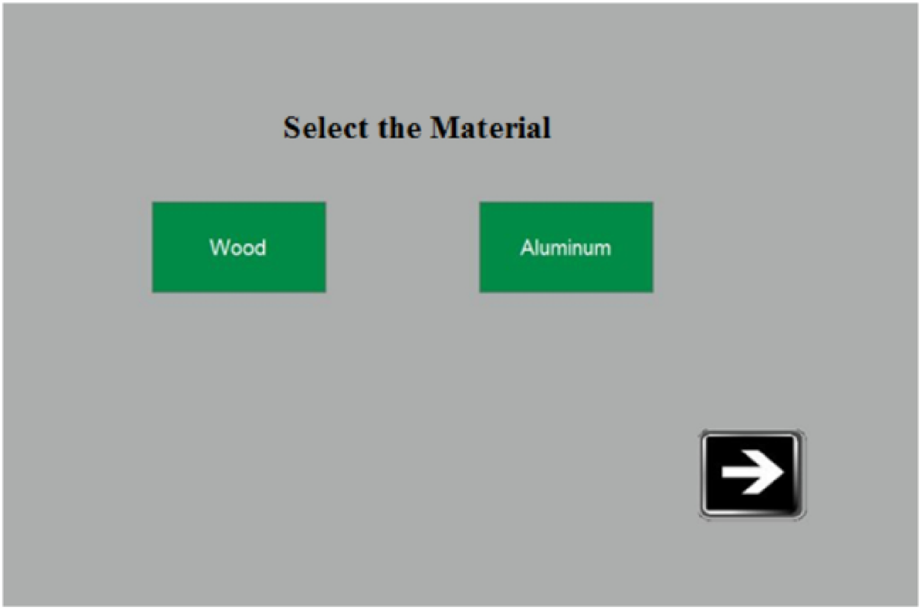



Figure 4.8 Material selection in Vijeo Designer.

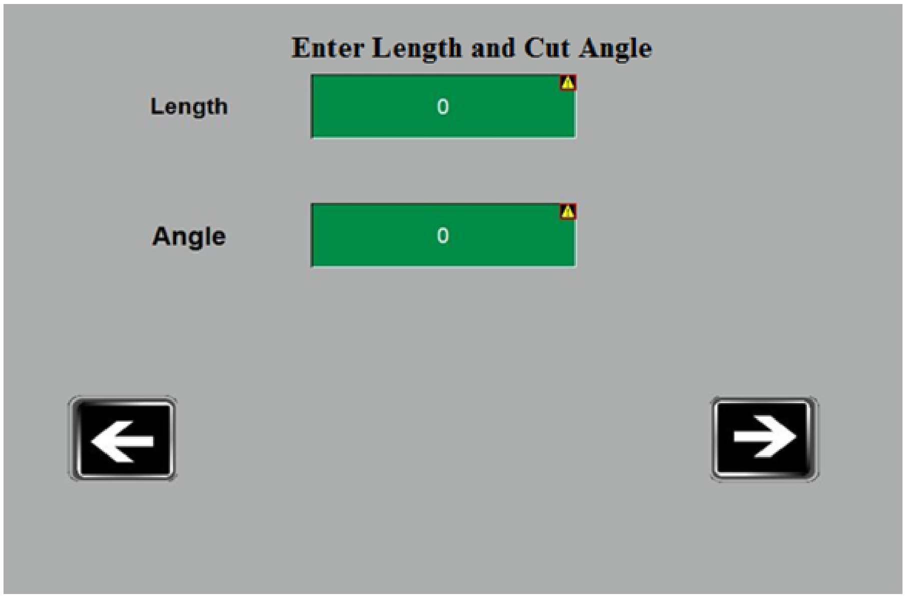



Figure 4.9 Operator input in Vijeo Designer

### 4.5.3 Ethernet/IP architecture

One of the complex tasks in the development of PLC-based control systems is wiring. Having a relatively small numbers of devices in a control system can result in a complex wiring system which occupies more space and is difficult to troubleshoot.

Ethernet/IP uses two protocols for the transport layer: Transmission Control Protocol (TCP) and User Data Datagram Protocol (UDP). TCP is acknowledged while UDP is unacknowledged protocol. TCP is used for non-control messages while UDP is used for Input/output (I/O) messages. Tested validated document and architecture (TVDA)-based Ethernet/IP improves efficiency in the design and planning phase (Electric 2018). Based on inputs/outputs described in Section 4.5.2 Ethernet/IP architecture is used for the machine described in this paper due to the following advantages:

- Ability to access the machine from anywhere, anytime via Ethernet for remote monitoring.
- Flexible in terms of adding an Ethernet/IP adaptor at any time.
- Efficient in terms of device integration and configuration, and the architecture can easily be modified.

With embedded Ethernet/IP communication, a PLC can communicate with 16 slaves in 10 ms. The Ethernet/IP architecture for the SCM is given in Figure 4.10.

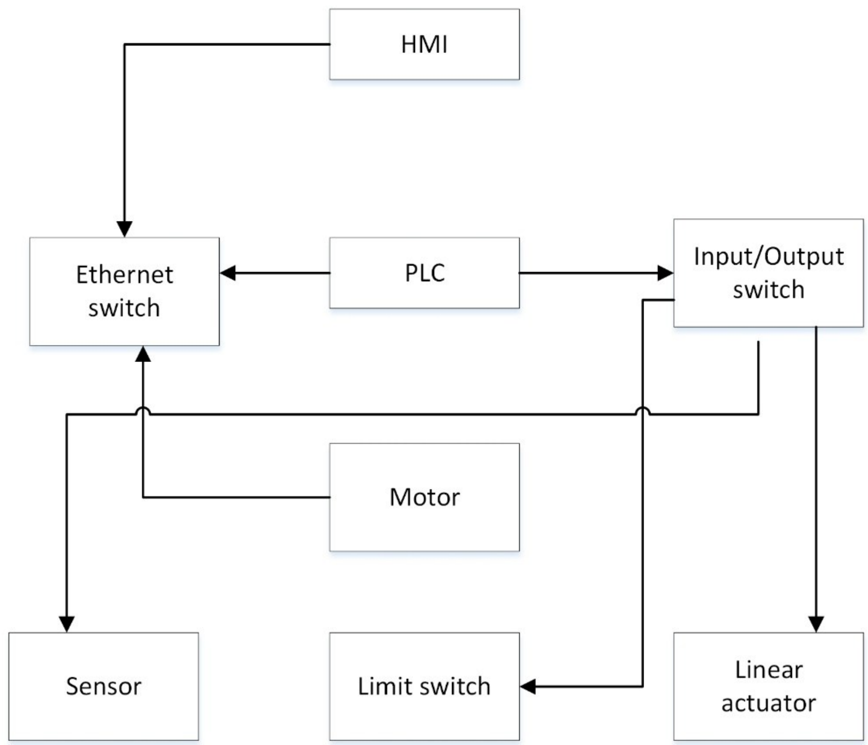



Figure 4.10 SCM Ethernet/IP architecture

**4.6 Discrete-event simulation**

Once the mechanical design and control system are finalized. It is suggested to evaluate the time that proposed machine will take to perform the cutting operation. The discrete-event model will aid the designer to further improve the machine's cycle time in the early design stage. Discrete-event simulation describes a process with a set of unique, specific events in time. Arena by Rockwell automation is used in the present research to build the SCM model with its key performance parameters such as cycle time and operator utilization. The model as shown in Figure 4.11 reads a CNC file that contains information about a profile, such as material, cut coordinates, and cut angle, in a sequential manner. The task times and triggers are assumed to provide the basis for statistical analysis and hypothesizing distribution.

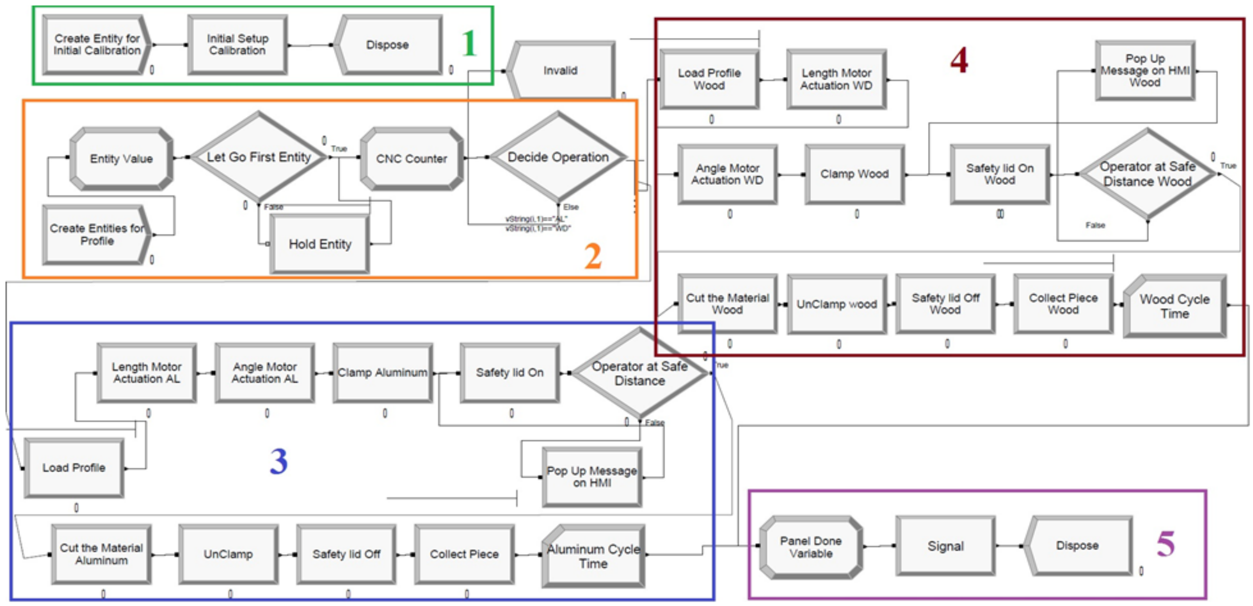



Figure 4.11 SCM simulation model

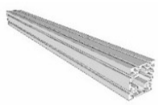
### 4.6.1 Model discussion

A discussion of the simulation model is given in this section. In Arena, a model is built using a "process" module that holds the "entities" for a specific period of time. The entities flow through different process modules to provide a valuable insight into machine's key performance indicators at the end of the simulation. The model for the SCM reads a spreadsheet extracted from a recipe file and scans the total number of cutting operations in the file prior to processing. It then generates entities equal to the number of cutting operations. The "Hold Entity" module holds the next entity, which is the next cutting operation, until the previous entity, which is the previous cutting operation being processed by the model, finishes. The "Decide Operation" module decides the material on the basis of a string variable that looks for either "WD" for wood or "AL" for aluminum in the file and then guides the respective entity to pass through the modules designated for the respective material. The "Load Profile" and "Collect Piece" modules share a common resource, which is the operator. The "Length" and "Angle" module task times, it should be noted, are dependent on the coordinates and proportional to the cut length and angle in the recipe file. The model consists of following main modules sections (1) initial calibration; (2) recipe file reading; (3) aluminum cutting; (4) wood cutting; and (5) ending. (1) accounts for the time taken in homing the motors and initial system delays when the machine is powered on, (2) deals with reading of the recipe file and deciding the operations accordingly, (3) accounts for the time taken in cutting the aluminum, (4) accounts for the time taken in cutting wood, and (5) indicates when all the operations on the profile are done.

#### 4.6.1.1 Case study

To illustrate the effect of different profiles with different cut and angle coordinates on the key performance indicators, for instance, cycle time and utilization of the operator, Table 4.6 shows the summary of results obtained from the model. For the profile case studies as illustrated in Table 4.6, the simulation model generates a total of five entities, as there are five cutting operations at time zero. The "Hold Entity" module holds the next cutting operation until the previous entity or cutting operation exits the model, and sends a trigger to the hold module through the signal module. The simulation keeps running until all the entities generated have exited the model.

Table 4.6 Simulation results summary

| | Profile | Dimensions WxHxL (inch) | Material | Cut Lengths (inch) | Cut Angle (θ) | Average Cycle Time (minute) | Average Operator's Utilization (%) |
|---|---|---|---|---|---|---|---|
| Profile 1 |  | 1.57x1.57x78.74 | Aluminum | 12,24,48 | 45,60,0 | 3.3 | 81 |
| Profile 2 |  | 1.5x3.5x78.74 | Wood | 12,36 | 0,0 | 2.1 | 70 |

### 4.7 Conclusion

This chapter aims to investigate the link between design, complexity, and controls. The limitations of the present table saw are used as a basis to demonstrate the effect of controls system on design and complexity. The traditional method for cutting wood using a table saw involves a stationary saw motor in which the wood is fed through the saw by hand. This approach entails serious safety hazards. On the other hand, aluminum cutting requires extra precaution and careful craftsmanship to ensure an accurate cut, and the cutting can be dangerous if not executed properly. Given the inherent risks of conventional sawing practice, limitations of cutting both materials, benefits of automation and to support panelized construction, in this chapter Axiomatic Design theory is applied for investigating the limitations of the present table saws in terms of design and complexity. As a result of mapping from functional domain to physical domain, the feed speed and RPM for wood and aluminum cutting found to be coupled. A complete controls system strategy from defining the process flow to its detailed implementation is crafted to meet the design objectives and based on the analysis an uncoupled design (less complex) of saw cutting machine is introduced. Discrete event modelling is employed to estimate the performance of the machine and implication of different sizes of profiles. The simulation results provide valuable insight into machine's key performance indicators, for instance, cycle time and operator's utilization.

# Chapter 5 Conclusion

## 5.1 General conclusion

While designing an industrial system, system designers are challenged with a number of design, complexity, and controls challenges. Assembly attributes account for major production time, and a number of electrical controls parts account for the major cost. Apart from assembly time and cost, complexity is also an important factor when it comes to difficulties being faced in manufacturing. Therefore, while designing, the controls complexity which is defined as the degree to which individual wires/cables are prepared, assembled, installed, attached, and the diversity in associated controls signals is worth exploring and modeling. The objective of this research is to assist system designer in reducing the number of electrical controls parts, calculate cost, and complexity through the development of an integrated framework. To achieve the research objective the following contributions have been made:

## 5.2 Research contributions

The contributions of this research can be summarized as follows:

First, a novel method is developed to reduce the number of electrical controls parts. This is composed of a design for electrical controls (DEC) methodology for generating alternative electrical controls concepts, and a cost function for evaluating the cost of the concept. The cost function calculates the total cost of a given concept while including part cost, wiring and connector cost, and associated assembly and labor cost. A Programmable Logic Controller (PLC) based system, a sensor-based system, and a three-phase motor based system are used to demonstrate the different possible scenarios and application diversity of the proposed approach. The proposed model reduced; the assembly time for PLC-based system by 59.12% and cost by 51.91%, assembly time for sensor-based system by 68.48% and cost by 59.62%, assembly time for a multiphase AC system by 36.90% min and cost by 42.84%.The successful application indicates that the proposed method is a useful tool for the system designers to reduce the number of parts, assembly time for wiring and ultimately the cost in the early design stages.

Second, a novel model is developed for measuring controls complexity by incorporating the principles of assembly complexity model, information content and assembly attributes for electrical connections and wire harnesses. The new model takes into account the complexity of individual wires/cables using indices which are added to assess the complexity of the overall controls system. To demonstrate the application of the proposed model, a sub-assembly in a semi-automatic machine is used with three different controls alternatives: pneumatics, bipolar stepper, and Ethernet-based stepper. The results show; (i) that the assembly time for electrical connections, and wire harnesses is directly related to controls complexity, and (ii) the information content and diversity in controls signals increase as the nature of controls system changes from basic controls in case of pneumatics to a conventional stepper and then further to a more sophisticated Ethernet-based stepper. Hence, vindicating that the proposed model is a productive tool for the designers in the early stages of design, to be aware of the complexity, they are going to introduce in the system by making certain control choices.

Third, a study is conducted to investigate the link between design, controls, and complexity. A control system strategy is devised to improve design and reduce complexity in the early design stages. To demonstrate, Axiomatic Design theory is applied for investigating the limitations of the present table saws. The mapping from functional domain to physical domain, resulted in a coupled (complex) design. A complete controls system approach from defining the process flow to its detailed implementation is crafted to reduce complexity by uncoupling the design.

The significance of these research contributions is that: the developed metrics can be used as decision support tools by system designers; to reduce number of electrical controls parts, assembly time, and ultimately cost. Quantify and reduce complexity and compare different design alternatives in the early design stages.

### 5.3 Research limitations and future work

This research is subject to the following limitations:

1. DEC methodology: the present research does not take geometrical attributes of the parts and effect of heat transfer and signal interference into account which is worth exploring to broaden the scope of the research further.
2. DEC methodology: due to the iterative nature of methodology, in case of a large system, the application process gets slow. However, it can be made faster and more interactive by making a GUI that let the system designer model the controls system, electrical connections, and dress the wires in a 3D environment
3. Controls complexity model: the current model does not take into account the coding complexity which is expressed in terms of space, time, and computational effort. It is worth exploring and modeling to extend the complexity model further.

4. Axiomatic Design: the concept of saw cutting machine presented is subjected to design objectives and formulation of the FRs. The present research does not take into account the quality of cut which is a critical factor when it comes to aluminum. Furthermore, apart from cycle time and operator's utilization, process complexity comparison between proposed saw cutting machine, traditional table saw for wood, and aluminum cutting is worth exploring.

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