Design of a Saw Cutting Machine for Wood and Aluminum

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Abstract: The intensive use of wood in furniture, building, bridges, and of aluminum in transportation and construction, underscores the economic importance of these building materials in North America. Power saws are very useful tools for cutting and shaping such materials; however, they can cause serious hand injuries. In a table saw operation for wood cutting, for instance, the operator's hands are vulnerable as they are used to guide pieces into the saw. In addition, the saw operator faces the risk of material being kicked back out of the saw or of sustaining an eye or respiratory injury due to the presence of sawdust and other debris generating by the operation of the saw. Meanwhile, aluminum cutting requires careful precaution and accuracy. The cutting can be dangerous if not handled properly. The greatest challenge in this regard is securely holding the material being cut. Furthermore, industrial requirements such as pneumatics and three-phase power supply preclude the ready use of such machines on a domestic scale. The cutting capability of existing table saws is coupled in such a way that it cannot cut both wood and aluminum. In this paper, a concept of a saw cutting machine (SCM) is presented using Axiomatic Design to ensure design objectives such as safety, user comfort, usage on a domestic scale and capability to cut both types of materials. In the presented case study, the mapping from Customer Attributes (CAs) to Functional Requirements (FRs) and then respective Design Parameters (DPs) resulted in an uncoupled design, in turn leading to a detailed mechanical design followed by the control system, all based on the aforementioned design objectives.

1 INTRODUCTION

Forest products are a major contributor to the Canadian economy. (Canada, 2013) 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).

The motivation for the development of the saw cutting machine (SCM) described in this paper arose out of a broader research initiative at the University of Alberta (Canada) to develop a semi-automated wood framing machine

Figure 1 and a semi-automated light-gauge steel framing machine Figure 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,

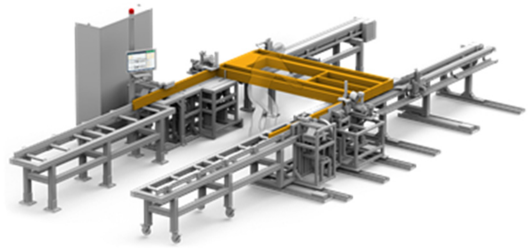

Figure 1: Wood framing machine.

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Figure 2: Steel framing machine.

and (4) capable of angled cutting started and resulted in a design discussed in the following sections.

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The paper is divided into eight sections. Section 2 reviews the relevant literature with a focus on potential safety hazards, Section 3 elaborates on the design objectives and describes the research methodology, Section 4 explains the implementation of Axiomatic Design to form an uncoupled design, Section 5 presents the mechanical design, and Section 6 the implementation of the control system to meet the design objectives mentioned in Section 3. Section 7 describes the discrete-event simulation model of the SCM, followed by Section 8, which summarizes the research achievements.

2 LITERATURE REVIEW

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) discuss 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. Product 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.

3 METHODOLOGY

The design objectives for the machine are as follows:

- Capable of cutting both wood and aluminum
- Can be used in a lab or domestic scale
- Ensures safety and operator comfort
- Can accommodate angled cutting

In general, the design of machines consists of conceptual and detailed design processes. Overall the factors which affect the most characteristics and the cost are determined in the conceptual stage. Axiomatic design is a design methodology to systematically transform the CAs into FRs and then respective DPs, and PVs. In this paper; Axiomatic design is utilized in the conceptual design process that further lead to detailed design. The FRs for the SCM are defined on the basis of CAs, and corresponding DPs are selected. The detailed design is carried out on the basis of decisions made in the conceptual stage. 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. Arena input analyzer by Rockwell automation is used to select the distribution of each task in the simulation model.

4 AXIOMATIC DESIGN

Design process in Axiomatic design is top-down, in which the initial concept is decomposed to design details by zigzagging. The relationship between FRs and DPs is given as

$$\{FRs\} = [A]\ \{DPs\} \tag{1}$$

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 which is ideal. When [A] is lower triangular matrix, the design is called decoupled and preferred in absence of uncoupled, while all the other designs are called coupled. DPs are the physical variables in the physical domain that characterize the design that satisfies the specified FRs. When DPs do not take their detailed physical form, the corresponding FRs need further division. Based on DP_3, FR_3 of the SCM is decomposed into two sections as $FR_{3.1}$ and $FR_{3.2}$. The FR_5 needs no further decomposition as DP_5 has taken its detailed physical form.

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 Table 1 illustrates the second level FRs and DPs.

FR_3= Facilitate operator
FR_4= Industry power & pneumatics alternative
FR_5= Angle cut
FR_6= Safety

DP_3= Automation using stepper motors & Human Machine Interface (HMI)
DP_4= Single phase power supply & force controlled actuators
DP_5=Rotary table
DP_6= Sensors based mechanical assembly

The low level FRs and DPs decomposition is as follows:

$FR_{3.1}$= Use automation
$FR_{3.2}$= Facilitate interaction with machine
$FR_{4.1}$= Use domestic power
$FR_{4.2}$= Use pneumatics alternative
$FR_{6.1}$= Incorporate safety measures against airborne debris
$FR_{6.2}$= Make sure user is at a safe distance

$DP_{3.1}$= Motors
$DP_{3.2}$= Human Machine Interface
$DP_{4.1}$= Single phase power supply
$DP_{4.2}$= Forced controlled actuators
$DP_{6.1}$= Safety enclosure
$DP_{6.2}$= Ultrasonic sensors

Table 1: Initial 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

Table 2: 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

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.

$$\text{Feed speed} = \frac{RPM \times no\ of\ teeth \times Chipload}{12} \qquad (2)$$

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

The initial design matrix results in a coupled design due to the fact that feed speed and RPM are related (2). Feed speed and RPM have to be adjusted according to the material being cut. The second concern is that the number of FRs is greater than the number of DPs. The first step towards uncoupling the initial design is a permutation that results in a better design but still a coupled one. To solve the issue of feed speed and RPM coupling, a software solution is used which is implemented on PLC that sets the desired feed speed and RPM to cut the given material. The second design issue of inequality in numbers of FRs and DPs is addressed by adding more DPs to make the design matrix square. The final uncoupled design matrix is shown in Table 2.

5 MECHANICAL DESIGN

The CAD model of the SCM as shown in Figure 3 and Figure 4 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

6 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.

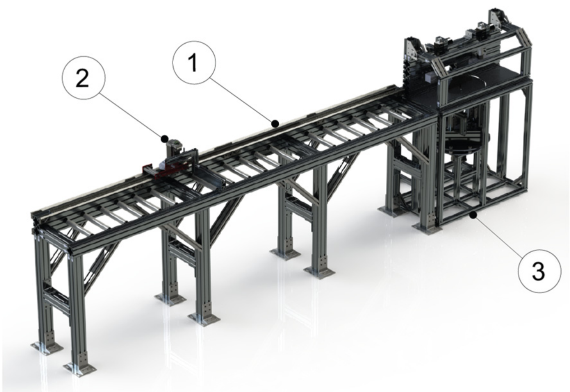


Figure 3: SCM CAD model.

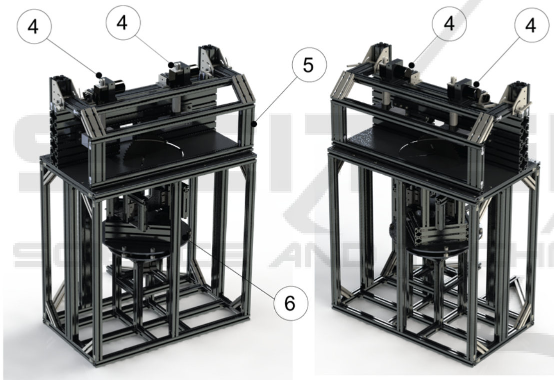


Figure 4: SCM main cutting station.

6.1 Process Flow

The process as shown in Figure 5 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.

6.2 Sequence of Operation

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. 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

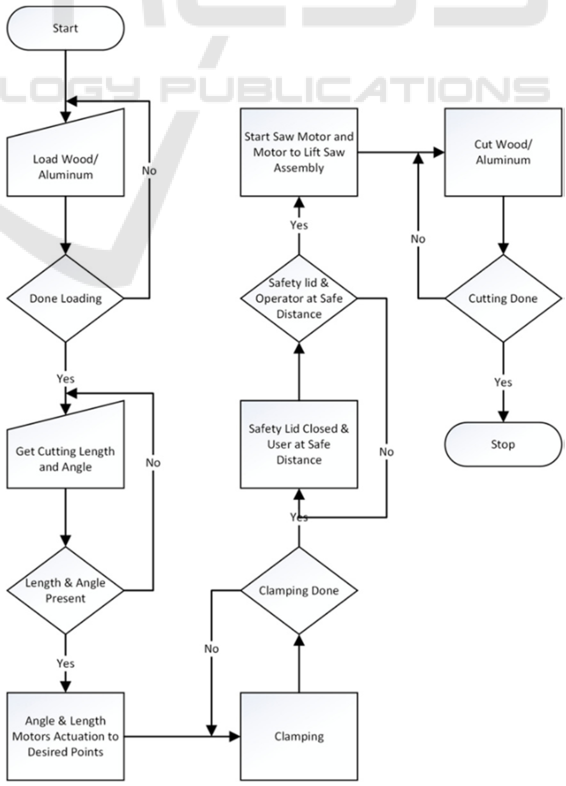


Figure 5: Process flow chart.

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.

6.3 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 harware operational. The PLC code is developed in SoMachine, while the HMI code is developed in Schneider Electric's Vijeo Designer. (Electric, 2018b) 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**.** (Plaza, Medrano and Blesa, 2006) 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. (Jetley *et al.*, 2013) discuss the comparison of graphical IEC 61131-3 programs, asserting that it is easier to trace the error with graphical languages as compared to textual.

6.3.1 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 6.

6.3.2 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

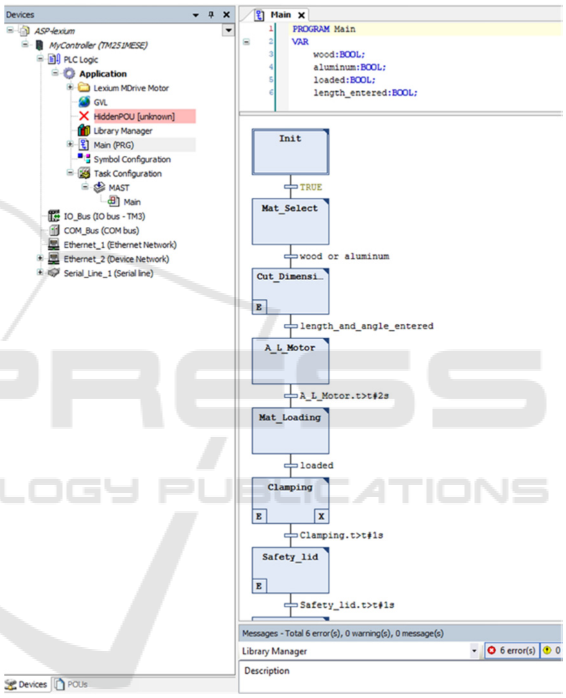


Figure 6: SCM code in SoMachine.

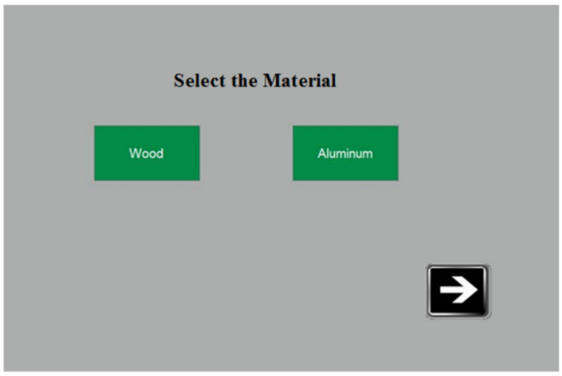


Figure 7: Material selection in Vijeo Designer.

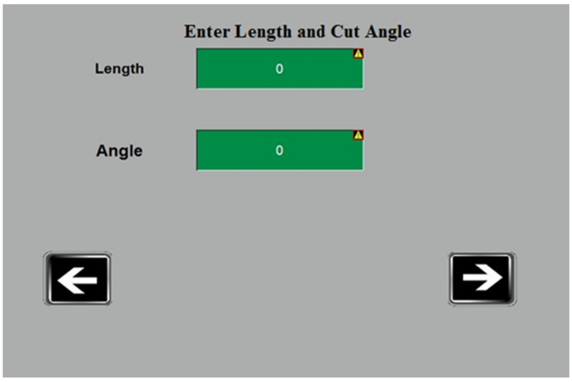


Figure 8: Operator input in Vijeo Designer.

terms of coding. The GUI implementation in Vijeo Designer is shown in Figure 7 and Figure 8.

6.4 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. (Electric, 2018a) 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. Based on inputs/outputs described in Section 6.3 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 9.

7 DISCRETE EVENT SIMULATION

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 10 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.

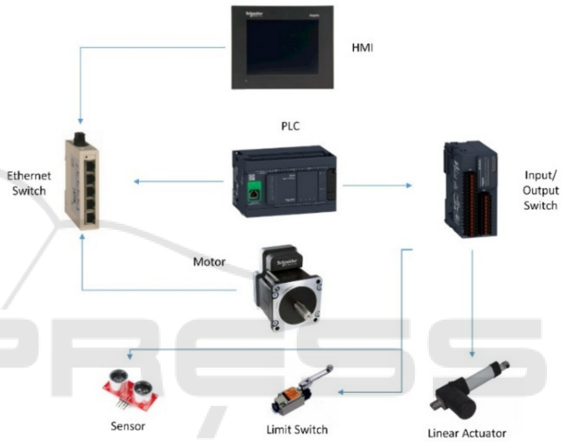


Figure 9: SCM Ethernet/IP architecture.

7.1 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 CNC 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 CNC file. The model consists of following main modules sections (1) initial calibration; (2) CNC 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 CNC 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.

7.1.1 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 3 shows the summary of results obtained from the model. For the profile case studies as illustrated in Table 3, 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.

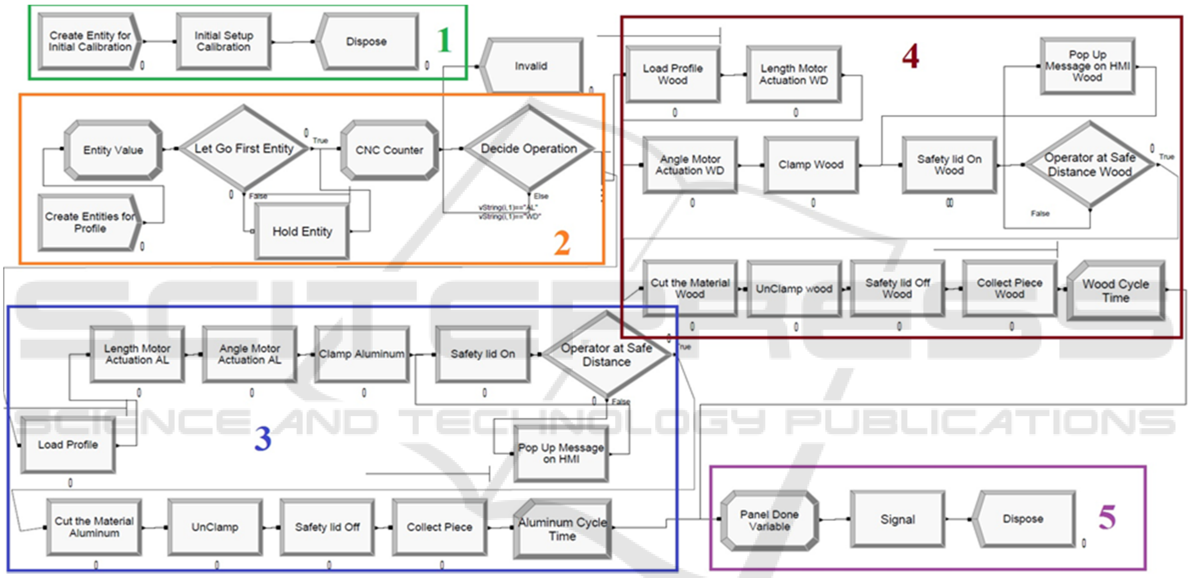
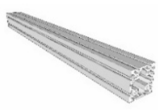


Figure 10: SCM simulation model.

Table 3: 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

8 CONCLUSION

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 paper Axiomatic design theory is applied for investigating the problems of the present table saws and for designing an uncoupled new one. As a result of maping from functional domain to physical domain, the feed speed and RPM for wood and aluminum cutting found to be coupled. A complete control system strategy from defining the process flow to its full implementation was crafted to meet the design objectives and based on the analysis an uncoupled design 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.

REFERENCES

Canada, N. R. (2013) *Forest and Aluminum Industry*. Available at: http://www.nrcan.gc.ca

Chung, K. C. and Shauver, M. J. (2013) 'Table Saw Injuries', *Plastic and Reconstructive Surgery*, 132(5), p. 777e–783e. doi: 10.1097/PRS.0b013e3182a3bfb1.

Electric, S. (2018a) *Industrial Ethernet*. Available at: https://www.schneider-electric.com/en/product-range-presentation/1106-industrial-ethernet?parent-category-id=2400&parent-subcategory-id=2410&filter=business-1-Industrial Automation and Control.

Electric, S. (2018b) *SoMachine*. Available at: https://www.schneider-electric.ca/en/product-range-presentation/2226-somachine#tabs-top.

Farid, A. M. and Suh, N. P. (2016) *Axiomatic Design in Large Systems*. doi: 10.1007/978-3-319-32388-6.

Graham, J. D. and Chang, J. (2015) 'Reducing the risk of injury from table saw use: The potential benefits and costs of automatic protection', *Risk Analysis*, 35(2), pp. 307–317. doi: 10.1111/risa.12258.

Jetley, R., Rath, A., Aparajithan, V., Kumar, D., Prasad, V. and Ramaswamy, S. (2013) 'An approach for comparison of IEC 61131-3 graphical programs', *IEEE International Conference on Emerging Technologies and Factory Automation, ETFA*. doi: 10.1109/ETFA.2013.6647938.

Lee, K. D., Suh, N. P. and Oh, J. H. (2001) 'Axiomatic design of machine control system', *CIRP Annals - Manufacturing Technology*, 50(1), pp. 109–114. doi: 10.1016/S0007-8506(07)62083-6.

Negahban, A. and Smith, J. S. (2014) 'Simulation for manufacturing system design and operation: Literature review and analysis', *Journal of Manufacturing Systems*. The Society of Manufacturing Engineers, 33(2), pp. 241–261. doi: 10.1016/j.jmsy.2013.12.007.

Plaza, I., Medrano, C. and Blesa, A. (2006) 'Analysis and implementation of the IEC 61131-3 software model under POSIX Real-Time operating systems', *Microprocessors and Microsystems*, 30(8), pp. 497–508. doi: 10.1016/j.micpro.2006.06.001.

Schwaneberg, O., Steiner, H., Bol\'ivar, P. H. and Jung, N. (2012) 'Design of an LED-based sensor system to distinguish human skin from workpieces in safety applications', *Appl. Opt.*, 51(12), pp. 1865–1871. doi: 10.1364/AO.51.001865.

Shields, B. J., Wilkins, J. R. and Smith, G. A. (2011) 'Nonoccupational Table Saw-Related Injuries Treated in US Emergency Departments, 1990–2007', *The Journal of Trauma: Injury, Infection, and Critical Care*, 71(6), pp. 1902–1907. doi: 10.1097/TA.0b013e3181b28ad3.

Suh, N. P. and Do, S.-H. (2000) 'Axiomatic Design of Software Systems', *CIRP Annals - Manufacturing Technology*, 49, pp. 95–100. doi: 10.1016/S0007-8506(07)62904-7.