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Design automation of control panels for automated modular construction machines

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Abstract

Modern modular construction demands high quality, cost-effective, and efficient production of components. These requirements have led to the emergence of offsite construction manufacturing, which necessitates the use of automated machines. Compared to traditional onsite methods, offsite modular construction has a positive impact on quality, safety, cost, and productivity. Methodologies exist in the design of automated modular construction machines. This automation consists of not only the machines but also the supportive electrical and pneumatic systems, which, regardless of the design approaches used for automated machines, can be applied to the design of their associated systems. To avoid costly design changes, there is a clear need for a systematic and iterative design methodology at the conceptual design stage. For the control panel, the conceptual design method introduced in this paper facilitates the subsequent computer-aided design to be performed at the detailed design stage. Integrated function modeling, combined with axiomatic design and design structure matrix, constitutes the conceptual design approach for the control panel. In this work, linear time complex algorithm is developed for automating the layout of the electrical devices and wiring connections in order to facilitate computer-aided design implementation in the detailed design phase. Furthermore, the control panel guidelines and standards that constitute the prior knowledge of the design process are embedded in the algorithm.

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Keywords: Integrated Function Modeling; Axiomatic Design; Design Structure Matrix; Control panel

1. Introduction

Construction automation is gaining popularity due to the performance limitations of conventional construction methodology [1]. For example, in modular construction, Tamayo et al. [2] describe an automated machine for steel wall framing and its associated control system in the supervisory control and data acquisition (SCADA)/Device level. Difficulties arise in developing a complex system such as that of construction automation. Abdelrazek et al. [3] list these difficulties and advocate for the use of model-based systems engineering (MBSE) methodology to overcome these issues. However, to effectively address the issues concerning a complex system, an MBSE methodology must be systematic, iterative, visual, and transdisciplinary and must be initiated at the conceptual design phase. An integrated function modeling approach, combined with axiomatic design and design structure matrix, satisfies these criteria. Control panels house the electrical components serving the field devices of an automated manufacturing system. Control panel design should be initiated at the conceptual design phase in order to: (*i*) consider optimal device layout and wiring connections, (*ii*) meet safety and maintainability guidelines and standards, and (iii) facilitate computer aided design in the detailed design phase. Thus, conceptual design of control panels can be incorporated into the integrated function modeling of automated construction machines. This paper extracts the control panel design aspect of the integrated function modeling of an automated modular construction system. It attempts to overcome the issues of systematic framework, iterative design and best practices in cybermanufacturing described by Shapiro et al. [4]. To illustrate the methodology used in the conceptual design of a control panel, this paper is organized as follows: Section 2 presents the integrated design methodology; Section 3 provides the application of the integrated design methodology to a control panel; Section 4 describes the algorithm for planning the control panel layout and wiring; and Section 5 provides a summary of the integrated function modeling approach.

2. Integrated design methodology

Integrated design methodology is essentially an integrated function modeling (IFM)[18] approach that is built from axiomatic design (AD)[6] and design structure matrix (DSM)[9].

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This methodology is useful in the conceptual design phase, which offers: (*i*) an effective visual means of communicating the design intent and customer requirements in terms of functional requirements (FRs) and associated design parameters (DPs), (*ii*) a compact representation of the interaction among actors, and (*iii*) a design approach that is systematic and scientific due to the incorporation of the mathematically based AD and DSM techniques. In this section, the main components that form the integrated design methodology, namely AD, DSM and IFM, are discussed.

2.1. Axiomatic Design

AD effectively addresses the issue of unfulfilled customer requirements in the difficulties and failures of complex systems mentioned by Abdelrazek et al. [3]. Foley and Harðardóttir [5] discuss how FRs and DPs are generated by filtering ideas through brainstorming sessions. Customer requirements, however, take the highest level in the hierarchy of FRs and DPs. Design matrix (DM), in binary format, describes the relationship between FRs and DPs. Mathematically, this is expressed in Equations (1) and (2) as follows [6,12].

$$\{FR\} = [DM]\{DP\} \tag{1}$$

$$DM_{ij} = \begin{cases} X, if\ an\ element\ or\ effect\ exists \\ 0, otherwise \end{cases} \tag{2}$$

where $i, j = 1 \cdots n$.

An acceptable design can be visualized through the DM. A lower triangular DM, which includes a diagonal DM, represents an acceptable design. Identity and lower triangular DMs, which fall into the acceptable design region, are referred to as uncoupled and decoupled design, respectively. A lower triangular DM satisfies the first axiom, the axiom of independence, of AD. On the other hand, a DM with an FR-DP relationship outside of this triangular region indicates an unacceptable design. Since a DM can be initiated even with less information about the system, AD is useful in the conceptual design phase.

Another axiom that must be satisfied in AD is that of simplicity of design. Applying this axiom for a system with multiple designs implies that the design with the least information is selected as the best design. This criterion is expressed mathematically using Equations (3) and (4) as follows [7,8,13].

$$I_{min} = min \left\{ \begin{matrix} n \\ \Sigma I_i \\ i = I \end{matrix} \right\} \tag{3}$$

where

$$\begin{aligned} I_i &= log_2 \frac{1}{p} \\ &= log_2 \left(\frac{System\ range}{Common\ range} \right) \end{aligned} \tag{4}$$

In the above equations, I_i and p are the information content and probability of satisfying the *ith* functional requirement respectively.

The advantages of AD include its: (*i*) usefulness in conceptual design, (*ii*) early consideration of customer requirements, (*iii*) regard for simplicity in design, (*iv*) use of a matrix for visual communication and (*v*) iterative aspect. However, it fails to consider interactions among DPs and it lacks the functionality of a transdisciplinary modeling framework.

2.2. Design Structure Matrix

Browning [9,10] describes DSM and its application as a modeling framework. DSM requires a significant amount detail for a product being designed. Its weakness lies in its limited use at the conceptual design phase since it cannot be used to design an entirely new product [14]. Using the DPs obtained from AD, however, facilitates the development of DSM at the conceptual design stage. This method of forming DSM from AD is described by Dong and Whitney [15]. However, DSM and AD can be enhanced with additional features in providing a truly transdisciplinary integrated design framework. By invoking the permutation and triangularization techniques described by Guenov and Barker [16] DSM becomes an iterative design methodology. Browning [11] presents several triangularization methods of row and column reordering by using optimization techniques. DSM provides a visual representation of the interactions among DPs. As in AD, the interactions are expressed in binary notation as

$$\{DP\} = [DSM]\{DP\} \tag{5}$$

where

$$DSM_{ij} = \begin{cases} 0, & if\ i < j \\ X, & otherwise \end{cases} \tag{6}$$

Similarities of the above equations with those of AD suggest that rules governing AD in terms of uncoupled, decoupled and coupled interactions apply to DSM as well. In equation (6), the strength of interaction is expressed as 1 if an interaction exists otherwise it is 0. However, the degree of interaction can also be expressed by other values [17].

2.3. Integrated Function Modeling

IFM has been developed to facilitate collaboration among disciplines involved in the conceptual design of complex systems [18]. It is structured to visually communicate the design intent among experts across all disciplines through its use of matrices to describe the different views, which include use case, process flow, actor, interaction and state. Eisenbart et al. [19] provide a more detailed description of the IFM framework. Incorporating the interaction view to visually represent system architecture makes IFM a DSM-based modeling framework [19]. Interaction view does not only consider the interaction among DPs (actors) but among operands as well. Since IFM is a DSM-based framework, it inherits the limitation discussed in the previous section. However, IFM combined with AD and DSM provides a powerful conceptual design approach that is systematic, iterative, visual and transdisciplinary. Such a combined design methodology is discussed in the next section.

2.4. Integrated Design Methodology

A truly transdisciplinary design approach is essentially an IFM that is systematically developed using AD and DSM. Due to the mathematical basis supporting AD and DSM, the resulting IFM establishes a scientific design approach. Fig. 1 illustrates a simplified flowchart of the development of an integrated design methodology that is basically an IFM formed using AD and DSM. Mapping the customer requirements to high-level FRs and DPs initializes the DM and IFM. At the AD stage, low-level FRs and DPs are provided by the experts across the disciplines to support the customer requirements. From the customer requirements, the process flow, use case and actor views of the IFM are formed. AD undergoes design iterations until the axioms of independence and information are satisfied. Once the DM is finalized, it is then passed on to the DSM stage. If the DM is not square, DSM undergoes design iterations through modifications, permutations, and triangularization as discussed by Guenov and Barker [16], otherwise the DSM is formed by defining output variables and permuting columns and replacing the FRs with their corresponding DPs [15].

At the final stage, the DSM and the operands are combined to form the interaction and state views. If any new details exist, the IFM is updated, otherwise the final IFM is presented.

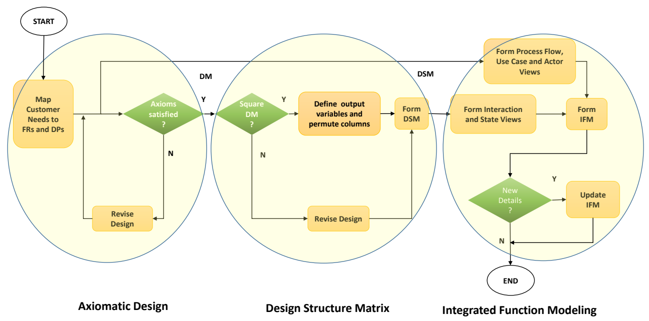

Fig. 1: Integrated design methodology.

2.5. A Simple Illustration

A simple example that describes the initial design of a control panel is discussed in this section in order to demonstrate the application of the basic steps of the integrated design approach depicted in Fig. 1. For illustrative purposes, this example only considers the high-level FRs of the control panel. In the next section, the integrated design approach will be applied to include the low-level FRs of the control panel as well. Table 1 provides the parallel steps of forming the high-level FRs, the process flow view, and use case view presented in Fig. 1. From this table, the DM can then be formed using the FRs and the following DPs: 120-volt AC control panel (DP0), backplate (DP1), electrical devices (DP2), and enclosure for the area classification (DP3).

Invoking Equations (1) and (2), the DM for the simple control panel design example is formed as follows:

$$\begin{Bmatrix} FR0 \\ FR1 \\ FR2 \\ FR3 \end{Bmatrix} = \begin{bmatrix} X & & & \\ & X & & \\ & & X & \\ & & & X \end{bmatrix} \begin{Bmatrix} DP0 \\ DP1 \\ DP2 \\ DP3 \end{Bmatrix} \tag{7}$$

Since the DM is uncoupled and there is only one set of FRs, both the independence and information axioms are satisfied and a revised design is not required. Thus, the DSM can immediately be formed by replacing the FRs with their corresponding DPs. These DPs become the actors that form part of the interaction

Table 1: Mapping of high-level functional requirements, processes, and use case

Customer Needs	Axiomatic Design	Integrated Function Modelling	Use Case
Provide an electrical enclosure conforming to standards/best practices	FR0: Build an electrical enclosure conforming to standards/best practices		Build control panel
Provide means of mounting of devices	FR1: Provide means of mounting of devices	P1: Provide energy to the system	
Provide the components of the system to be enclosed	FR2: Provide the components of the system to be enclosed	P2: Process input and output signals	
Provide an enclosure appropriate to the environment	FR3: Build an enclosure appropriate to the environment	P3: Transmit signals to and from the field	

view of the IFM in Fig. 2. Wires that transmit electrical signals through the various devices in the control panel are included as actors. Operands affecting the actors of the control panel are the users, electricity, and environment, which complete the interaction view. In the actor view, how the actors affect or are affected by the processes are marked as ‘X’ or ‘O’, respectively. Change of states of actors and operands due to an execution of a process by an actor is shown in the state view. Interaction of the actors and operands is addressed by considering safety to users and signal interference affecting signal transmission through the wires in the design of the control panel through the application of engineering standards and guidelines. A more detailed perspective about the application of control panel design standards and guidelines and how they are incorporated into the control panel design algorithm are discussed in the subsequent sections.

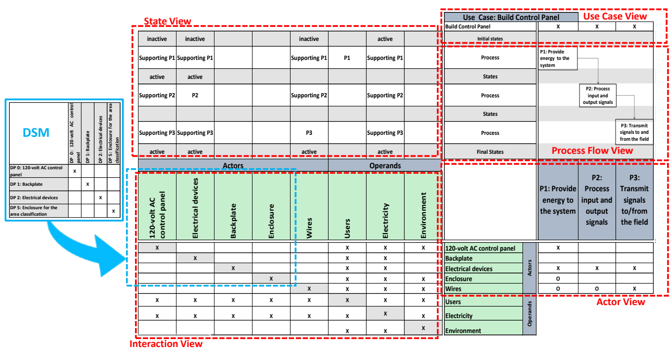

Fig. 2: Integrated Function Model incorporating the Design Structure Matrix of the design example.

3. Integrated design methodology for a control panel

An example of a control system for an automated modular construction machine is described in a study conducted by Tamayo et al. [2]. In this construction automation or in any manufacturing system automation, control panels play a vital role in: (*i*) housing the electrical devices supporting the field devices and (*ii*) maintenance and troubleshooting of these field devices. Control panel design and otimization is usually carried out at the detailed design phase using computer-aided design (CAD) tools. Computer-aided engineering (CAE) assists in the planning and design of a control panel involving engineers, customers, suppliers and system integrators [20]. Kang et al. [24] describe a computer-aided design method of a control panel to meet functional requirements and ergonomic restrictions. The present research approaches a collaborative control panel design at the conceptual design phase prior to any activity, such as computer-aided design, at the detailed design phase.

3.1. Formulating the Design Matrix

Developing the DM requires identification of customer requirements. For the above-cited control panel of the automated modular construction machine, the customer requirements include: (*i*) provide a 120 VAC control panel, (*ii*) must conform to standards and (*iii*) must conform to best practices. All other requirements, such as maintainability, safety, and prevailing guidelines, which are included in these customer requirements, comprise the high-level functional requirements. These requirements can be combined into one main requirement, which is to build a 120 VAC control panel. Thus, building a control panel will also be understood to be fulfilling its safety, functionality, and maintainability requirements. Through the application of engineering knowledge, low-level FRs are generated to support the main requirement. Fig. 3 presents the DM formed from the mechanical, electrical and safety FRs and DPs that conform to control panel design standards. Engineering standards required for the design of a control panel include: (*i*) CSA 22.2 No. 14-13, (*ii*) CSA 22.2 No. 301-16, (*iii*) UL 508A, (*iv*) NFPA 79, (*v*) IEC 61439-1, (*vi*) ISO 9001:2000 and (*vii*) NEMA [22,23].

	DP 0: 120-volt AC control panel	DP 1: Backplate	DP 2: Electrical devices	DP 2.1: AC terminal blocks (TBs)	DP 2.2: Main circuit breaker	DP 2.3: Power supply unit (PSU)	DP 2.4: Programmable Logic Controller (PLC)	DP 2.5: Contactor and relays	DP 2.6: DC terminal blocks	DP 2.7: DIN rails	DP 2.8: Ethernet switch	DP 2.9: Grounding	DP 2.9.1: AC grounding	DP 2.9.2: Instrument grounding	DP 2.10: Segragation/shielding	DP 2.10.1: Grey wire duct for AC wires	DP 2.10.2: White wire duct for DC wires	DP 3: Enclosure for the area classification	DP 3.1: NEMA-compliant enclosure	DP 3.2: Cooling system
FR 0: Build an electrical enclosure conforming to standards/best practices	x																			
FR 1: Provide means of mounting of devices		x																		
FR 2: Provide the components of the system to be enclosed			x																	
FR 2.1: Provide a means of terminating AC field wires				x																
FR 2.2: Provide a means of disconnection and electrical safety protection					x															
FR 2.3: Provide a system to energize field devices						x														
FR 2.4: Provide the machine control system							x													
FR 2.5: Provide a means of protecting users and field devices								x												
FR 2.6: Provide ta means of terminating DC field wires									x											
FR 2.7: Provide a means of mounting the components in the enclosure										x										
FR 2.8: Provide a means of communication with field devices/sensors											x									
FR 2.9: Provide grounding												x								
FR 2.9.1: Provide AC grounding													x							
FR 2.9.2: Provide instrument grounding														x						
FR 2.10: Provide segragation/shielding															x					
FR 2.10.1: Provide a systematic wiring for AC devices																x				
FR 2.10.2: Provide a systematic wiring for DC wires																	x			
FR 3: Build an enclosure appropriate to the environment																		x		
FR 3.1: Provide a standard-compliant enclosure																			x	
FR 3.2: Provide cooling																				x

Fig. 3: Control panel design matix.

3.2. Building the Interaction Matrix

Forming the interaction view of the IFM requires completing the DSM. Since the DM is square, the DSM is obtained by following the steps presented in Fig. 1. These DPs become actors in the interaction view. Users are incorporated as actors as well since they affect and are affected by the processes. In addition to the actors, the following operands are provided: (*i*) electricity and (*ii*) environment. Operands are specifications of energy, material and signals to the system [18]. Electricians are considered as users of the control panel. They play the role of maintaining the integrity and reliability of every electrical component of the system. Electricity is an operand, since the control panel is required to be energized with 120 VAC. Wires transmit electricity throughout the electrical system. With respect to the control panel, electrical devices listed as actors in the interaction view are interconnected with wires. Electrical energy affects the environment through electromagnetic interference (EMI), heat and hazards within the control panel. Interactions of these actors and operands of the control panel form the interaction view in the IFM stage observed in Fig. 1. Refer to figure 3

3.3. Completing the Integrated Function Modeling

Using the interaction view, the standards and best practices are applied to the design of the control panel. For in-depth discussion on control panel best practices see Control Design [20], Al-Abeediah [25], IEEE 1100 [26] and Ennulat [27]. The control panel design follows a sequence of processes: (*P*1) provide energy to the system, (*P*2) process input and output signals, and (*P*3) transmit signals to and from the field. These processes are depicted in the process flow view of the IFM. Actors affecting and affected by the processes are indicated as 'X' and 'O' respectively in the actors view. Fig. 4 presents the state, interaction, use case, process flow and actors views of the control panel design. A linear time complex algorithm is discussed in the next section to illustrate the use of standards and best practices to address the interaction of actors and operands of the IFM in planning the device layout and wiring of the control panel. Mechanical aspects of the control panel design will not be explored in this paper. Meller and Deshazo [28] provide greater details in the mechanical design of electrical box and enclosures. It should be noted that the interaction of the actors and operands involves the safety aspect of control panel design. Thus, a safe environment conforms to the NFPA 70E standard [21], which addresses arc flash hazards, hazard risk assessment and arc flash labeling for the purpose of protecting the users of the control panel.

4. Control panel design algorithm

This section provides an algorithm for planning the layout and wiring of a control panel. This algorithm, as previously indicated, utilizes control panel design best practices and mainly comprises: *(1)* input-output declaration and panel partitioning and placement of devices, *(2)* placement of wireways and *(3)* wire connections. In the absence of information, the lower bound of recommended allowances for future expansion can be used to arrive at a reasonably sized control panel. Aside from the cooling requirement provided in Fig. 4, heat dissipation and ergonomics are considered in the recommended spacings given in control panel design best practices.

Inputs to the algorithm comprises high voltage and low voltage devices. These devices are classified into power supply unit (PSU), circuit breaker (CB), low voltage devices (LV) and low voltage devices that have both high and low voltage terminals

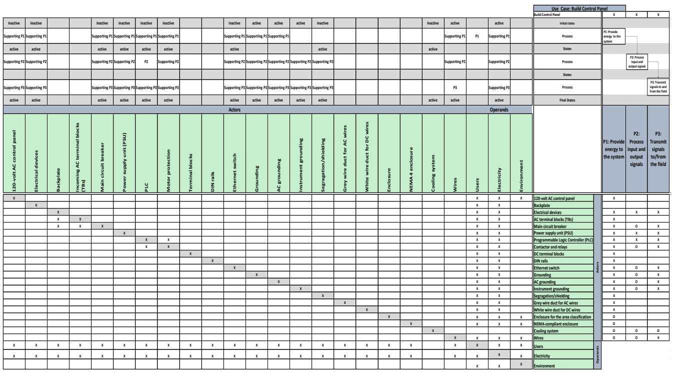

Fig. 4: State, Interaction, Use case, Process flow and Actor views.

(DLV). Distinct from these live inputs are the passive components, i.e., clean and noisy wireways and terminal blocks (TBs). Having defined the inputs, the objective of the algorithm can then be carried out, which is to lay out these inputs into the $left_{section}$, $middle_{section}$ and $right_{section}$ of the control panel. The middle section is further divided into top_{row}, mid_{row} and bot_{row} where the devices are placed and spaced using the functions, *Placedevice* and *Aligndevice*. Applying control panel design best practices: (*i*) places the high voltage devices in the top row, top_{row}, and (*ii*) facilitates the calculation of the top row area, $TopRow_{area}$, that defines the height and the common width of the top and subsequent rows. Similarly, the height of the subsequent rows are obtained from the calculated areas $MidRow_{area}$ and $BotRow_{area}$ for the mid and bottom rows respectively. If the row width is known, low voltage devices are placed from largest to smallest in the middle row and the remaining devices that cannot fit in this row are placed in the bottom row. Devices are mounted on DIN rails whose positions are determined in the *Aligndevice* function. In the calculation of the area of each section, the physical dimensions of horizontal wireways are considered. A device is subtracted from the set of devices, defined at the beginning of the algorithm, after it is placed on the panel.

Having dimensioned the middle section, the remaining wireways and TBs are placed for the high and low voltage sides while honoring best practices and standards on ergonomic spacing and EMI segregation. EMI segregation is performed by ensuring that 120 VAC and 24 VDC wires are run separately in noisy and clean wireways respectively. Similarly, the left and right sections of the panel should only contain 120 VAC and 24 VDC TBs respectively. Part 2 of the algorithm is executed by the function *Placewireway*. For conciseness, the remaining functions are presented at a high level in the algorithm. However,enough details will be provided to describe these functions. *Placewireway* begins with the declaration of the set of wireways and wires and the initialization of the left and right TB variables. This initialization of variables ensures that only one set of TBs is placed in the left or right section of the panel. As in part 1, wireway positions are determined and a wireway is subtracted from the set of previously defined wireways.

Finally, Part 3 of the algorithm involves connecting wires with the function *Connectwires*, which ensures that wires are run and terminated according to (*i*) the correct classification of devices, i.e., CB, PSU, LV or DLV; (*ii*) the correct and shortest wireway, i.e., clean or noisy; and (*iii*) the correct TBs, i.e., 120 VAC TB (leftTB) or 24 VDC TB (righTB). *Connectwires* follows best practices to run wires along their designated wireways and to prevent crisscrossing of noisy and clean wires. These wires are terminated at: *(1)* the device, and *(2)* TBs and another device identified as inputs to the function. It should be noted that for the control panel presented by Tamayo et al. [2], 120 VAC and 24 VDC are considered high-voltage and low-voltage, respectively. Fig. 5 illustrates an application of the algorithm, where wireways are numbered and colored to distinguish the clean from the noisy.

Algorithm 1 Control Panel Layout

$Panel_{area} \leftarrow \langle left_{section}, middle_{section}, right_{section} \rangle$;
$Left_{area} \leftarrow \mathbb{R}$;
$Right_{area} \leftarrow \mathbb{R}$;
▷ Part 1 of the algorithm: Placing devices on the control panel surface
$HighVoltageDevices \leftarrow \{set\ of\ high\ voltage\ devices\}$;
$LowVoltageDevices \leftarrow \{set\ of\ low\ voltage\ devices\}$;
$middle_{section} \leftarrow \langle top_{row}, mid_{row}, bot_{row} \rangle$;
$MiddleTop_{area} \leftarrow \mathbb{R}$;
$MiddleMid_{area} \leftarrow \mathbb{R}$;
$MiddleBot_{area} \leftarrow \mathbb{R}$;
while
  $(\exists\ device \in HighVoltageDevices \wedge (middle_{section} = top_{row}))$ **do**
    Placedevice(device);
    $HighVoltageDevices \leftarrow HighVoltageDevices \setminus device$;
    Aligndevice(device);
    $MiddleTop_{area} \leftarrow Calculatedarea()$;
end while
while
  $(\exists\ device \in LowVoltageDevices \wedge (middle_{section} = mid_{row}) \wedge (Middlemid_{area} \leq MiddleTop_{area}))$ **do**
    Placedevice(device);
    $LowVoltageDevices \leftarrow LowVoltageDevices \setminus device$;
    Aligndevice();
    $MiddleMid_{area} \leftarrow Calculatedarea()$;
end while
while
  $(\exists\ device \in LowVoltageDevices \wedge (Panel_{area} = middle_{section}) \wedge (MiddleMid_{area} > MiddleTop_{area}))$ **do**
    Placedevice(device);
    $LowVoltageDevices \leftarrow LowVoltageDevices \setminus device$;
    Aligndevice(device);
    $MiddleBot_{area} \leftarrow Calculatedarea()$;
end while
Placewireway(wireway);
▷ Part 2 of the algorithm: Placing wireways and TBs
Connectwires(wires, leftTB, rightTB, device);
▷ Part 3: Connecting devices and TBs with wires

5. Conclusion

IFM combined with AD and DSM results in a conceptual design methodology for automated modular construction machines that is systematic, visual, iterative, and transdisciplinary; and due to the mathematical basis of AD and DSM, the result-

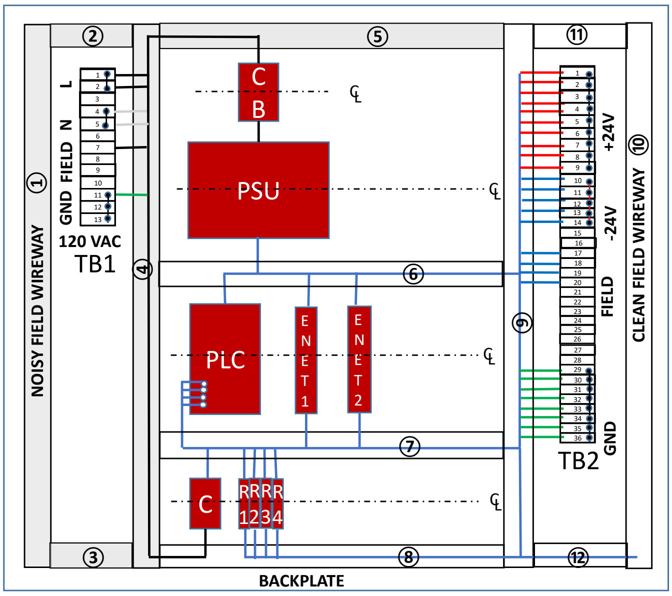

Fig. 5: Control panel layout and wiring.

ing integrated design approach also inherits a scientific property. The research presented in this paper illustrates that the integrated design methodology can be applied to the design of an associated component such as a control panel of an automated modular construction system. Control panels are important subsystems given that they: (*i*) house the devices that comprise the control system, (*ii*) facilitate the upkeep of the control system and most importantly (*iii*) account, in the design process, for safety hazards that affect the users and the environment. Interactions among elements of the system, such as electricity and the environment, are clearly communicated across disciplines through a matrix-based interaction view of the integrated design methodology. A linear time complex algorithm is introduced for planning the control panel device and wiring layouts. Such an algorithm that embodies best practices, complements the computer-aided design of the control panel at the detailed design stage.

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