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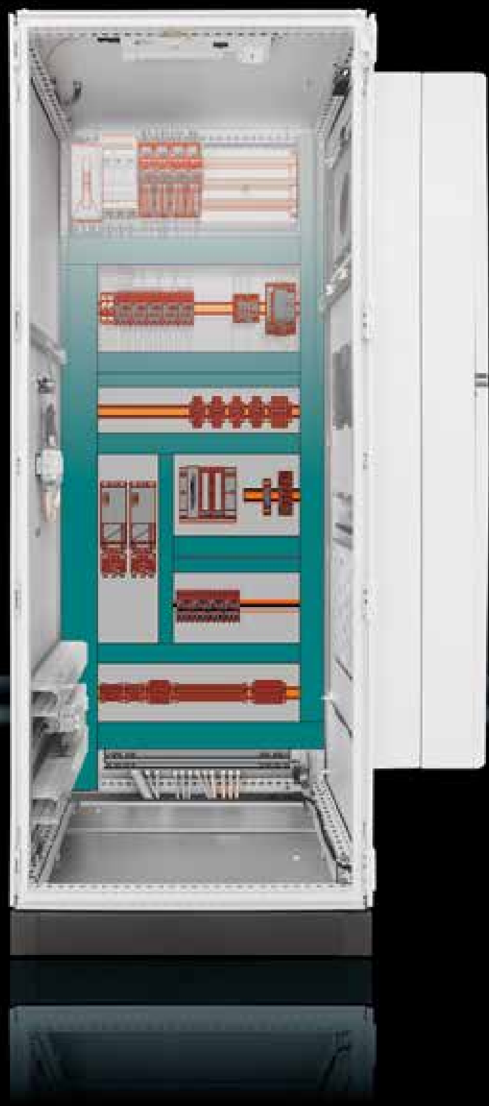
Control Cabinet Manufacturing 4.0

A study on the potential of automation and digitalisation in the manufacturing of control cabinets and switchgears in machine and systems engineering



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Control Cabinet Manufacturing 4.0

A study on the potential of automation and digitalisation in
the manufacturing of control cabinets and switchgears in machine and
systems engineering

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Contents

Index of figures

Index of tables

1 Introduction

The trend towards Industry 4.0 is not a new topic in mechanical engineering. This is evident both from the activities currently taking place in mechanical engineering companies, and has been evident for years in academic research such as that taking place at the University of Stuttgart's Institute for Control Engineering of Machine Tools and Manufacturing Units (ISW). Numerous research projects are being studied here including cloud control engineering, value-added services for mechanical engineers and users, and a modern interconnected production facility, the Arena 2036. Although the ISW focuses on modern manufacturing facilities for vehicles of the future, the issue is the same for general mechanical engineering: How to interconnect manufacturing and apply the data it creates to the entire value chain rather than to just one manufacturing phase? Design and production are two main areas within a product's value chain where personnel undergo differing training and also apply differing working practices, methods and tools. Engineers frequently have differing expectations of the production practices that are eventually applied. Both design and production aspire to the same outcome but use differing vocabulary to express this.

Using control cabinet manufacturing as an example, this study applies knowledge gained from research, and analyses the value chain for a control cabinet for tooling machines and systems. Of the phases in the development of a tooling machine or system (see Figure 1.1), the "Order receipt/creation" and "System start-up" sub-steps are not examined in this study. Manufacturing a control cabinet is primarily manual and faces pressure from increasingly shorter delivery times and a high level of individualisation of tooling machines. Cabinet manufacturers need to respond quickly and flexibly to requirements and to efficiently manage existing and future challenges: the 4th Industrial Revolution offers a multitude of opportunities to master such challenges. The cornerstone of this study is the question "How will control cabinets be manufactured in the future?". Companies from different areas of mechanical engineering have participated in the study providing a broad cross-section of German engineering businesses. Small machine and systems manufacturers with an annual output of only several dozen control cabinets and systems, as well as major, well-known companies took part in the study and provided us with insights into their processes of control cabinet manufacture. In total, 12 companies took part in the study.

Figure 1.1: The phases studied in control cabinet manufacturing. Order creation and control cabinet/machine system start-up are not included in this study

Table 1.1: Categories for the surveyed companies in design/engineering and production/assembly

Category	Design/Engineering	Production/Assembly
Classic	Project/order based approach Creation of a circuit diagram (CD) Schematic layout plan Bills of material in Excel (manual)	Circuit-diagram based production performed page by page. No prefabrication
Standardised	Transition from project-based to template-based engineering Templates available Creation of automated wire lists High level of repetition	List-based manufacturing Prefabrication NC machine Wire sets Partial continuous production
Automated	Techniques of generation, option and maximum project Manufacturers with configurators	Line production Processing systems Prefabrication of all components Good utilisation of machinery

A questionnaire was used to categorise the companies to gain an impression of control cabinet manufacturing in the branch. This served as preparation for on-site discussions carried out according to the categories in Table 1.1. The categories differentiate between "Classic", "Standardised", and "Automated" control cabinet manufacturing. These classifications were applied to the areas of design/engineering as well as to production/ assembly. The companies were also asked to provide statistics on their control cabinet manufacturing to enable comparisons to be made based on an average control cabinet as shown in Table 1.2. Such quantification enables an objective, quantitative response to the study questions rather than subjective impressions. The distribution of working times in both areas of control cabinet manufacturing as can be seen in figures 2.1 and 3.1.

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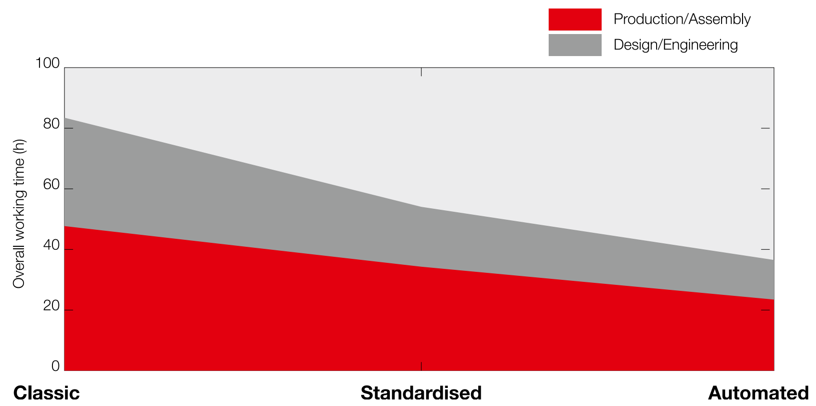
Figures 1.2: Working times from classic, standardised and automated control cabinet manufacturing for design/engineering and production/assembly



From these figures, time-savings between the categories can be determined which can be further improved through exploiting potentials. For example, companies which still work on a project/order basis can make time savings of up to 45% in their engineering processes by shifting to function-based, modular circuit diagrams. In addition to proposing several pragmatic measures to achieve improvements, the study also engages with the use of 3D production data. What potential and opportunities are offered by 3D engineering drawings and are they the key to the digital factory? The study also looks at working approaches in production facilities and contrasts these to car manufacturing. It is well-known that car manufacturing applies continuous production; despite a high product individualisation, a high degree of component standardisation has still been achieved. Is there a similar approach for control cabinet and switchgear manufacturing?

This study is structured as follows: Section 2 engages with the potentials in design and engineering. Section 3 deals intensively with the area of production and assembly. Both sections describe individual areas of activity, the problems these have, possible solutions and opportunities. Section 4 reports on trends, from the companies' perspectives, in control cabinet manufacturing. Section 5 concludes the study with a summary and outlook of Control Cabinet Manufacturing 4.0 of the future.

Table 1.2: Components in an average control cabinet and the average working times per component. This determines the overall average production time for a control cabinet

Component (average)	Work unit (WU)	Time/WU min
Holes (drilling in body)	10	5
Cut-outs (body)	4	10
Cable ducts (sections)	20	1.5
Holes/Threads mounting panel	100	2
Installing devices	30	2
Labelling (devices)	200	2
Wiring connections	500	4.5
Terminal construction plans	130	1
Testing	1	240
Production time (total in h)		**57 h**

2 Design and engineering

This section examines phases in the design and engineering of control cabinets. It is assumed that requirements for the machine, system or control cabinet are already known which have then been used to create engineering drawings and circuit diagrams (CD) from which bills of material can be derived and ordering triggered. The phases that are examined as well as their core timings are portrayed in Figure 2.1. The project planning and circuit-diagram creation phases require more than 50% of overall time, and are where significant potentials for savings exist. The subsequent phases of CD checking and documentation require almost a third of the overall working time. As this section will reveal, these phases contain optimisation potential for time and financial savings.

2.1 A consistent engineering chain/software

Current-day product development processes (PDP) are usually possible only through the intensive utilisation of software-based systems to perform tasks. This is the reason why a multitude of different software systems exist: good software is usually restricted to specific rather than general applications. For example, CAD systems are available for architects and engineers but they lack costing or ordering functions. These are provided by solutions such as Excel or ERP systems. Different software systems therefore need to be used for different phases in control cabinet manufacturing. An engineering drawing created with CAD software will need to be converted into a different format before being used by procurement or logistics.

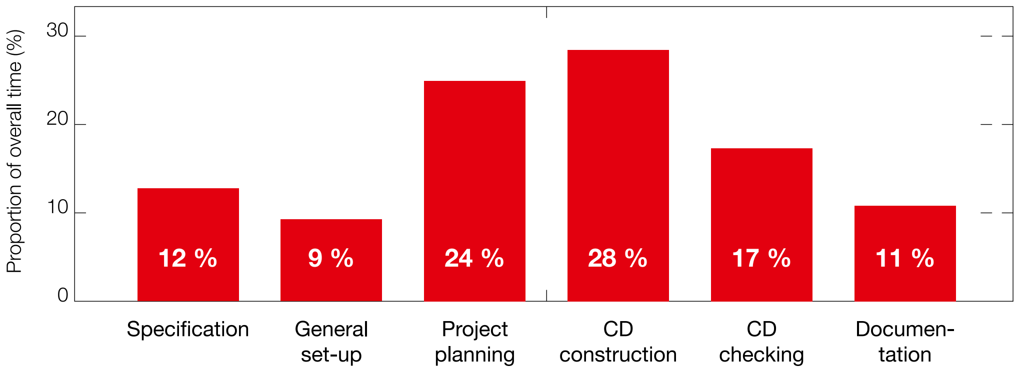


Figure 2.1: Phases in the design/engineering of a control cabinet and times as a proportion of overall time

Software landscapes of the past has led to the creation of a multitude of small stand-alone systems which makes a smooth transfer of CAD data to procurement, pre-planning, logistics and quality control systems impossible without additional actions. Although there are now integrated solutions such as the EPLAN Engineering Configuration which can process CAD/CAE designs as well as the entire product development processes, many companies do not use them. Just 18% of the participating companies have recently begun using the EPLAN tool to manage new machinery and systems series more quickly and configure more simply, also by making using an integrated configurator. The remaining 82% of companies use highly diverse software systems for their CAD, CAE, ERP etc. tasks. Many use the well-known SolidWorks CAD software, but in combination with different ERP systems such as from abas, SAP, Infor or BAAN. For CAE design, EPLAN Electric P8 in combination with EPLAN Pro Panel are used with only few exceptions.

The use of separate, specialist software systems creates the problem of data isolation. File formats and stored files from, e.g. SolidWorks, cannot be imported directly into, e.g. SAP and then processed without further ado. Most companies have therefore created their own data transfers solutions. For companies with a low annual output of control cabinets, documents and data are manually transferred to the relevant software for further processing. 90% of companies have created their own largely automated solutions using XML-file exports which can then be re-imported semi-automatically. The desire to have a continuous (or at least a minimally fragmented) engineering chain means software engineers have developed their own macros or plug-ins for the relevant software systems. Maintaining and adapting such software plug-ins is extremely time consuming and costly and so is not being seriously pursued by companies. Furthermore, the latest versions of the software systems are not always being used.

This highly diversified range of software systems present many customers with obstacles not only in engineering but also in production. Companies categorised as classic perform a multitude of manual phases in data transfer (e.g. the creation of bills of material or terminal labelling). Companies who have standardised their control cabinet manufacturing are already able to automatically generate the necessary documents from engineering drawings. Automated control cabinet manufacture, on the other hand, gives access to an integrated software solution so that data no longer requires transferring from one software system into another.

There are three feasible approaches to overcome this issue. The first is to use a single software system which can be applied to all, or at least the main, phases in control cabinet manufacture (these phases being CAD/CAE design, the generation of production drawings, prefabrication of wires and terminals). The second is to use open interfaces within the software chain to permit the required information to be simply extracted/imported. This of course has limitations because the information required cannot/must not always be recorded within a specific software system, i.e. data models are generally not designed for recording extra information. For example, saving list prices for a converter is not important in a CAD/ CAE drawing, while details on a device's dimensions is largely irrelevant for bills of material. A third approach is the introduction of a standardised file format for recording the project. CAD/CAE would then only read in and re-save data necessary for its phase. This would apply also to the other software systems being used by the project.

Assuming a fully integrated, project-management system actually exists for control cabinet manufacturing, the question of data transfer still remains. Many companies have been using the same software systems for years thereby having gained vast experience in using them. This accumulated knowledge is a major aid to inducting new colleagues into their tasks. But it represents a not to be underestimated obstacle to implementing new software into established engineering processes. New software implementation means engineers need to invest extra effort familiarising themselves with it, and requires a data compatible transfer of ongoing and completed projects.

On the other hand, not implementing new software hinders improvements to working procedures. An integrated software solution enables faster completion of projects and results in fewer errors occurring than in the manual transfer of data. The surveyed companies estimated efficiency gains of up to 43% in engineering.

2.2 Less diversity, more thinking in functions

Similar to the car industry in which no two finished vehicles are identical, control cabinet manufacturing has a high degree of functional variance. The range of combinations is obviously not as extensive as in vehicles but diversity is however extensive. 63% of surveyed companies claimed that the proportion of special parts in their control cabinets exceed 50%. 27% have a low-level of variance (smaller than 20%) as well as a 50% ratio of serial parts to special parts. Just 9% have mainly serial products in their control cabinet manufacturing.

Engineering of control cabinets still takes place in 27% of companies on a project/order basis (classic engineering). A list of devices to be installed is derived from the requirements of a machine (or a control cabinet/switchgear in job order/contract production). This list is then transferred to a CAD/CAE system to create a 2D CAD engineering drawing for precision component placement, and a CAE drawing or a circuit diagram. The documents are then used to derive detailed bills of material, i.e. including the number and type of terminals, contactors, etc. The obvious disadvantage with this approach is that the wheel literally has to be reinvented for each new control cabinet. This is more time-consuming and costly than working with standardised components. Furthermore, habitual errors can often occur using this method so that wiring always requires manual checking.

In contrast, 72% of surveyed companies are already using template-based engineering. Using project templates based either on a series or specific functionalities enables a high rate of reusability. Furthermore, in engineering only the additional components need to be integrated – when these have already been created as functional units, the integration phase should be short and error-free. 23% of the companies using standardised engineering have recently begun using a configurator for creating engineering drawings. The separate functional units of a machine or system are stored in a database along with their corresponding interfaces and additional information. This reduces design effort to a minimum because the configurator undertakes most of the work. Engineers use the configurator to select a basis machine and then the functions that the customer requires. After the machine has been assembled in this way, CAD and CAE drawings are automatically generated. The configurator undertakes control cabinet testing, e.g. for missing components, conflicting combinations or the erroneous allocation of terminals and contactors.

The current approach to control cabinet manufacturing is deeply rooted in the development of a cabinet. Most engineers of today are familiar with a task-based approach in which the requirements of a given task/project are to be fulfilled. This approach does not permit unconventional ways of thinking (or in this case, functional ways thinking). Work phases can, however, be greatly simplified and speeded up by the use of functional units (FU). Functional units are to be seen from the basis of the machine or system and are reflected in a control cabinet. An example is a tool holder compressor in a machining centre. From an electrical engineering perspective, it requires pressure sensors including I/O terminals, the I/O terminals of the compressor, and a power supply. This functional unit (FU) can be designed once, the internal circuit diagram created and tested (i.e. without having to communicate with the FU), enabling the FU to be then used in engineering. Testing of these components are therefore unnecessary or only minimal, i.e. testing is required only of the circuit diagram at the interface to the FU.

One fact that needs be mentioned that could prevent implementation of standardised engineering is that design engineering training must undergo change. It requires a shift from project-based thinking to modular, mechatronic based thinking. A restructuring of training is required not only in universities and vocational colleges but also for in-house and further training of personnel.

For the majority of the surveyed companies (55 %), a modular approach to engineering and production is not an option. The main argument against implementation of functional development was given as the effort required for FU creation as well as the high level of diversity in control cabinets and machinery/systems. It was also argued that there is a lack of expertise in FU creation due to the lack of clarity on how a control cabinet or machine/system can be structured according to functional units. This process may, in certain circumstances, be rather a task for the development of a new machine series rather than for control cabinet production.

Companies who are already working according to functional engineering, thereby enabling the use of (online) configurators, report substantial time gains in control cabinet manufacture. Up to 44% savings in time and costs are possible. The main work in a project then concerns only the availability of the components and a quick optical inspection of the engineering drawings (CAD and CAE). However, new areas of activity need to be created for machine standardisation and the creation and maintenance of FUs. But this can be achieved independently from ongoing orders and can therefore be seen as a part of a process of ongoing improvement.

The benefits of function-based engineering are obvious. Using functional units minimises checking effort and can be performed independently of ongoing project work. Not least of all, design plans derived from a standardised engineering chain-, can be assumed to be basically error-free. This eases the work of design engineers, and mechanical and electrical technicians can work more efficiently due to the production plans generally being correct.

2.3 3D engineering drawings

An engineering drawing is only as good as the information it contains and the information that can be directly derived from it. A good engineering drawing also enables information to be read and understood quickly without requiring detailed knowledge of the object to be created. An engineering drawing is essential to enable mechanical and electrical technicians to carry out error-free production tasks. However, from a designer‘s/engineer’s perspective, an engineering drawing is much more than this.

It is an evolutionary document which will undergo adaptation and changes beyond a specific project period. Minor aids, such as improved virtual portrayal for better visual perception, can generate significant benefits and simplify manufacturing. Modern day computers are capable of portraying complex, 3D objects that are recognisable to even untrained viewers. However, 63% of companies still use only 2D engineering drawings in control cabinet manufacturing. The disadvantage to engineers is that only two of the three dimensions are being used in design. Because space is limited in control cabinet manufacturing, components need installing also on the side panels and doors. Without good visual aids, it is impossible to identify spatial collisions in flat drawings. Furthermore, a flat representation of a control cabinet does not permit the extraction of meta information such as wire lengths because the information on device height is missing to enable a determination of correct wire lengths.

But the majority of surveyed companies still rely on 2D engineering drawings. The reason given is the time and costs involved in conversion. In addition to 3D drawings offering improved visual representations and overviews, extra information can also be saved for use in other process phases. The required wire and cable lengths between individual components and cable duct capacities can be automatically determined. Dimensions can be correctly determined because the spatial arrangement of devices can be checked beforehand thereby enabling automation of the control cabinet’s mechanical processing. A design model can be virtually displayed during mechanical and electrical production, providing technicians instant visual feedback to check the correctness of their work.

In addition to direct checking during work phases, information from a 3D control cabinet can also be used for the “digital twin”, i.e. the virtual portrayal of a control cabinet that can be constructed and tested in parallel to its actual manufacturing. This virtual digital twin can be used, prior to actual manufacturing, to virtually run the control software, eliminating the need for this task to be carried out at the end of manufacturing.

This topic raises the general question of why 2D engineering plans are still being created in engineering when manufacturing of a control cabinet takes place anyway in three dimensions. Working in 2D is counter-intuitive and counter-productive yet is being practised more often than not.

To gain the full benefits of 3D design requires companies to exploit the potential of this technology in multiple manufacturing phases. The most benefits are in the engineering phase where data is created and modified. In subsequent phases, data is generally only read. In addition to the implementation of a CAD and CAE systems with 3D drawing capabilities, existing data also needs to be extended and possibly migrated. The effort required to extend data (adding component heights, recording CAD models etc.) is usually the biggest hurdle given by many companies for not migrating data. Correctly processing CAD data can be difficult especially in the context of modularisation and the structuring of a control cabinet into functional units. But the time gains should not be ignored – up to 35% of engineering time and up to 22% of production time can be saved because drawings can be fully trusted.

3D engineering drawings also offer benefits for technicians in production. These are provided separately in the following sections.

Production and assembly

This section examines the procedures in the production and assembly of control cabinets. It assumes that certain documents have been available from engineering that have triggered component orders, the majority of which have already been delivered. The phases as well as their core timings are portrayed in Figure 3.1. Almost 75% of time is required for the phases of mechanical component assembly and wiring (including electrical component assembly) where significant potential for optimisation can be assumed. The phases before and after these account for the remaining 25% where no significant improvements can be realised. As this section will reveal, these phases contain optimisation potential for time and financial savings.

3.1 Preplanning, component picking and logistics

Preplanning is a major element in control cabinet manufacturing. Control cabinets generally comprise a multitude of terminals and wiring. Well prepared production begins with component picking, i.e. the assembling of the components required for a specific control cabinet. A long outdated approach is undertaken by the technician who alone organises the required components. This results in lengthy, criss-crossing procedures. The move towards Industry 4.0 involves isolating tasks and areas of expertise so that savings in time and costs can be made via picking of the majority of components for a control cabinet.

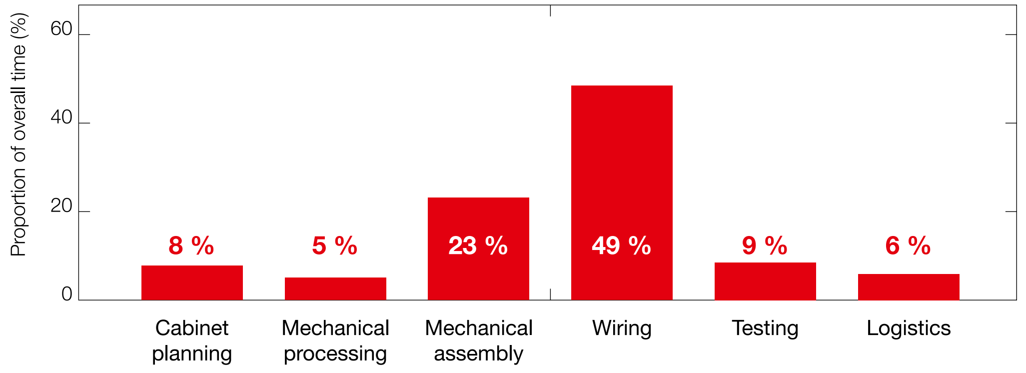


Figure 3.1: Phases in the production/assembly of a control cabinet and times as a proportion of overall time

Components in control manufacturing can be classified into three categories according to their size and purpose and are therefore generally located in different areas within production halls. Quantifiable components, such as drive amplifiers and terminals are held in large storerooms. Wire and cable spools are located near the production machines where wiring and cabling takes place. At the companies visited, non-quantifiable components, i.e. bulk material, used different storage methods ranging from centralised kanban systems through to mini stockholding systems at the workplace.

As already mentioned, control cabinets are comprised of a multitude of components making mechanical component assembly and wiring a lengthy, manual process. This can, however, be made significantly faster by intelligent use of existing information in 3D models. A dedicated procedure of preplanning and commissioning enables the prefabrication of terminals (positioned in strips and labelled) to make installation significantly faster and eliminating transfer routes. The same applies to wiring which accounts on average for almost 60% of production time. By using prefabricated wiring or wiring sets (at the required length and thickness and with connectors added), time savings of up to 35% can be achieved. In combination with list-based wiring, up to 50% is achievable. To exploit such potential, workplaces need to be adapted with boxes or mobile shelving for storing the picked goods. Furthermore, detailed and checked bills of material from engineering are needed to guarantee accurate picking.

This study makes it clear that for control cabinets of the future, components need to be prefabricated and available at the relevant workplaces, and bulk materials need to be provided to technicians via kanban systems, irrespective of whether nested or continuous production systems are being used.

3.2 Multimedia devices for information portrayal

People today are surrounded by digital devices and multimedia information sources. The latest stock exchange indices, news or images of friends are just a click away. Routine use of smartphones or tablets is no longer the exception. It was common in the production halls of the surveyed companies for primarily paper-based production to be seen as no longer appropriate. However, all surveyed companies, with few exceptions, rely primarily on analogue documentation in production.

Preplanning digitally access component and stock lists and then print them out for the picking trolleys. In the actual production of the control cabinet, i.e. mechanical and electrical processing and assembly, only printed documents and handwritten notes are being used in the form of circuit diagrams and wiring lists through to change management and testing documentation. Masses of documents numbering several hundred pages are not unusual.

A paper-based production system is not really a disadvantage, but does represent a major challenge to keep order of the vast quantity of paper. For example, a circuit diagram is made up of an average of 320 pages with electricians needing to browse through them several times during wiring to find wire destinations. Simple portrayal of routing information, such as that provided by a wiring list or a digital circuit diagram, is not possible. Furthermore, paper documents are exposed to surrounding conditions, e.g. the grime of a production hall can make documents unreadable. Changes taking place during production (e.g. component repositioning because of a collision, or the re-correction of wiring details due to a triplicate terminal connection) are not major problems but need to be recorded and subsequently reconciled with the digital documentation. For such change management, the surveyed companies use two main approaches: changes are either marked in the relevant engineering documents (e.g. circuit diagrams) with a cover sheet listing all amended sections, or changes are made exclusively in a detailed log/table of changes. Both approaches are based on having one further, multi-page, detailed paper document and therefore do not help the paper problem. They also introduces an additional task at the final documentation phase of having to transfer changes from handwritten notes to the digital engineering drawings.

A further problem with paper documents, according to all surveyed companies, is the persistency of changes being made to control cabinets. Comments or changes to a document are easy to make using a pencil. However, major changes, e.g. customer changes requiring different components, cannot take place without further action. Such modifications generally take place within the engineering department so it can take time until the updated data arrives at production. According to the surveyed companies, this can take up to a week or even 2 in exceptional cases.

During this time, further changes might have taken place further complicating change management and highlighting the problem of paper-based data processing.

The surveyed companies were not only open to the proposition of digital document folders, some had already considered doing it. Two companies had already carried out initial evaluations on the feasibility and effort required to implement digital document folders. Overall, many engineers and production supervisors as well as mechanical and electrical technicians would welcome digital document folders to enable faster viewing of engineering drawings as well as the relevant production information. They see major benefits in this respect. For example, such information can be displayed relatively easily for wiring. The average time for wiring using a circuit diagram is 54 h with around 31%

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of the time required for preparatory tasks such as reading the diagram and locating source and destination points. A further 13% of time is required for preparatory work on the wire – initial routing and estimating wire lengths. The remaining 56% is for the actual wiring – cutting, adding connectors, crimping. A third of the time is therefore spent reading the document – with an average of 500 wires per control cabinet and an average time of 54 hours for wiring, this equates to 16.74 hours per control cabinet. A software-based system which can visually portray the source and destination points of a wire – whether in a digital circuit diagram or a virtual 3D CAD/CAE drawing – can reduce this effort by up to 81%.

Digital devices can also be profitably applied in other areas of control cabinet manufacturing. In electrical component can be visually displayed assembly, information on the location of a component by highlighting it in a CAD drawing. To use such new media requires consistent and accurate engineering drawings. Information to be displayed in production must be created in a preceding phase. This requires at the least a detailed and tested 2D engineering drawing – whether this has been created using maximum techniques or configurators is of less importance. In addition to the generation of accurate production data, production availability also needs to be achieved. This is generally an information technology task which can be undertaken by internal IT departments or outsourced.

Depending on the existing production halls, wireless communication is possible but a cable-linked system would also be sufficient. Providers of such software systems need to develop detailed security systems with role-based permissions to prevent unauthorised changes taking place. This might be achieved using an approvals function at final testing of the control cabinet. Furthermore, issues such as what to do with contradictory or simultaneous changes need to be addressed as well as the issuing of change notifications.

3.3 Mechanical processing and assembly

Mechanical production comprises mechanical processing and mechanical assembly and is the first of two basic phases to produce a functioning control cabinet from engineering drawings. Among the surveyed companies, both phases are mainly performed manually so it can be assumed that major potential exists for digitalised and (semi)-automated production. This section looks more closely at the phases “mechanical processing” and “mechanical assembly”.

3.3.1 Mechanical processing

Mechanical processing of a control cabinet includes processing of the body via drilling and the creation of recesses for switches, buttons, cooling units and cut-outs, as well as the processing of mounting panels (none of the surveyed companies use rail systems in their control cabinets). Only 45% of companies carry out this phase themselves. A small majority obtain their control cabinets prefabricated from a supplier. Although this has the advantage of eliminating the need for a mechanical processing department – which, for low annual outputs of control cabinets, would be underutilised and have a high rate of downtime – control cabinet manufacturing then becomes dependent on supplier delivery terms. Companies with low annual outputs of switch-gears and cabinets lose competitiveness because under certain circumstances the terms and conditions offered by suppliers are not competitive.

The surveyed companies with in-house mechanical processing perform it exclusively with automated processing machines – either punching machines or CNC milling/drilling machines. Apart from different processing techniques, the main differences between these companies concern the use of engineering drawings in the processing procedure. In 58% of cases, machine instructions are performed by manually inputting dimensions for cut-outs and drilling. This creates susceptibility to incorrect input and requires accurate reading of the engineering drawing. High precision is required here because drill holes for fixing components generally involve low production tolerances – screw positions for voltage inverters are specified by the manufacturer. The remaining 42% have mainly automated processing. The loading and unloading of CNC machines takes place manually but processing profiles already exist in the machines and require only correct loading by the technician. These profiles can be taken from 2D or 3D CAD drawings or can be based on standardised components– e.g. just one specific type of kill switch for ISO certified control cabinets.

In addition to the mechanical processing of a control cabinet body and mounting panel, the cutting to length of DIN rails and cable ducts can also be standardised and automated. Surprisingly, all of the surveyed companies perform manual cutting and installation of components based on an evaluated engineering drawing. Minor mechanical aids are used to simplify cutting but details on the length and diameter of cable ducts are taking from engineering drawings – no list of the lengths to be created exists similar to a wiring list.

It is easy to see that among the multitude of these manual tasks errors can occur which could be avoided by a few easily realisable steps. As a rule, the engineering drawings for a control cabinet exist prior to production beginning so they can be used to obtain production information needed for mechanical processing. By implementing this step in the engineering of a control cabinet, the mounting panel could be clamped in the relevant processing machine and automatically provided with the required drill holes and cut-outs. This approach could also be applied to the walls of a control cabinet body as these are generally detachable from the cabinet frame. Up to 55% of time savings in mechanical processing can then be achieved.

The use of a CNC mini/drilling machine (manual or automated programming) is an option for some of the surveyed companies (27 %) due to the purchasing and operating costs exceeding capacities. This issue is mainly academic for companies with low annual manufacturing output because the high rate of utilisation necessary for these machines cannot be provided. On the other hand, obvious benefits are provided by CNC-based processing such as a high level of absolute and repeat precision.

3.3.2 Mechanical assembly

Following mechanical processing of a control cabinet (mounting panel, side walls and doors), DIN rails, cable ducts, seals and brackets for the components are installed. For all surveyed companies (only 45% mechanically process their control cabinets in-house), this phase takes place manually with mechanical aids being used only for cutting the DIN rails and cable ducts to length. The production instructions are obtained by technicians from the available engineering drawings and transferred to the process.

The required small parts (screws, nuts, sleeves etc.) are generally acquired by technicians themselves in a component picking phase. In any event, there is no packaging of the required bulk parts although this would bring benefits by avoiding transfer routes and incorrect estimations of the required quantities. However, much more serious is the non-utilisation of existing information from engineering drawings for automated production.

Engineering drawings today can be provided with additional information which can also give production instructions. Engineering drawings exist prior to production starting so in principle it is possible to use the drawings to obtain the lengths of DIN rails and cable ducts for automated cutting. It is even feasible to use a processing centre where cutting is carried out as well as the fixing or riveting of DIN rails and cable ducts. In fully automated production, this can enable up to 83% time savings, and in semi-automated production, up to 47% is achievable. In addition to these possible time savings, automated control cabinet manufacturing can also save on material costs. Digital engineering drawings can be used to optimally obtain the required lengths of cable ducts from existing stocks thereby reducing or possibly even preventing wastage. This provides both economic and ecological benefits. However, such automated phases require consistent and checked 3D engineering drawings of the control cabinet.

3.4 Electrical assembly and wiring

All participating companies perform the assembly and wiring of the cabinet in-house. 27% of companies still acquire their control cabinets pre-fabricated, i.e. already with cut-outs and recesses. The proportion of mechanical assembly and wiring therefore takes up almost 75% of processing time (see Figure 3.1). Electrical assembly and wiring is the phase in control cabinet manufacturing that is capable by far of benefiting from digitalisation and automation. “Electrical assembly” and “electrical wiring” are examined separately in the following.

3.4.1 Electrical assembly

The electrical assembly of a control cabinet is the first of two steps in electrical production in which devices (transducers, contactors, signalling devices, power supplies etc.) as well as smaller components such as terminals, switches and buttons are installed. As a basis for assembly, technicians use either bills of material (for 45% of the surveyed companies) or circuit diagrams (55 % of the surveyed companies). Assembly using bills of material is beneficial because such bills are pre-sorted by component thereby giving an easy overview. Using a circuit diagram to determine components requires much more effort and is more prone to errors with several hundreds of pages needing to be browsed. 81% of companies do not pick bulk goods (terminals, screws, jumpers) due to it being impractical. Technicians are therefore required to maintain a certain amount of bulk goods at their workplaces. 22% of companies use a kanban systems while all other cases require technicians to take responsibility for monitoring stocks themselves and, when necessary, replenishing them from a centralised store. The remaining 18% of surveyed companies obtain their terminal strips prefabricated from suppliers thereby saving both picking and terminal-strip fabrication. Installing such terminal strips reduces effort by up to 92%.

The installation of devices can take place only when a relevant engineering drawing is available. Such drawings provide the positioning of cable ducts and DIN rails, with specific areas then being designated for inverters, bus couplers and terminals. In 18% of cases, control cabinets are assembled without engineering drawings and use only circuit diagrams as a basis. Reasons given for this are too shorter project times and therefore no option for preplanning and the corresponding engineering.

As in other phases of control cabinet manufacturing, automated assembly using terminals or devices requires a detailed model of the control cabinet. In the majority of surveyed companies (72%), the number of terminals are manually taken from the circuit diagram. Increased effort is therefore required due to the task being manual and error prone. This can be avoided and made faster by taking relevant action in the engineering phase. A digital model of a control cabinet can also be used for terminal prefabrication by in-house preplanning or an external service provider. This delivers time gains of up to 90% and stockholdings can be reduced via a just-in-time supply of fabricated terminal strips.

If standardised components or "functional units" are used in the engineering of control cabinets, terminal packages or complete terminal strips can, due to standardisation, be kept in stock as prefabricated parts. These can then be supplied in preplanning and/or picking, together with the functional units. If this approach is combined with the outsourcing of terminal prefabrication to external service providers, up to 90% time-savings can be gained because terminal-strip bundles are capable of high-speed installation using special clip systems.

3.4.2 Electrical wiring

A main phase in control cabinet manufacturing by far is electrical wiring in which devices are connected to each other to produce an electrically functioning control cabinet. This phase is also by far the most time-consuming phase for all surveyed companies, requiring 49% of overall production time irrespective of the quality of information coming from engineering. The technicians performing the work need to be highly trained to read circuit diagrams and have the skills to spot possible errors. In 90% of companies, the circuit diagrams is used as a basis for wiring which provides information only on the source and destination of a connection. Additional information such as wire length, colour, thickness and cable-end configuration would enable faster wiring.

The correct selection of wire thickness is important for correct cabinet functioning and depends on the technician being highly trained. Circuit diagrams, which frequently comprise hundreds of pages, are not very informative, generally lack important information for wiring and can be considered as a complex portrayal of a list of links. Circuit diagrams are also difficult to work with because of their counter-intuitiveness and non-linearity: components that in a control cabinet are placed sequentially to each other will not necessarily be described on sequential pages in the corresponding circuit diagram. It is more the rule than the exception that technicians need to browse through the complete circuit diagram multiple times during the wiring process to connect all components together. In addition to the average 42 seconds required for wire routing, a further 67 seconds are needed for reading the circuit diagram and locating the components on the mounting panel and/or side walls. Another wiring task is wire preparation, i.e. cutting to length, crimping and labelling, which requires another 157 seconds. In total, an average technician requires an average of 266 second to wire together two control cabinet components – this represents a good 4 1/2 minutes per wire.

To perform wiring using a wiring list is a more advanced approach than classic wiring using a circuit diagram. The wiring list method is being used by only 9% of the surveyed companies. Even in these cases, control cabinets are usually wired according to circuit diagrams due to technicians finding them easier to read. Interestingly, this is exactly the opposite to what a wiring list should achieve. The information in a wiring list includes, in addition to source and destination points, additional information such as wire length, diameter, colour and labelling. Further information is also available as required. A wiring list allows a much more linear realisation of the wiring then a circuit diagram. To create a complete and correct wiring list requires, however, additional information from engineering such as the type of wire as well as its thickness – this information depends on the component to be wired and therefore needs to be recorded in the CAD-/CAE models.

In 72% of the surveyed companies, errors are usually first detected at the production stage because drawings are not checked in engineering. Such errors include overfull cable ducts, collisions between devices and body components, and hindrances to thermal convection. Electrical technicians are trained well enough to enable them to rectify such errors and to record the changes to a change log. At the end of control cabinet testing, the information in the logs is transferred to the digital documentation to ensure it matches the end product. This step would be unnecessary in fully digitalised production because technicians would enter the changes directly into the digital engineering drawings.

To revolutionise wiring, different solutions and approaches need to be considered. If circuit diagrams are being used, time savings of up to 32% can be achieved through the structured portrayal in a wiring list of the procedure, especially the actual wiring. Furthermore, wiring using a wiring list does not require the skills of highly qualified technicians, which represents an economic benefit when requiring extra staff in peak periods. In addition to the reading of wiring instructions, cutting wires to length is also a time-consuming process which usually requires years of experience until it becomes fast and virtually error-free. A circuit diagram contains no information about the routing of a wire. It is therefore impossible to use fabricated wires so technicians need to perform multiple tasks: the laying of wires, preparation, completion and installation. 3D engineering drawings, however, provide information on wire routing and length. Furthermore, the full-capacity of cable ducts can already be determined during engineering. This is all possible in just a few clicks using relevant 3D development software.

As well as the already mentioned approaches, some control cabinet manufacturers are considering digital production systems in which wiring takes place without any human input. The market currently has only a few providers pursuing such systems. However, their presence alone shows the direction in which control cabinet manufacturing is going. The use of such systems is perhaps debatable for companies with a low output of more individualised control cabinets, but those with high outputs can achieve time savings in wiring of up to 63%. It must be observed, however, that these machines are far from working as intelligently and experienced as trained technicians. Minor deviations in mechanical or electrical assembly can result in a component being incorrectly connected making a control cabinet inoperable. To use wiring robots or wiring machines requires product development processes to be applied to the control cabinet from the very start to deliver high-quality engineering and production data. Only in this way can the benefits be enjoyed of semi or fully automated production.

3.5 Testing

Testing of a control cabinet is necessary for all control cabinet manufacturers to ensure the correct production and functionality of all components. Testing does not just cover final testing of a control cabinet but also ongoing tests during production. This includes checking of production drawings prior to the different phases as well as optical inspection following conclusion of a phase. 36% of surveyed companies performed intensive testing during phases which are performed by the technician doing the work and then checked for correctness by the next technician. This approach requires extra effort during the individual phase but has the benefit of identifying and rectifying errors at an early stage. Furthermore, each technician indirectly becomes his or her own tester and therefore carries out his/her work more reliably.

25% of surveyed companies carry out electrotechnical final testing including functional testing following wiring – the remaining 75% carry out only electrotechnical testing. Electrotechnical testing checks only correct wiring of the control cabinet and not the correct functioning of individual components. Functional testing of a control cabinet additionally tests performance thereby also validating safety circuits. Of the 75% of companies performing electrotechnical testing, 16% also carry out functional testing during engineering in a virtual start-up procedure. Errors in control software can therefore be rectified prior to production. Final electrotechnical testing takes place in all cases by checking electrical potentials using potentiometers. The testing methods differ only by the equipment being used (standard or programmable potentiometers). Functional testing of control cabinets and switchgears use test controller equipment. In all cases, these are controllers, programmed by the company and created from a corresponding machine's "maximum project". This enables self testing of production tasks as well as components. 18% of cases also perform load testing on the cabinets. This requires additional preparatory effort but enables problem-free connection in the field to be performed. If control cabinet testing is performed only when the cabinet is located in the field (18% of companies perform field testing or leave testing to the customer), damage can occur to the machine or system resulting in expensive repairs.

Unfortunately there is no general solution to control cabinet testing due to the multitude of possible configurations. Furthermore, there are also issues of different customer requirements and delivery conditions, e.g. to foreign locations. For the series-type manufacturing of control cabinets, a general routine can be created for functional testing which can then be extended for specific modules. Such test procedures can be carried out either manually or automatically whereby an average testing time of at least four hours (providing no errors exist) makes a semi or fully automated system (e.g. by a test robot) preferable. Testing can then take place overnight with the results being analysed the next morning and erroneous systems then subjected to closer examination. Unnecessary production downtimes are then avoided.

A further option to achieve continuous testing in control cabinet manufacturing is through augmented reality plus continuous process monitoring in the production phases. Augmented reality merges the real and virtual worlds and enables technicians to obtain information, for example, through eyeglasses or a monitor positioned above the assembly surface. Any information can be displayed, such as details on drill holes or a component, as well the start and destination points in wiring. Continuous process monitoring results in the work undergoing permanent testing to enable early and automatic detection of errors. This requires detailed and checked engineering drawings which have at least a 2D model of the control cabinet. A circuit diagram is insufficient here to identify incorrect drilling, components and wiring.

The benefits of continuous visual inspection of performed tests are an argument for implementing this approach. Any error (e.g. missing components or incorrect wiring) can then be identified and rectified before the phase is concluded. This is less time-consuming and costly than identifying and rectifying irregularities during the production phase. For example, to rectify drill holes that are too small and identified only during electrical assembly require more effort because components may need to be removed prior to re-drilling. Visual inspection at the end of a phase by the technician himself/herself makes the technician his/her own inspector and thereby promotes a more careful approach to the task. Companies which apply this approach report a reduction in errors of up to 85% and a subsequent rise in efficiency of at least 37%.

3.6 Ergonomics and workplace design

On the basis of on-site analyses, a number of improvements were identified in respect of ergonomics and workplace design. During wiring, technicians often need to rotate by 180° from viewing the circuit diagram to wiring the control cabinet. This is not only time-consuming but also damaging to health. A physically and mentally balanced workload is required to promote health and achieve optimal performance. As already mentioned, the assistance of multimedia user devices is one option to simplify wiring and ease the work of the technician by optimising the workplace. Time savings can also be gained.

The study identified different approaches on how a control cabinet is positioned to perform assembly. This takes place mostly with the cabinet in a horizontal or vertical position and rarely at an angled position. Some components, such as drive amplifiers, are heavy. The positioning of the main panel and/or the cabinet plays an important role. The study made a detailed analysis of working procedures in production and determined that technicians can assemble components faster and more ergonomically when the cabinet is in a horizontal rather than a vertical position. When positioning heavy components, lifting aids can be beneficial. Wiring on the other hand, requires the cabinet to be in a vertical position. Wiring is then much easier for the technician, whether sitting or standing.

In addition to the positioning of the control cabinet, the tools and equipment at the workplace also play major roles in optimising production. Tools, wires and the required bulk material need to be sorted and within easy reach of the technician. 11% of the companies use kanban systems at the workplace which provide materials automatically. This ideal workplace design avoids long transfer routes to centrally located stores. For the other 89% of firms, the technicians themselves are responsible for replenishing bulk-goods containers. Time savings of up to 35% are achievable by exploiting aforementioned potentials.

Trends in control cabinet manufacturing

As part of the study, companies were also asked about the trends they predict in engineering and production. These are briefly presented in this concluding section.

Components with greater complexity and more software

Today's components have an increasingly larger share of software which needs to be accounted for primarily within engineering. The positioning of these components is generally no longer restricted and they can be installed anywhere required within the control cabinet. However, this results in the need for intensive software testing of the control cabinet.

A greater number of field components through decentralisation

Today's machines and systems are so complex and are equipped with so many functions that there is a diminishing need for the manufacturing of large control cabinets. The trend is towards decentralised, field-located control cabinets containing the necessary components and a minimum of control logic. A central control cabinet will continue to provide primary control cycles but will have a much reduced level of complexity. Such decentralisation has a direct affect on the complexity, density and quantity of control cabinets that need to be installed for a machine or system.

Restrictions on component diversity

Although the majority of participants in the study referred to a large diversity of components (63% have a more than 50% share of specialist components), many also wished for a reduction in such diversity. The reason for this is, on the one hand, the effort required in administration and the multitude of specialist parts required in engineering. On the other hand, a high level of diversity affects production by requiring highly trained technicians capable of managing the corresponding high rate of production variance. Therefore, 36% of companies are pursuing a reduction in component diversity by using only one or two variants, e.g. pressure generators. This of course requires a new way of thinking and may result in oversized systems and components, but will reduce effort both in engineering and in production.

Outsourcing

It was important for the study to survey companies who perform in-house control cabinet manufacturing. This was the case for only 78% of the surveyed companies. This means that every fifth control cabinet for a machine or system is already being manufactured by external providers. It should also be mentioned that 27% of surveyed companies do not carry out their own mechanical processing on control cabinets but obtain these prefabricated. Time and cost pressures mean some companies – especially those with a low annual output of control cabinets and switchgears – are asking themselves whether to have their control cabinets manufactured externally. Other companies want to continue manufacturing their cabinets but using, when possible, prefabricated terminal strips and wire harnesses. The extent to which the trend towards outsourcing continues is difficult to predict. However, the attractive conditions from external providers are not to be underestimated.

Summary

5

This section briefly summarises the findings of the study. More detailed explanations can be found in the relevant sections.

Automated production using 3D engineering

A clearly identifiable trend among the surveyed companies is towards the creation of 3D engineering drawings. This may involve complications and flat learning curves in the transitional phase from 2D drawings and circuit diagrams, but clear benefits can be achieved by using 3D models. Ultimately, 3D models enable the fully automated, continuous production of control cabinets – or corresponding semi-automated control cabinet manufacturing.

Outsourcing or in-house production?

For companies with a low annual output of control cabinets with relatively high and non-profitable development and production activities, there is the question of whether to outsource control cabinet manufacturing. Some of the surveyed companies consider this not only a loss of in-house skills but also a dependency on the delivery terms of contracted manufacturers. This is generally not a problem in the series manufacturing of machines because time is less restricted compared with the manufacturing of systems. There are no statistics available to evaluate this so a separate analysis is required.

Standardisation in engineering

To ensure in-house control cabinet manufacturing remains competitive in the coming years, production approaches require increased standardisation and unification. In view of the high level of specialist parts in mechanical engineering, this may at first sight seem impossible. However, the majority of these special parts are simply options based on a single type of specific machine. It should therefore be possible to create a list of production instructions for virtually any machine. This will significantly benefit production because such lists would leave practically no room for differences in interpretation. Errors can then be avoided-, and, in peak periods, untrained operators can be quickly deployed.

Thinking in functions

Similar to the engineering of tooling machines or systems, control cabinet manufacturing must also be considered in functions or functional units. Today's engineers, however, generally design their control cabinets from bills of material. In the long term this is impractical and requires a rethinking of engineering training and the use of software. A control cabinet needs to be developed in functional units whereby each unit can be independently tested and managed. This enables significant potentials in engineering and production.

List-based production documentation

Documentation used in production is generally based on bills of materials, circuit diagrams and engineering drawings. It is not easy to extract information from these to complete a specific phase and depends on the ability of each individual technician. By using list-based production documentation which is clearly structured and sequenced, production instructions can be carried out faster and with fewer errors. Capacities can then be easily increased during peak periods because highly trained staff are no longer required. List-based production is the key to error-free, faster and more flexible production.

Preplanning and component picking for faster production processes

To enable continuous control cabinet manufacturing in the future requires more attention to preplanning. Pre-picked boxes of components for each individual control cabinet need to be assembled by logistics in the component stores. With the exception of procured wires and the associated bulk material, technicians can rely on having the correct quantity of required components. The need for technicians to source for themselves the components needed for a control cabinet must become something that belongs to the past.

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