How to Design Assembly Instructions

Sven Hinrichsen[1], Dominic Bläsing[2]
[1] Ostwestfalen-Lippe University of Applied Sciences and Arts
32657 Lemgo, Germany

[2] University Medicine Greifswald
17475 Greifswald, Germany

ABSTRACT

Employees in mixed-model assembly perform much informational work by constantly making decisions about the part to be assembled, the tool to be used or the working method to be applied. The proportion of informational work in manual assembly is likely to increase, since more and more products are configured according to customer demands and additional functions are integrated. Whereas assembly has so far been understood primarily as energetic work, the informational aspects of assembly work will have to be considered to a greater extent in the future. Assembly system design is thus more and more a domain of cognitive ergonomics, whereas in the past the focus was on biomechanical aspects. Taking this into consideration, the design of assembly instructions in line with individual requirements is becoming increasingly important. This article therefore discusses important design principles of such instructions.

Keywords: Assembly Instruction, Compatibility, Assistance System

INTRODUCTION

Manual assembly of products that consist of multiple components in different constellations is a serious challenge for employees in an assembly system. Each new product to be assembled requires an immediate adaptation of familiar assembling habits to the order's actual demands. The higher the complexity of the assembly task, the higher the resulting entropy and the more uncertainty has to be coped with. For the employee, this implies to be more attentive, to recognize and process more information, to make more decisions and invest more cognitive capacity in the behavioral control. Generally, a high level of task complexity leads to a high mental workload (Young et al., 2015). As a consequence, excessive load can affect selective attention, leading to an increase of lapses and errors as well as performance degradation. An ergonomic preventive strategy that can help to make the experienced complexity manageable for the employees consists of a better design of assembly instructions. These instructions aim to select and present information on the assembly process in a way that the sensory reception, the cognitive processing of this information as well as the response selection and control lead to more effectiveness (error prevention) and increased efficiency (short execution time). However, there is often a discrepancy between intended and realized effects. Hollnagel (1997) offers two explanations for these discrepancies: Operators do not have a proper understanding of their work and designers´ conceptualizations of the operator´s mental models are far from perfect. In practice, this can lead to a disagreement between designer and operators whether information is useful or not. In an empirical study, five categories of informational deficits in manual assembly could be identified (Hinrichsen and Bendzioch, 2018): (1) Necessary information is missing in the assembly system. (2) Unnecessary information is displayed. (3) Information is supplied at the wrong time and in the wrong quantity. (4) Information is not up to date and/or (5) not prepared in such a way that it is easy for the assembly worker to comprehend and process. The design of assembly instructions plays a decisive role in avoiding these deficits. Therefore, this paper discusses important design principles for assembly instructions. These principles are classified in terms of content (What information to present), presentation (How and when to present the information) (Hollnagel, 1997; Claeys et al., 2016), and technology (What technology is used for information presentation?). Finally, suggestions for the organization and implementation of digitally prepared assembly instructions are given. The design principles described are based on literature analysis and include results from field and laboratory studies (Hinrichsen and Bendzioch, 2018; Bendzioch and Hinrichsen, 2020; Hinrichsen et al., 2017).

CONTENT

Although the content of assembly instructions is highly dependent on the customer-specific assembly order and the product to be assembled, general requirements for the content of assembly instructions can be established. Important content requirements for assembly instructions refer to (1) order overview and status, (2) relevance and completeness, (3) adaptation to the user, (4) compatibility with other work system components and (5) being up-to-date.

An important requirement for an assembly instruction is to allow the assembly worker, at the beginning of a new order, to gain an understanding of the upcoming assembly task by providing an order overview. An order overview indicates the target state of the product (e.g. picture of the finished product, parts list) and important information (e.g. lot size, list of assembly operations). This way, the employee is able to anticipate the assembly process before starting. If, for example, the worker finds out that special devices or tools are necessary to perform the assembly process, those can be made available in advance. In addition, the overview helps to compare the achieved actual state at the end of the job with the target state in order to be able to complete the job successfully (Mattsson and Fast-Berglund, 2018). During the assembly operation, additional guidance can be given to the employee by displaying the processing status of the product (e.g. step 37 of 50 assembly steps).

Relevance and completeness mean that on one hand – following the principle of "less is more" – only that information is presented that is crucial for carrying out the assembly task (Fässberg et al., 2011). On the other hand, assembly instructions must contain all information that enables the assembly worker to carry out an assembly task correctly. The requirement for relevance and completeness is challenging in that employees have different qualifications and experiences resulting in inter-individual differences in information demands (Claeys et al., 2016; Mattsson and Fast-Berglund, 2016). This is further complicated by the fact that a person's information demands can vary over time due to processes of learning and forgetting. The usefulness of an assembly instruction, the competency development of employees and the complexity of the assembly task are closely interrelated. Thus, the increase in the employee's experience with the assembly task leads to a reduction in the perceived task complexity. As a result, a detailed assembly instruction loses its usefulness from the employee's point of view and can even be perceived as annoying and will no longer be accepted (Hinrichsen and Bornewasser, 2019). Information density should therefore be adapted to the needs of individual users or user groups as dynamically as possible. Someone who has extensive experience with the assembly of a certain product usually needs significantly less information than an employee who is assembling that type of product for the first time. A pragmatic implementation of adapting the information output to the user's needs can be done, for example, by an assembly instruction containing a short form (overview with all relevant information for an experienced employee) and a long form (e.g. step-by-step instructions with all important information for a less experienced employee). This allows the user to choose between the two offered types of instructions.

The content of the assembly instructions has not only to be adapted to individual users or user groups. Rather, compatibility with other work system elements must also be established. For example, color markings can be used on parts containers, tools, devices and assembly instructions. Identical color markings signal to the worker that the objects marked with that color are assigned to an assembly or a product (Takeda, 2006). In addition, it can be helpful to adapt assembly instructions to job- or task-specific peculiarities, for example by pointing out quality-critical processes or risks of injury during individual assembly steps. These additional or warning notices can be conveyed, for example, with the help of pictograms (see next section “Presentation”).

Being up-to-date means that an assembly instruction must always have the same revision status as the product data on which it is based (e.g. parts list, CAD drawing). If there are discrepancies between the representations of the assembly instructions and the actual conditions in the assembly system, cognitive dissonance occurs, which in turn can lead to increased mental stress and reduced performance.

PRESENTATION

Even if all important contents of an assembly order are presented in an instruction (see previous section “Content”), two basic problems can occur. Firstly, the assembly worker's focus can be exclusively on the execution of the assembly task, so that, due to processes of selective attention, important information presented in the assembly instruction are not perceived. Consequently, the worker might assemble, for example, an incorrect part (Case et al., 2008). Therefore, signals of an information system must be designed in such a way that during the execution of an assembly task, the worker becomes aware of important information at the right time. These signals are known as triggers. Case et al. (2008) were able to show that, for instance, the introduction of "simple color-coded cards and symbols" as triggers can significantly reduce the reject rate in an assembly system.

Secondly, there may be the problem that the worker is aware of the assembly instructions but sees little use in them. Such a case is due to the information not being prepared in a way that allows the employee to find it quickly, capture and interpret it correctly. It follows from this second problem that important rules for providing information must be followed. Information can be understood as interpretable code or interpretable data (Hacker, 1986). Data, signals or codes are objectively perceptible, but can only be used if they can be interpreted by the employee. A human's interpretation can be described as decoding (Hacker, 1986). Via decoding, meaningful and process-dependent information is created. A prerequisite for being able to decode is that the person has suitable mental models, i.e. is able to correctly interpret activity-guiding signals or data (Rasmussen, 1983; Hacker, 1986; Strasser, 2021). The more abstract and extensive the transmitted information or data is, the longer the decoding process takes. That is why the compatibility principle states to provide data or information in such a way that the employee can identify and correctly interpret the information needed to perform the task in the shortest possible time in order to perform the appropriate action without error. “Examples show that cognitive compatibility might conflict with organizational, i.e. hierarchical, compatibility. From an organizational point of view, CAD sketches and article numbers are an important prerequisite for the effectiveness and efficiency of the entire organization, their use in the context of assembly instructions usually leads to incompatibilities" (Bläsing et al., 2021). Therefore "all technical elements and interfaces have to be designed in such a way that they do not exceed human capacity in order to optimize human well-being and overall system performance" (Strasser, 2021).

Important requirements for the provision of information relate to (1) the communication mode, (2) the structuring of information, (3) the timing of information output (timeliness), (4) multiple coding and (5) the design of individual elements of information output. The communication mode can be optical, acoustic and/or tactile. When selecting the output channel, the output medium must, on the one hand, be selected in such a way that the worker's attention is directed to important information (attention trigger) and that important information can be received and processed by the worker – if possible – without interrupting the assembly task. On the other hand, the theory of multiple resources (Wickens, 2008) must be taken into account when selecting the information output. According to this theory, focusing on purely visual information output, which is common in the design of assembly instructions, can lead to bottlenecks in the use of the employee's cognitive resources. Taking reduction of stress and increase in performance into consideration, it would rather be helpful to combine visual coding, for example, with acoustic coding. Often, this combination of multiple sensory perceptions could positively influence human performance (Schlick et al., 2018). With this in mind, assembly instructions should in future and to a greater extent be regarded as an integral component of multimodally designed assistance systems.

Due to the large amount of information that assembly instructions need to convey to employees working in the mixed-model assembly of complex products, the structuring of information is of great importance. The basis for this structuring is formed by hierarchical product models (Söderberg et al., 2014), in which a product is subdivided, for example, into assemblies, subassemblies and parts. Assembly precedence graphs are another basis for planning. They subdivide the entire assembly task into activities and show, like a network diagram, which dependencies exist between individual activities (e.g. activities 7 and 8 must be completed before starting activity 9). Such a precedence graph can be used to determine the sequence of assembly activities and to structure the assembly instruction on this basis. The assembly worker is guided through the assembly process step-by-step by means of such an assembly instruction. The scope of an activity (step), and thus the amount of information to be provided, should be based in particular on the requirements of the employees. In addition to this, one should take care that the number of simultaneously presented stimuli does not exceed the amount of information that can be retained in working memory (7±2 chunks) (Miller, 1956). The minimum scope of an activity includes picking up and joining of a component as well as the handling of the required tools. Therefore, the following information must usually be output for each operation:

(1) designation of the part to be assembled, (2) storage location of the part, (3) installation location of the part on the product, (4) tools (e.g. screwdriver) and auxiliary materials (e.g. adhesive) to be used for joining. However, it is also possible to output information on several assembly processes in an overview display. The advantage of this type of information output can be that the employee is given – as opposed to step-by-step instructions – the freedom to determine the order of specific activities according to their individual preferences. The disadvantage of this concept is usually a higher cognitive load and longer orientation times that are not used productively. A uniform layout must be developed for structuring the information of individual activities in visual assembly instructions (Söderberg et al., 2014; Wolfartsberger et al., 2019) so that employees can quickly find their way around. The structuring of information into activities determines the timing of the information output. However, when using a digital assembly assistance system, workers should always be able to control the system. Specifically, they themselves should be able to determine the moment of information presentation for the next assembly process. Furthermore, it should be possible to return to already completed activities in the assembly instruction or to skip activities.

Multiple coding of an information can provide the employee with additional orientation (Hacker, 1986). This means, for example, that in addition to information conveyed via a drawing, a short text note is given in order to largely exclude possible uncertainties of the employee about the activity to be carried out – in this case due to double coding. Therefore, when designing the layout, different elements (e.g. picture, drawing, text note, pictogram) must be taken into account (Ganier, 2004) and arranged in a fixed order. Individual elements of the information output are to be designed in such a way that the reception and processing of the information is as simple and fast as possible. To this end, images, figures and drawings have an advantage over texts because information can usually be provided very realistically and compactly. These representations also correspond with the employees' existing mental models (Ganier, 2004). Color coding within figures or drawings can create additional orientation. For example, color coding of the part to be assembled in the next step – within a black-and-white representation of the overall product – can help to attach the part to the right place immediately (Hacker, 1986). Pictograms can also make it much easier to absorb information or draw the user's attention to an important issue (Ganier, 2004). An overview with explanations of all pictograms used in assembly instructions can help to convey the meaning of individual pictograms to new employees. Pictograms can, for example, indicate the tool to be picked up or convey a warning. If possible, text information should only be used in conjunction with graphical or drawn information. Texts should be phrased comprehensibly, precisely and using uniform terminology (Kothes, 2011). A sufficiently large and easily readable font should be chosen (Kothes, 2011). In case of a digital information output, the user should be able to make adjustments to the software (e.g. change the font size to compensate for impaired vision).

TECHNOLOGY

Assembly instructions can be issued in paper or digital form. If instructions are to be used in digital form, screens and tablets, light and laser projectors as well as wearables can be used as visual output devices. These latter output devices can in turn be classified according to the parts of the body on which they are worn. Currently, the most relevant are the head (smart glasses), hand (smart glove) and wrist (smart watch) (Hinrichsen et al., 2017). Individual output devices are usually part of informational assistance systems, which are currently being developed with much drive. They can have a variety of functions (e.g. automatic error detection via image processing, integration of screwdrivers with torque monitoring and documentation). When selecting output devices, several criteria must be taken into account. One such criterion is whether the output devices will be in stationary or mobile use. In addition, the effects of the output devices on training times, work productivity and acceptance should be considered. Furthermore, the purchase price, running costs and implementation effort influence the choice of device. Laboratory studies comparing paper-based instructions with output devices (AR glasses, beamer, tablet) show that a tablet-based assistance system leads to comparatively short training times (Bendzioch and Hinrichsen, 2020). One can assume the reason for this is that users are already familiar with tablets from their everyday lives. The projection-based assistance system led to the lowest number of errors during picking and assembly in the study. The reason for this may be that information conveyed by in-situ projections is particularly easy to perceive and can be intuitively translated into the right action. However, the costs and implementation effort for projection-based information output are quite high, so that companies often favor tablets over beamers.

ORGANIZATION

In order to achieve the desired goals of assembly instruction design (high effectiveness, high efficiency and user acceptance), appropriate organizational prerequisites must be created. These differ from company to company. However, general guidelines can be formulated. Assembly instructions are to be designed uniformly within a company. This requires a manual with guidelines on content, presentation and technology usage. In order to ensure a high usability of the instructions, the assembly workers as users of the instructions should be included in the process of developing such standards. Based on the guidelines developed, the process of designing assembly instructions must be streamlined (Wolfartsberger et al., 2019). The objective must be to build assembly instructions in a modular way and to generate them automatically from existing order and product data as well as based on the individual characteristics of an assembly worker (e.g. the worker´s experience) (Claeys et al., 2016; Hinrichsen et al., 2017). In addition, a process is required that includes a continuous improvement of assembly instructions. This process should also be digitized as far as possible. The assembly employee should be able to forward the identified errors or deficits in an instruction quickly and easily – for example, via a workflow within the assistance system software – to the corresponding industrial engineering employee. The employee can then optimize the instruction using the software solution.

In order to be able to design usable instructions for assembly processes on the one hand and to automate the processes of generating and providing information on the other hand, different competencies are required. One approach could be to make the function of industrial engineering, which has a high degree of process knowledge, more interdisciplinary. For this, the existing know-how should be supplemented by competencies from the field of information and communication technology as well as cognitive (neuro-) ergonomics. In companies that have a number of production plants, such a function can be centrally located in order to utilize synergies.

CONCLUSION AND OUTLOOK

In manual mixed model assembly, a lot of information must be made available to the employees via assembly instructions. For industrial companies with large manual assembly areas, it can be helpful to compile company-specific guidelines for the development of assembly instructions and for their integration into assistance systems in a manual. These guidelines should address information content, presentation and technology. The aim should be to realize continuous digital process chains from order and product data to the output of assembly instructions. When preparing information, individual user settings and characteristics should also be taken into account (e.g. font size, extent of experience with a task) in order to meet the needs of individual employees.

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