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Exploration of digitalized presentation of information for Operator 4.0: Five industrial cases

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ABSTRACT

In the digital transformation of manufacturing companies towards Industry 4.0, shop-floor operators of the future, Operator 4.0, will require digitalized presentation of information as cognitive support for their work. This paper explores five industrial cases where Information Support Technology have been conceptualized and developed. These cases have exemplified how digitalized presentation of information can be approached with considerations of operators with varying cognitive work situations and production characteristics. Furthermore, these new technical capabilities have increased the level of cognitive automation to support operators' individual abilities to perform their work in an increasingly more complex production environment. In conclusion, Information Support Technology in the service of Operator 4.0 is intimately linked with digitalization strategies for transformation towards Industry 4.0.

1. Introduction

The complexity for shop-floor operators increases as manufacturing companies increase product variety to meet a wider variety of customer demands (ElMaraghy, ElMaraghy, Tomiyama, & Monostori, 2012; Hu et al., 2011). In this complex environment, human operators remain as the most valuable resources (Toro, Barandiaran, & Posada, 2015) because of their abilities of problem-solving (Brettel, Friederichsen, Keller, & Rosenberg, 2014), decision-making (Stankovic, 2014), and flexibility (Gorecky, Khamis, & Mura, 2017).

With the development of Industry 4.0 enabling technologies, digitalization that can support operators has become more attainable. To achieve an efficient transformation, organizational and human-centred approaches are of importance. The concept of Operator 4.0 was introduced to help understand how these enabling technologies can support the individual operator's physical, cognitive, and sensorial abilities (Romero, Bernus, Noran, Stahre, & Fast-Berglund, 2016b). To create good operator support, all three abilities need to be considered. Using effective presentation of relevant information as cognitive support for operators in an increasingly complex work environment has the benefit of both lowering the workload and improving assembly quality (Kaasinen et al., 2020). However, traditionally, automation design decisions have focused on optimizing the capabilities of the technology (technology-centred automation) (Endsley & Kaber, 1999). If a more human-centric approach is in focus more effort should be put into optimizing the abilities of the operator (Fantini, Pinzone, & Taisch, 2020). A system that fails to trigger operators' attention has an increased risk for errors (Endsley, 1995).

Regarding the current presentation of information for the shop-floor operators, the carrier of information is often paper-based, despite being created in a digitized setting (Johansson, Malmsköld, Fast-Berglund, & Moestam, 2019; Palmqvist, Vikingsson, Li, Fast-Berglund, & Lund, 2021). Increased digitalization and implementation of Industry 4.0 enabling technologies can support manufacturing companies to manage shop-floor-related information but comes with challenges on its own (Johansson et al., 2019). When increasing the digitalization of the instructions, the interaction between the operator, the systems and the machines is important to consider, i.e., the interoperability. With the levels of interoperability considered, the conceptualization of new approaches to present information for operators can be realized. Such provision of information contributes to developing more socially sustainable workplaces for the future Operator 4.0 (Romero, Stahre, & Taisch, 2020). This is because, on shop floors, Industry 4.0 can facilitate human cooperation as it supports how data, information, and knowledge

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is disseminated (Li, Paulin, Berglund, Gullander, & Bligård, 2018). To be able to send data and information, and knowledge between two or more systems, this needs to be codified in a standardized way. The format is one of the important aspects when designing information systems, both regarding quality (Kehoe, Little, & Lyons, 1992) and interoperability (Panetto, Iung, Ivanov, Weichhart, & Wang, 2019). Furthermore, instructions that are of poor quality or too generic for the task at hand are challenging for operators due to their assembly work being unsupported or hindered (Johansson et al., 2019), which also decreases the use of the instructions themselves. If there is a need for information, but there is no trigger for demanding the information there is a risk for quality issues and more variability in cycle times (Case, Bäckstrand, Högberg, Thorvald, & Vin, 2008).

This paper aims to explore what drivers to focus on when designing digital instructions. The paper will compare and evaluate different solutions for presenting information to Operator 4.0 to increase the quality of both the product and the workplace. The novelty and contribution of this paper lie in the five qualitative industrial cases, the exploration of how these industrial cases have developed their systems, and the comparison of their outcomes.

2. Frame of reference

This section describes concepts needed to understand gaps within the capabilities and abilities connected to Operator 4.0.

2.1. Defining Operator 4.0 abilities and the task capabilities

Since 2016, Operator 4.0 has been envisioned as the “Operator of the Future”, a smart and skilled operator who performs work aided by machines if and as needed. For Operator 4.0, factory work will be qualitatively enriched, more flexible, and require new qualifications to master the digital technology entering the shop floors (Kaasinen et al., 2020). The Operator 4.0 concept aimed at enhancing the operators’ abilities with help of the Industry 4.0 enabling technologies (Romero, Stahre, Wuest, Noran, Bernus, Fasth, & Gorecky, 2016a) by increasing the level of automation as their support, illustrated in Fig. 1.

Ability is derived from the word able and can be described as *the skill or power to perform a task*, while *capability* is derived from the word capable defined as *the extent of ability*. Different levels of automated solutions can be used to support the operators’ different abilities by using different technical solutions to increase the capability of the performance. Therefore, in this context, *abilities* refer to what operators can do and *capabilities* refer to what production systems are capable of providing in terms of technical support.

The tasks’ physical support will help the operator’s capacity and ability to undertake physical activities needed for daily work, which can be characterized by multiple attributes, including the description of the physical function (e.g., ability to lift, walk, manipulate, and assemble) together with its non-functional properties (e.g., speed, strength, precision, and dexterity). Examples of Industry 4.0 enabling technologies are collaborative robot applications (Fast-Berglund & Romero, 2019), autonomous mobile robots (AMRs) (Fragapane, Ivanov, Peron, Sgarbossa, & Strandhagen, 2020) and exoskeleton (Huysamen et al., 2018).

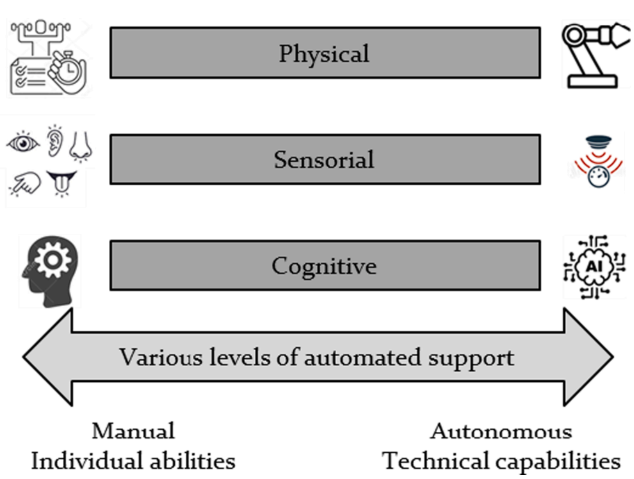


Fig. 1. Levels of automation, i.e., capability to support operators’ abilities.

The tasks’ sensorial support will help the operator’s capacity and ability to acquire data from the environment, as a first step towards creating information necessary for orientation and decision-making in the operator’s daily work (Romero et al., 2016b). There are two components to sensing: (1) the physical ability to collect data from the environment (by vision, smell, sound, touch, vibration) and (2) the ability to selectively perceive it. Furthermore, it is difficult for large sets of data generated by the physical sense of an operator to enter the short-term memory (Cowan, 2000). Examples of Industry 4.0 enabling technologies are sensors and visual computing technologies (Segura et al., 2020).

The tasks’ cognitive support will help the operator’s ability to undertake the mental tasks (e.g., perception, memory, reasoning, decision, motor response, etc.) needed for the job and under certain operational settings (Carroll, 1993). Examples of Industry 4.0 enabling technologies are Machine Learning, AI, real-time optimization (Bortolini, Ferrari, Gamberi, Pilati, & Faccio, 2017).

2.2. Cognitive automation strategy and assembly modes of operators

To create a cognitive automation strategy, the different phases of an operator is vital to consider.

How information is presented to operators, can support them working in these different modes, by designing the information based on the operators’ desired behaviour (Mattsson, Fast-Berglund, Li, & Thorvald, 2020). When an operator is learning new tasks, instructions need to support reasoning to the concentrated operator to learn knowledge by heart (Rasmussen, 1983). In contrast, after the initial learning phase, when an operator enters an operational assembly mode and performs daily assembly tasks, instructions need to support intuition, e.g., by displaying standardized symbols and highlighting variations (Osvalder & Ulfvengren, 2009). However, there is a risk that if the assembly instructions are not designed to support rule-based behaviour, cycle times and quality may vary greatly between operators (Fast-Berglund & Thorvald, 2021).

Whenever an operator needs to learn something new, he or she works in the learning phase. To support this type of behaviour, the operator needs to be actively aware and reasoning. These non-automatic processes are often energy and time-consuming (Evans, 2003; Tsujii & Watanabe, 2009) and can lead to a variety in cycle times. In the operative phase, the operator instead needs to work based on his or her experience and skill. For the disruptive phase, the operator needs to think consciously about a solution. This means using reasoning and intuition; in other words, both knowledge-based and rule-based behaviour is used.

The learning, operational, and disruptive phases that use different cognitive processes are based on a theory of operator work concerning learning, cognition and disruptive work need different support

Table 1
Model for learning, operational, and disruptive phases (Mattsson et al., 2020).

Phase of assembly work	Operator behaviour	Support needed by operator
Learning	Knowledge-based	Reasoning
Operational	Skill and rule-based	Intuition
Disruptive	Rule and knowledge-based	Reasoning and intuition

(Mattsson et al., 2020), as listed in Table 1.

2.3. Information quality supports dynamic decision-making for Operator 4.0

Information that exists in the environment (in displays, the natural world, or other artefacts) but of which the operator is not aware (due to other attentional demands, out-of-the-loop problems, poor interfaces, hidden screens, interference effects, etc.) does not constitute situational awareness. It is by definition information of which the operator is not aware (hence the opposite of situational awareness). To create a well functional and well-used support system for assembly operators, an understanding of the relation between the three technologies (Information (IT), Operational (OT) and Information Support (IST)) is vital. From a manufacturing strategy perspective, IT, OT, and IST can be described in terms of capabilities, or lack thereof (Skinner, 1969; Slack & Lewis, 2019).

Empirical studies have shown that the capability of combining IT, OT (Åkerman, 2018; Goto, Yoshie, & Fujimura, 2017), operator perspectives, and the need for support (Li, Fast-Berglund, & Paulin, 2019; Mattsson et al., 2020) is lacking in the manufacturing industry today, which is highly relevant for operators in Industry 4.0 environments. Slack and Lewis (2019) describe process technology and development of the organization as two (out of four) decision areas that constitute the base for a competitive manufacturing strategy, and managerial decisions regarding IST capabilities are related to both decision areas. The capability of OT exists to some extent at companies today but knowledge and skills about enabling technologies within Industry 4.0 are still lacking.

2.3.1. Information Technology

Information Technology (IT) can be traced back to 1958 when it was defined as the use of the computer to support decision making and organizational information processing (Leavitt & Whisler, 1958). The IT oversee the design, deployment, and maintenance of IT infrastructure and systems that automate and facilitate business procedures (Li & Chan, 2019). Information Technology is usually a term used to describe all general technical developments and advances in-office communication or an office environment (Boaden & Lockett, 1991). From a more managerial perspective, Information Technology can be described as a computer used in various ways in industry and commerce. In more recent research information technology becomes increasingly integral to business processes the service portfolio can be extended from managing backend IT functions to deploying up-to-date IT resources to accomplishing high-visibility (Wagner, Beimborn, & Weitzel, 2014). IT system is impacting the organization and the IST system is impacting the individuals (Fast-Berglund, Li, & Åkerman, 2018). Referring to the situation awareness the IT and OT is mostly supporting or affecting the task/system factors while the IST is affecting the Individual factors.

Information Technology is also closely connected to *Information Systems (IS)* and *Information Management (IM)*. Information Systems refer to specific systems while Information Management is managing the interfaces between the different Information Systems (Boaden & Lockett, 1991). As a continuation of information systems and information management systems, the *Decision Support System (DSS)* was developed. The DSS was developed during the late 1960s when implementing the minicomputers. The first definition of a DSS can be found in 1971 as "a supporting information system for semi-structured and unstructured decisions" (Gorry & Morton, 1971). In 2001, a framework for DSS was developed and has been widely used since then. This framework divides the support systems into communications-driven, data-driven, document-driven, knowledge-driven, and model-driven. DSS can be used at all parts of the company, both in groups and for single person decisions, e.g., it can be used in the areas of operational management decisions (Lee-Post & Chung, 2008), marketing decisions (Hart, 2008) and finance (Weber, 2008). In industry and manufacturing systems the DSS is not as widely spread even though there are some examples of using DSS in manufacturing, mostly within the supply chain (Delen & Pratt, 2006; Hernández, Lyons, & Stamatopoulos, 2016).

2.3.2. Operational Technology

Operational Technology (OT) can be defined as technology that focuses on the monitoring and control of the physical process (Hahn, 2016). Operational Technology is defined as hardware and software that detects changes, monitors, or controls assets or processes. Operational Technology controls or manages functions such as monitoring the condition of machinery and the operation of transportation systems and communication between machines, robots, and other hardware. Shop-floor IT could be a broader view on OT to distinguish from the "office" IT and to get closer to a definition of the IST, i.e., shop-floor IT can be defined as the information technologies, software and hardware, that enables digital applications in production (Åkerman, 2018). The manufacturing industry already requires new innovative IT solutions, but integrators tend to still provide traditional operational technology (OT) solutions that their customers are less interested in. This is a cause of a lack of knowledge of IT technology that OT engineers have never experienced (Goto et al., 2017).

2.3.3. Information Support Technology

Information Support Technology (IST) can be both analogue and digital. The research area within manufacturing and operator support are the least developed compared to the areas of IT, IS, IM, and DSS. Some studies have been done on introducing customized ICT tools for operators in manufacturing (Åkerman, Fast-Berglund, Karlsson, & Stahre, 2016) and strategies for cognitive support (Mattsson et al., 2020). IST can be hardware and software usually used in an office environment (traditional IT services) or society. These can also be used as support for operators at the shop floor, maintenance or learning and can then be defined as Information Support Technologies, e.g., computers, tablets, or even smartphones (Billskog Johansson & Chowda Shetty, 2020) and augmented reality technologies (Longo, Nicoletti, & Padovano, 2017), as well as other carriers of information.

3. Applied methods

This paper is based on five industrial cases, conducted between 2018 and 2021. The developmental work and creation of new Information Support Technology in the cases were mainly conducted with resources by the case companies themselves. All the cases have parts of their developmental work supported or carried out by thesis students (referenced in Table 2) working under the supervision and guidance of at least one of the authors of this paper.

The five industrial cases are listed in Table 2, along with their production characteristics in terms of product volume, product variety, and assembly time per workstation. This serves as a baseline to create a sense of what type of environment the cases are set in. Note that cases C1 and C2 are at the same company, but operators are performing different types of work. While operators in cases B and C1 work under predetermined takt times on an assembly line, the operators in cases A, C2, and D work without a set takt time. Instead, the approximate times for these cases are based on statistical data or estimations by the companies.

3.1. General approach

Because of the exploratory nature of this paper, a pragmatic approach to applied research was used to find out "what" and "how" (Creswell & Plano Clark, 2018) the different cases have independently developed their Information Support Technology solutions. Therefore, a variety of qualitative research methods were applied in the cases for data collection.

The cases were developed independently by the companies, with the help of thesis students (referenced in Table 2), under the supervision of the authors.

Table 2
Production characteristics for the five industrial cases.

Case	Product volume	Product variety	Assembly time per workstation	Environment for the Information Support Technology	References
Case A	Low	Very high	Takes approximately 1 workday	Test workstation	Helldén and Karlsson (2020) Holmgård (2020)
Case B	High	High	Takt time around 7 min	Test workstation	Asklund and Eriksson (2018) Johansson et al. (2018) Bäckström and Westberg (2021)
Case C1	Very high	High	Takt time around 1 min	Live production	Palmqvist and Vikingsson (2019) Andersson and Trogen (2020) Palmqvist et al. (2021)
Case C2	Low	High	Takes approximately 1 workday	Live production	Billskog Johansson and Chowda Shetty (2020)
Case D	Very low	Low	Takes approximately 1 month	Proof-of-concept demonstrator	Hellgren and Munge (2018)

For analysis, an instrumentalism philosophy has been applied, where the earlier presented models (operator abilities and assembly modes) and the production characteristics (Table 2) serve to provide contextualization (Knowles, 2006). The outcomes of the cases were compared according to these same criteria (Yin, 2009). In the spirit of pragmatism and instrumentalism, this paper has been guided by abductive reasoning, or inferring the best explanation, dealing with plausibility and likelihood (Knowles, 2006).

The cases were selected because of their varying characteristics in order to demonstrate the variety of challenges faced by manufacturing companies with regards to providing Information Support Technology for operators.

Because of the variety of production characteristics, the companies developed different types of Information Support Technology. This variation between cases meant that a multiple case study approach was selected as it supports the gathering of different types of research data, as long as it is rich enough to be analysed with regards to similarities and differences between the cases (Flynn, Sakakibara, Schroeder, Bates, & Flynn, 1990). This is enabled by the qualitative research characteristics of the individual cases, which is followed by qualitative comparisons of the outcomes (Yin, 2009).

Therefore, there is not a set of decided methods that were common for all cases. However, a triangulation of methods was applied in the different cases to ensure a level of saturation to make the cases comparable in terms of:

- the characteristics listed in Table 2
- the cognitive situation of operators
  - o the state before the cases started
  - o learning or operational assembly mode
  - o carrier and content of current cognitive support
- the rationale for the cases, as given by stakeholders at the manufacturing companies
- the Information Support Technology developed in the cases
  - o carrier and content of the developed cognitive support
  - o the type of abilities expected by operators
  - o the type of capabilities companies are creating
- a future outlook to give a sense of where the case companies are headed

3.2. Data collection

To collect the data and information, a multitude of methods were applied continuously at times when progress have been made in the cases. The principal methods were unstructured interviews, workshops, analysing documentation, gemba walks, semi-structured interviews, and structured interviews. Table 3 provides an overview of workshop participants, formal interviewees from the semi-structured interviews, and people informally interviewed during the gemba walks. Where the same persons were both part of workshops, interviews, and gemba walks, they are denoted by an asterisk (*).

Unstructured interviews were conducted throughout the entire duration of the cases, eliciting general information about the cases. These informal interviews were held with both company representatives (stakeholders such as managers, technicians, and engineers) in the cases, as well as with the thesis students listed in Table 2. Information about case progress was documented.

Workshops were held at the beginning of all cases, where operators together with the above-mentioned company representatives mapped information flow, described information needs, and assessed the current level of digitalized support.

Analysing documentation includes the company's internal documents on operators' tasks, both *which* operations to perform and *how* to perform them. Documentation also includes the references listed in Table 2.

Gemba walks were performed in all cases during various progress of them. This includes observations of the cognitive support tools, as well as informally interviewing operators as they work.

Semi-structured interviews were held with various stakeholders, including operators, to collect data and information useful for the analysis, where previously applied methods have missed.

Structured interviews were held to ensure that a satisfactory level of

Table 3
Overview of the participants from the companies and cases.

	Case A	Case B	Case C1	Case C2	Case D	Sum
Workshop						
Production engineers	1		1	1	2	5
Managers	1				2	3
Quality managers				1		1
Research engineer		1				1
Semi-structured interviews						
Operators	2		2	3	1	8
IT technicians	1	1	1	1	1	5
Production managers	1		1			2
Production technicians	1		1	1	1	4
Production engineers	1*			1*		2
Manager					1	1
Object leaders	1					1
Project managers	1			1		2
Quality technician				1		1
Quality managers				1*		1
Research engineer		1*				1
Thesis students	3	4	4	2	2	15
Gemba walk						
Operators	2			3*	2	7
Production engineers			1*	1*	2*	4
Production managers	1*				1	2
Object leaders	1*					1
Quality managers				1*		1
Total	14	6	10	11	13	54

saturation has been achieved to make the analysis. Often, this meant that a second source of information was sought after, which helped confirm (or dispute) previously documented statements.

These methods, as listed, should not be regarded as a strictly applied sequence. Rather, depending on the progress in the cases, different methods were selected to face that situation. Saturation was considered sufficient when at least two roles (listed in Table 3) for each case provided similar statements.

3.3. Analysis

The results from the industrial cases were analysed with regards to the demands on individual operators' abilities, and the capacity of the cases to develop capabilities to support the operators (as illustrated in Fig. 1). These are discussed in light of the case companies' production characteristics (as listed in Table 2) and the assembly situation (in terms as introduced in Table 1). Furthermore, the progress of the cases is elaborated upon based on the rationale behind the case and its contribution towards Operator 4.0.

4. Results from the industrial cases

In this results chapter, the industrial cases are described as follows:

- A general summary of the manufacturing company, and their operations
- The *cognitive situation of operators*: the work tasks of operators and the information presented to operators before the development of the cases, as well as a rationale for the case
- A *rationale for the case*: the motivation and reasoning for the company to undertake the project of developing new Information Support Technology to support the cognitive situation of their operators
- *Information Support Technology*: the current frontier in digitalized information presentation, based on the development during the case studies
- *Future outlook*: possible future development that or considered by the companies or actual planned development work

4.1 Case A.

The company of case A manufactures custom-engineered antennas and circuit boards. The production is characterized by low product volumes, a large variety of products, high demands on product quality, and a long assembly time of around 1 day. Case A studies detailed assembly work in cleanrooms.

4.1.1. Cognitive situation of operators

Operators are performing manual tasks, including mechanical assembly, soldering, and glueing of very small and mostly fragile components, where some of such detailed work requires microscopes for precision. All operators undergo rigorous training before receiving certificates for performing specific procedural work tasks. The work is performed at individual workstations, which in addition to tools, also are equipped with desktop computers from where operators access documents for cognitive support. For each work order, operators log on to the ERP system, where documents are attached. There are mainly two types of documents that operators use as instructions:

- *Assembly procedures* document for each work order, detailing step-by-step assembly operations, i.e., *what to assemble*. This document also contains hyperlinks to other referred documents, e.g., quality standards, process descriptions, and project-specific documents.
- *Quality standards* documents for various types of assembly operations, clarifying details on quality demands for operations, i.e., *how to assemble*. Experienced operators that know the operational standards by heart use this document as a reference, while novice operators consult this document to a higher degree.

A commonality for these documents is that both are mainly text-based descriptions. On a few occasions, these descriptions are accompanied by some visualizations, such as photo pictures, highlighted drawings, or digital models of components or products.

4.1.2. Rationale for the case

The intention with case A was that easier access to relevant information for operators could decrease time spend on finding work orders and instructions, thus contributing to more time spent on value-added operations. For operators, this would mean that information that they previously had to locate from various sources could be presented in a unified view.

4.1.3. Information Support Technology

Based on the information that can be found in the ERP system, assembly procedures documents, and quality standards documents, Holmgård (2020) developed a model for information dissemination and Helldén and Karlsson (2020) developed a concept for information presentation. The model and concept were developed with feedback from operators, technicians, designers, and planners.

The model of where information exists and how it disseminates through case A was done to ensure that it is possible to digitally access and subsequently present relevant information for operators (Holmgård, 2020). Concurrently, the concept for how to visually present this information was developed to simplify access to relevant information for operators (Helldén & Karlsson, 2020). While information from the ERP system can be retrieved, requiring little change for planners, the concept requires technicians and designers to disseminate information differently. Fig. 2 visualizes the workstation and shows a screenshot of the operators' view, which combines work order-specific information from the ERP system, assembly procedure document, and quality standards documents.

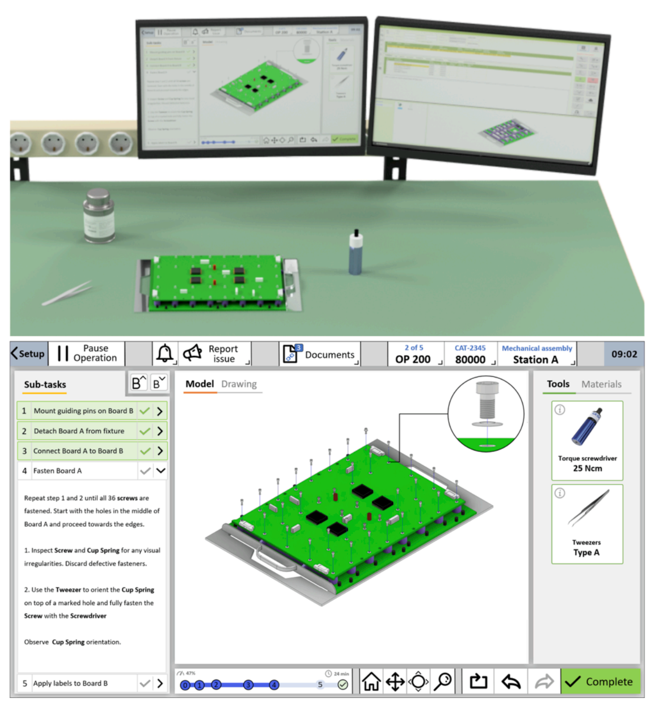


Fig. 2. Concept for the digitalized presentation of information at case A: workstation (top) and screenshot (bottom) (Helldén & Karlsson, 2020).

4.1.4. Future outlook

Case A, with working demonstrators, plans to make a trial run with work orders to validate the concept for information presentation.

4.2. Case B

The company of case B is a manufacturer in the automotive industry. The production is characterized by higher product volumes, a large variety of products, and short takt times around 7 min. Case B is set in a demonstration area that emulates the pre-assembly in the final assembly plant, where operators assemble mid-sized rigid and flexible components with power tools before the product moves on to the main assembly line.

4.2.1. Cognitive situation of operators

For case B, two main document types support operators in their assembly work:

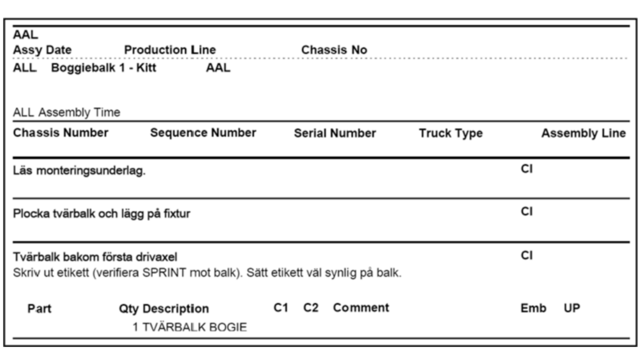
- *Assembly instruction*, which despite its name, is rather a bill of materials than actual instructions. These text-only documents are printed out on papers for each product and consist of a list of all components and material used in the assembly procedures, modified to include comments on positioning and orientation of some specific components, i.e., *what to assemble*. In addition, it also contains information that is unnecessary for operators' assembly tasks, serial numbers and packaging that are interesting for technicians. An example of this document can be viewed in Fig. 3.
- *Standard operating procedure* documents contain information that the assembly instruction lacks, including images and detailed instructions on the assembly procedure, i.e., *how to assemble*. However, these documents are mostly used as training material or when operators require further support and need to be retrieved specifically.

4.2.2. Rationale for the case

The intention with case B was to explore the possibility to present relevant information for various operators. Because more experienced operators tend to skip comprehensive information if they already feel comfortable or think they know the operations by heart, a condensed version can support experienced operators without creating an information overload for the operators. For experienced operators, this would mean that much trivial information would become hidden, but is still accessible if needed. For novice operators, detailed instructions would be the default setting.

4.2.3. Information Support Technology

For case B, Asklund and Eriksson (2018) developed a concept that presents various amounts of information depending on the operators' experience (Johansson, Malmsköld, Fast-Berglund, & Moestam, 2018). This concept features mainly picture based step-by-step instructions, accompanied by text. For experienced operators, mainly information from the assembly instruction is presented. Meanwhile, for novice operators, information from the standard operating procedure is also presented.


AAL
Assy Date Production Line Chassis No
ALL Boggiebalk 1 - Kitt AAL

ALL Assembly Time

Chassis Number	Sequence Number	Serial Number	Truck Type	Assembly Line

Läs monteringsunderlag. CI

Plocka tvärbalk och lägg på fixtur CI

Tvärbalk bakom första drivaxel CI
Skriv ut etikett (verifiera SPRINT mot balk). Sätt etikett väl synlig på balk.

Part	Qty Description	C1	C2	Comment	Emb	UP
	1 TVÄRBALK BOGIE					

Fig. 3. Example of assembly instruction at case B (Asklund & Eriksson, 2018).

Visualization of the workstation and a screenshot example of the interface is shown in Fig. 4, with some highlights:

- Main operations, in a list allowing navigation to previous and succeeding steps.
- Customization of layout and font size.
- Steps of the active operation, which mainly contains images. The amount of information here may vary depending on the operator's experience level.

4.2.4. Future outlook

The concept by Asklund and Eriksson (2018) ran at four test stations (Johansson et al., 2018). For this concept to function on a large scale, Bäckström and Westberg (2021) developed an information model with the purpose to be able to automatically generating instructions. This information model explains how existing data and information can be gathered from these software systems:

- AviX, a line balancing software, information regarding tasks, tools, and components.
- IPS IMMA, a manikin simulation software, data regarding actions, tasks elements, and instruction language.

Both software systems are used to assist manufacturing preparation processes. With the interoperability of these software systems, the time spent in these preparation tools also contributes to instruction creation. The interoperability between involved systems was achieved by using an Internet of Things platform as middleware, Thingworx, which enabled

Fig. 4. Concept for the digitalized presentation of information at case B: workstation (top) and a screenshot of an example for experienced operators (bottom) (Asklund & Eriksson, 2018).

the orchestration of how data and information are shared between systems to populate the information model.

4.3. Case C1

The company of case C1 is a manufacturer in the automotive industry. The production is characterized by higher product volumes, a large variety of products, and a very short takt time around 1 min. Case C1 studies the shop floor with a moving assembly line.

4.3.1. Cognitive situation of operators

At case C1, with short takt time to perform assembly tasks, operators are expected to remember operations by heart. Many product variants on the mixed-model assembly line add further complexity, which may lead to quality issues for infrequent product variants, e.g., forgotten cable connections, correct tool usage, and alignment positions of panels (Palmqvist & Vikingsson, 2019). Notwithstanding, existing paper-based assembly instructions remain unused by operators as a consequence of the short takt time.

4.3.2. Rationale for the case

There is a lack of cognitive support for operators at case C1. However, due to the short takt time, the presented information needs to both be useful for operators and at the same time avoid occurring extra stress for the operator because of comprehensiveness. Furthermore, quality assurance data show that some operations are more frequently assembled incorrectly, which suggests that extra reminders for those operations should be highlighted with this solution.

4.3.3. Information Support Technology

To decrease quality-related issues and cognitive workload of operators, a concept for digital assembly instructions was developed (Palmqvist & Vikingsson, 2019; Palmqvist et al., 2021) and subsequently implemented at two workstations on the assembly line (Andersson & Trogen, 2020). Operators' view of the presented information can be seen in Fig. 5.

Because of the short takt time, with only seconds possible to be allocated for reading instructions, operators are still expected to learn operations by heart, i.e., both *what to assemble* and *how to assemble*. Therefore, the implemented instruction concept focuses on providing reminders that highlight important tasks, i.e., a subset of *what to assemble*, e.g., frequent quality issues and infrequent product variations. These reminders are visualized as symbols, presented to the operators on monitors as the product moves to the workstation, depicted in Fig. 6.

By utilizing the interoperability possibilities of the quality assurance system and the manufacturing preparation system, the presented information could be matched to urgencies, such as statistically known

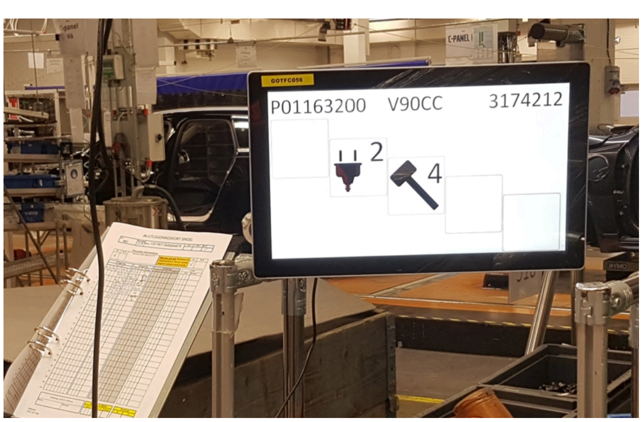


Fig. 5. Operators' view of the implementation of case C1 at one of the workstations (Andersson & Trogen, 2020).

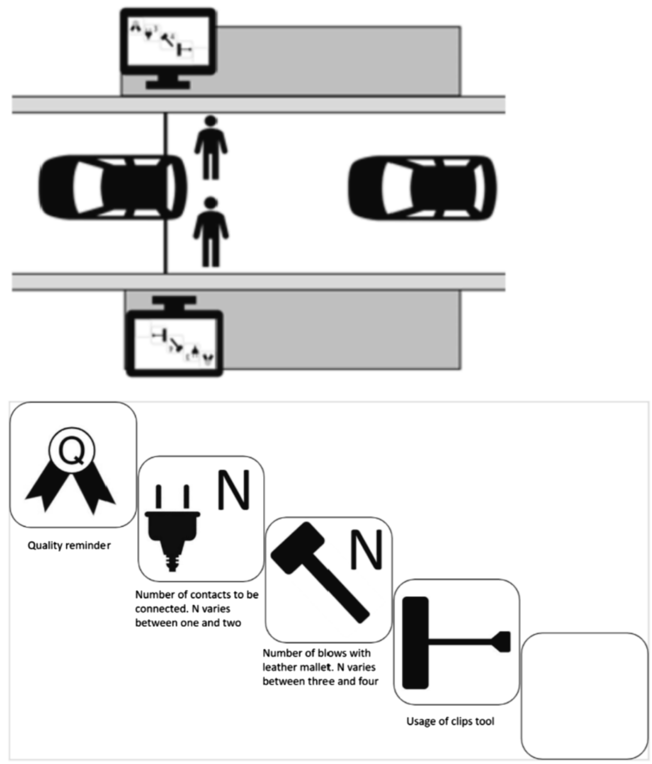


Fig. 6. Placement of monitors (left) and example of presented information (right) at case C1 (Andersson & Trogen, 2020).

quality errors or newly introduced operations. Further, the interoperability of sensors at near-workstation-start-positions, the presented instructions could be shown promptly, at the beginning of each cycle.

4.3.4. Future outlook

Case C1, with implementation at two workstations, is considering to scale-up this concept to more workstations in the factory.

4.4. Case C2

Case C2 is at the same automotive manufacturer as in case C1. However, case C2 studies the final quality inspection of gaps and flushes, where products are moved off from the moving assembly line and operators are inspecting a subset of the products.

4.4.1. Cognitive situation of operators

Operators are measuring between 1000 and 3000 measurement points, depending on product variant and the operational stability of the overall process quality. The measurements are performed with a variety of gauges and measurement tools, both inside and outside of the product. The time consumed for inspecting a single product may vary from 4 to 12 h. Such an inspection session is initiated by the operator at a moveable computer station, where the operator is presented with text and picture-based instructions, i.e., information and specifications regarding the measurement points, their tolerances, and the tools to be used. The computer station is usually moved next to the product, so to easier access the information. However, this information is not available to the operator whilst working inside the product. The measurement data is transmitted to the computer after each point is measured. After all measurements have been done, the operator needs to verify if the data points are within tolerances or not.

4.4.2. Rationale for the case

The main motivation for case C2 is the long transportation time between taking measurements within the product and entering their data at the computer station, as expressed by the operators. By digitalizing this process, better data quality could also be achieved with automatic data transfer from the measuring devices to the company's data lake, rather than depending on operators' manual data entrance.

4.4.3. Information Support Technology

To increase the information range and reduce operators' distance to information, i.e., improve accessibility, a smartphone solution was implemented (Billskog Johansson & Chowda Shetty, 2020). Originally, also AR goggles and smart glasses were considered but was eliminated because of the risk of scratching the product. Both the selection of technology and the software design features were developed with regular feedback from operators. The feedback from the operators mainly affected the amount and kind of information shown on the smartphone.

The development of interoperability features was designed to show proof-of-concept within the framework of existing infrastructure. A locally hosted server was programmed with HTML, where smartphones could be connected. The synchronization of instructions and measurement data was enabled by Python scripts.

While performing work tasks outside the product, operators consider it to be easier to use the already existing computer station. However, the smartphone attached to the operators' forearm makes the workflow less interrupted while working from inside the product. Examples of operators at work can be seen in Fig. 7.

4.4.4. Future outlook

The technical interoperability of this approach to presenting information digitally is functioning, with little extra work for the operators to set up. However, delays for the smartphones to send and receive information frustrates users, which affects the intention to use negatively.

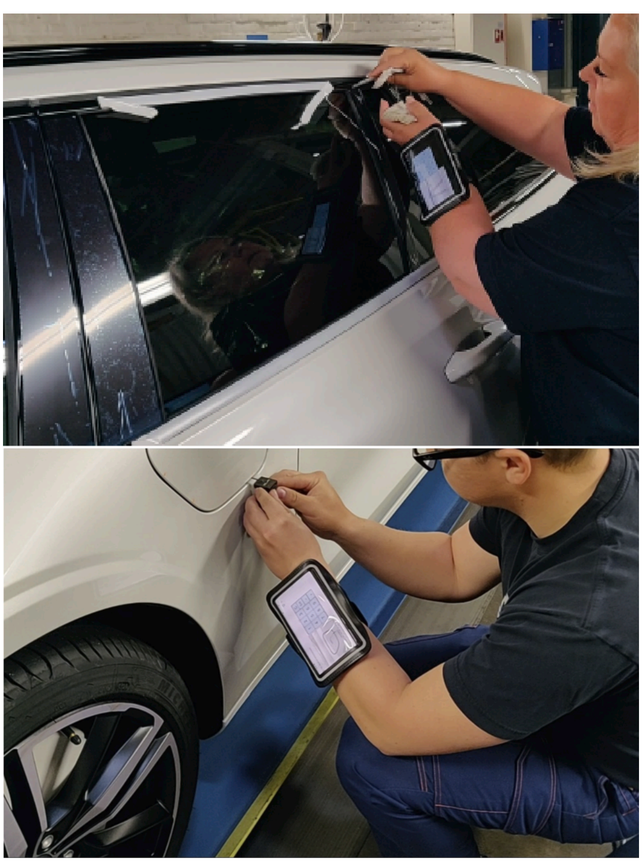


Fig. 7. Two operators measuring, with information presented on a forearm-attached smartphone, at case C2 (Billskog Johansson & Chowda Shetty, 2020).

After such connectivity issues have been sorted out and further usability considerations have been addressed (e.g., traceability, data privacy, and scalability), the case company intends to expand this concept to the moving assembly line, where measurements are taken on all products, but with fewer measurement points. Such expansion puts demands on system reliability and responsiveness.

4.5. Case D

The company of case D is a manufacturer in the aeronautics industry. The production is characterized by very low product volumes, a low variety of products, and very long assembly times, where a group of operators roughly work around 1 month per product before the product moves on to the next assembly station. Case D studies the part of the final assembly where large parts are joined.

4.5.1. Cognitive situation of operators

Because of the infrequency of repeated assembly operations, operators are not expected to learn the operations by heart. However, operators need to attain a specific amount of experience in operational procedures to be certified to perform corresponding operations.

To attain high demands of quality and address operational infrequency, operators are provided with step-by-step assembly instructions that are mainly based on 3D models, accompanied by descriptive text instructions. These models are based on underlying design models, further adapted, and exported to a lightweight format presented to operators. However, this solution is effortsome for production engineers to develop and provide.

This model-based design format of the instructions is shown at desktop computers a couple of meters away from the product itself during assembly operations. The operators can interact with, zoom in and out, and rotate the 3D models. An example of this interface is visualized in Fig. 8. Typically, operators need to remember a series of operations, as it is difficult to reach the computer station with the instructions when performing operations with the operator positioned inside or on the other side of the product.

4.5.2. Rationale for the case

Because operators need to enter the product to assemble in narrow positions, it is difficult to interact with the instructions at the computer station. Therefore, case D focus on how to shorten the distance for operators to interact with their instructions, to provide better basis-for-decisions for the operators.

4.5.3. Information Support Technology

To shorten the distance between operators and instructions, a demonstrator with augmented reality goggles have been developed. This demonstrator utilizes the same underlying design models as the standardized assembly instructions interface. The augmented reality goggles are programmed to recognize the shape of the hitherto assembled

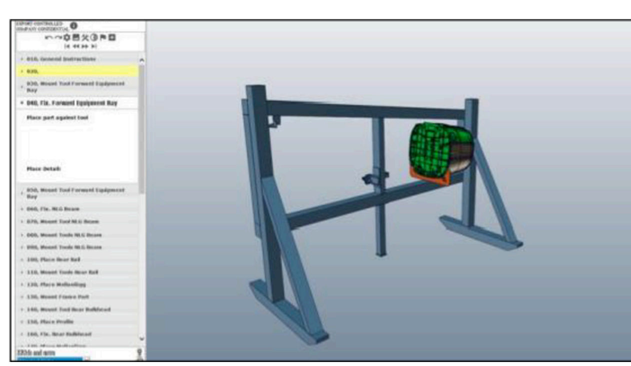


Fig. 8. Assembly instructions interface with 3D model, at case D.

Table 4
Production characteristics and assembly mode of operators.

Case	Production characteristics			Assembly mode
	Product volume	Product variety	Assembly time per workstation	
Case A	Low	Very high	Takes approximately 1 workday	Learning
Case B	High	High	Takt time around 7 min	Operational
Case C1	Very high	High	Takt time around 1 min	Operational
Case C2	Low	High	Takes approximately 1 workday	Operational
Case D	Very low	Low	Takes approximately 1 month	Learning

product and overlay an image of the next component to be assembled in the 3D space. So far, this demonstrator has served as a proof-of-concept.

4.5.4. Future outlook

As a next step, the approach to present information with the augmented reality demonstrator is planned to be applied in the company of case D's training facilities, where new operators are trained. After such pilot testing in the training facilities, case D aims to gradually implement this concept for assembly operations with a large distance between operators and the standardized assembly instructions.

5. Discussion

Based on the Information Support Technology of the five cases, this discussion focuses on evaluating the demand on individual abilities of operators and the technical capabilities to support operators and their assembly modes.

5.1. Assembly modes of operators

The operators in the cases face different production characteristics and assembly modes for their everyday assembly work (Mattsson et al., 2020). Most novice operators start in a learning mode and move to operational mode as they become more experienced. The disruptive mode for when unexpected challenges arise is more commonplace for maintenance operators, which places higher demands on problem-solving. The relation between assembly mode of operators (introduced in Table 1) and various production characteristics of the cases (presented in Table 2) are summarized in Table 4.

The low product volumes and infrequency of assembly operations puts the operators of cases A and D in a learning phase (Mattsson et al., 2020). While assembly skills should have been trained beforehand, operators in an assembly work situation need to learn the procedural steps of the assembly operations (Rasmussen, 1983). This is because of either a very high product variety, e.g., a batch of 20–25 products is internally regarded as high volume (case A) or very infrequent assembly, e.g., it becomes difficult to remember what to assemble if a month passes since last time (case D). Such demands on operators to repetitively learn and understand operations puts higher demands on the level of automated cognitive support to decrease the demand on operators' abilities (Fast-Berglund & Thorvald, 2021).

The high complexity levels of cases B and C1 are evidenced by the high product volumes and product varieties (ElMaraghy et al., 2012). Further, both of these cases have takt times, which have prompted the development of Information Support Technology that facilitates some degree of adaptability of the presented information. While case B prioritized the adaptability of assembly instructions to match individual operators' varying needs and wishes for such a support tool, case C1, with much shorter takt time and operators expected to learn operations by heart, prioritized the presented information to be adapted depending on product and quality necessities (Åkerman, 2018; Goto et al., 2017). In comparison, case C2 also have operators in an operational mode of assembly work, but due to lower product volume and longer time, the complexity is slightly lower (ElMaraghy et al., 2012). Hence the focus was not on adaptability and flexibility of the presented information, but rather on how to simplify its use (Johansson et al., 2019).

5.2. Physical abilities and capabilities

With regards to the demand on physical abilities of operators in the five industrial cases, the level of automated support can be considered very low in cases A, C2, and D, i.e., reliance on operators' individual physical abilities on performing assembly operations with manual tools. This is characterized by the prioritization of quality over speed and low product volumes, which infer less susceptibility to physical automation (Fast-Berglund & Romero, 2019).

On the other hand, cases B and C1 have a slightly higher level of automated physical support, where operators use power tools to support their assembly work. This is necessitated by the higher product volumes and predetermined takt times. Hence, there is a slight shift to also include reliance on technical physical abilities rather than solely basing the physical abilities on individuals (Fast-Berglund & Romero, 2019). The demands on the operators' individual physical abilities and the corresponding level of technological capabilities to provide automated physical support for the cases are summarized in Table 5.

Table 5
Demand on *physical* abilities of operators and corresponding level of automated support.

Case	Level of demands on *physical* abilities of operators	Corresponding level of capabilities regarding automated *physical* support
Case A	High demands	Low level of automated support
Case B	Medium demands	Medium level of automated support
Case C1	Medium demands	Medium level of automated support
Case C2	High demands	Low level of automated support
Case D	High demands	Low level of automated support

Table 6
Demand on *sensorial* abilities of operators and corresponding level of automated support.

Case	Level of demands on *sensorial* abilities of operators	Corresponding level of capabilities regarding automated *sensorial* support
Case A	High demands	Low level of automated support
Case B	High demands	Low level of automated support
Case C1	Medium demands	Medium level of automated support
Case C2	High demands	Low level of automated support
Case D	High demands	Low level of automated support

5.3. Sensorial abilities and capabilities

For many of the cases, operations demanding sensorial abilities are characterized by a low level of automated support, placing high demands on individual sensorial abilities of the operators' situational awareness (Romero et al., 2016b). This is especially true for cases A and C2, where operators need to visually assess their own assembly work and where to take measurements respectively. While this also applies to some extent for the other cases, some power tools (cases B and C1) and manual tools (case D) that operators use have the capacity to give operators tactile feedback for when the operation is finished based on torque and angle settings. The higher product volumes of cases B and C1 have necessitated this increase of automated support for operators' sensorial abilities, which in extension saves time and enables the shorter takt times of these cases. The demands on the operators' individual sensorial abilities and the corresponding level of technological capabilities to provide automated sensorial support for the cases are summarized in Table 6.

5.4. Cognitive abilities and capabilities

Before the Information Support Technology of the cases were developed, cases A and D already had a higher level of automated cognitive support. This higher level was necessitated by long assembly times, where operators are not expected to learn the assembly tasks by heart (Carroll, 1993). Further, the infrequency of the same operations reappearing puts operators in a state of learning mode (Mattsson et al., 2020). In contrast, in cases B, C1, and C2 where operations reappear more frequently, operators are expected to learn some operations by heart, thus, putting higher demands on operators' individual cognitive abilities.

However, the level of automated support of cognitive abilities has increased with the introduced concepts, thus decreasing the demands on the operators' cognitive abilities, which is expected considering the focus of the industrial cases. The demands on the operators' individual cognitive abilities and the corresponding level of technological capabilities to provide automated cognitive support for the cases are summarized in Table 7.

5.5. The industrial cases

For case A (Helldén & Karlsson, 2020; Holmgård, 2020), the motivation for method development of instructions was to improve their standardized work. Operators were required to first find their work instructions, and then actively search how to perform the prescribed operations, i.e., locate the assembly procedures document in the ERP system, and then review the quality standards document to find appropriate descriptions. This two-step approach to assembly instructions creates hurdles for operators to find and understand the information (Case et al., 2008). The new Information Support Technology concept collects these various information sources into one holistic platform for operators to access (Johansson et al., 2019). Thus, the demand for operators to search for information is reduced, shifting the focus to presenting relevant information. However, this transition towards more automated support will increase the demands on technical capabilities (Romero et al., 2016b).

For case B (Asklund & Eriksson, 2018; Bäckström & Westberg, 2021), the motivation to increase digitalization is to improve flexibility for how information is digitally presented in order to enable the cognitive support of operators with various needs and wishes, predominately related to the experience of the individual operator, or the lack thereof (Johansson et al., 2019). The transition from using a text-based bill of materials as assembly instructions to text-and-picture-based instructions that may be adapted depending on operator experience increases the level of automated cognitive support, lessening the demands on individual abilities, and increasing the demand on technical capabilities to present such instructions (Johansson et al., 2019; Mattsson et al., 2020).

For case C1 (Andersson & Trogen, 2020; Palmqvist & Vikingsson, 2019; Palmqvist et al., 2021), the motivation for presenting information about important reminders are mainly to decrease quality errors, due to operators forgetting some critical tasks (Kehoe et al., 1992). This line of reasoning differs from the other cases but is a consequence of the short takt time, where operators are expected to learn assembly tasks by heart and don't have time for reading more detailed instructions (Bortolini et al., 2017). While increasing the level of cognitive automated support with reliance on technical capabilities to provide the required information, individual cognitive abilities remain relied upon as operators continue to learn operations by heart (Cowan, 2000).

Table 7
Demand on *cognitive* abilities of operators and corresponding level of automated support.

Case	Level of demands on *cognitive* abilities of operators	Corresponding level of capabilities regarding automated *cognitive* support
Case A	Medium demands	Medium level of automated support
Case B	Low demands	High level of automated support
Case C1	Medium demands	Medium level of automated support
Case C2	Medium demands	Medium level of automated support
Case D	Low demands	High level of automated support

Table 8
Summary of the cases and their rationale for change.

Case	Rationale for change	Cognitive support for operators before cases		Information Support Technology developed in the cases		Future outlook
		Information carrier	Information content	Information carrier	Information content	
Case A	To lower cognitive workload for operators	Desktop computer with two monitors	Text documents, with some pictures	Desktop computer with two monitors	Comprehensive 2D drawings and text instructions	Trial runs, with work orders
Case B		Information on paper, used	Bill of material, text-based	Touchscreen monitor	Step by step text and pictures	Development of interoperability to facilitate automatically generated instructions
Case C1	To improve assembly quality	Information on paper, unused	Text-based	An automatically updated monitor	Symbols reminding of important considerations	Scale-up to more workstations
Case C2	To present information closer to the assembly area	Desktop computer	Specification of measurement information	Smartphone placed on the forearm	Specification of measurement information	Application at other workstations
Case D			Interactive 3D models	Augmented reality goggles	Overlayed 3D models	Implementation in a training context

For case C2 (Billskog Johansson & Chowda Shetty, 2020), where operators need to move between the computer next to the workstation and the product, the motivation for using smartphones is to bring information closer to the operator during work. While the information content hasn't changed, the introduction of smartphones as mobile carriers of information positively affected the workflow of operators (Fast-Berglund & Thorvald, 2021). However, this decreases the mental workload of operators needing to memorize measurements for input at the computer station, instead the increased level of automated cognitive support reduces the demand on the individual ability to memorize at the cost of increased reliance on technical capabilities (Bortolini et al., 2017).

For case D (Hellgren & Munge, 2018), the benefits of 3D model-based assembly instructions include standardization of instructions, detailed information, easier to update instructions, which supports the infrequency of assembly tasks. The motivation to utilize the already existing 3D model data for instructions in an augmented reality context is to enable both easier training of new operators and for operators to easier access instructions when working away from computer stations (Bortolini et al., 2017). While operators are required to learn the assembly skill, the high level of automated cognitive support, whether before or during this case study, reduces the demand on individual operators' abilities to learn operations by heart, which can be difficult due to the long assembly times and infrequent repetitions (Cowan, 2000; Mattsson et al., 2020).

A summary of the cases, comparisons, and their rationale for change are presented in Table 8.

5.6. Implications for the manufacturing Industry

The cases in this paper have been ongoing for several years. While it is easier to create demonstrators and try out concepts, it is not simple to develop a cognitive support system that is sustainable over time. Especially when content needs to be created to populate the Information Support Technology. For some of the cases (A and C1), the concepts have been positively received by both operators and technicians at the respective companies, but continuous content creation has been difficult because of the necessity to involve other parts of the organizations for overcoming interoperability challenges. For other cases (B, C2, and D), the focus has been on creating long-lasting solutions, where the information presented can be generated with less manual touch (almost automatically). This will require Information Technology and Operational Technology that can support and provide the required information to be presented to operators. If this is not in place and much effort is required in the information-creation process, then it becomes less feasible. Therefore, this circles back to the importance to understand the informational needs of operators in order to provide adequate cognitive support, but is extended by the additional importance of securing support and prioritization within the organization to create such solutions that require collaboration between Information Technology and Operational Technology.

The cases provide five examples of how manufacturing companies approach the development of cognitive support solutions in terms of new *Information Support Technology* to support Operator 4.0, and it should be understood as that. Creating useful cognitive aids for operators require different approaches depending on a variety of factors, including those highlighted in this paper. Thus, this paper is limited in generalizing or prescribing Information Support Technology solutions, but instead may provide inspiration and show how manufacturing companies can approach this topic.

6. Conclusion

Lower levels of automated physical, sensorial, and cognitive support put higher demands on the individual operators' abilities to manually manage their assembly work. With increasing levels of automation, operators are provided with more support in their daily work with fewer demands on individual abilities and more focus on supporting the abilities to flourish. However, with increased automated support, the company introduces a reliance on automated support tools to perform and function. Thus, creating a demand that is placed on the technical capabilities of physical, sensorial, and cognitive automation.

Most manufacturing companies focus on Information Technology and Operational Technology, with these two dominant areas claiming, sharing, or even worse, evading, ownership on the issue of providing automated cognitive support for shop-floor operators. However, some manufacturing companies may not have the capability to bridge this gap. The cases in this paper have either focused on cross-functional collaboration or on a dedicated Information Support Technology function to provide a stronger emphasis on automated cognitive support, but both approaches need to be considered for long-term development to be successful.

The cases in this paper have exemplified how manufacturing companies with varying production characteristics can approach the presentation of information in an Industry 4.0 context. While the different approaches were developed independently, all cases have developed digitalized solutions to support the operators, despite the varying production circumstances facing the operators. The technological solutions were able to match the various cognitive difficulties. However, because all manufacturing companies have different characteristics and operators work under varying circumstances, unique types of cognitive support are required for these different production characteristics and situational circumstances.

CRediT authorship contribution statement

Dan Li: Conceptualization, Methodology, Formal analysis, Writing – original draft, Writing – review & editing, Visualization, Project administration, Funding acquisition. **Åsa Fast-Berglund:** Conceptualization, Methodology, Writing – original draft, Writing – review & editing, Visualization, Supervision. **Dan Paulin:** Conceptualization, Methodology, Writing – review & editing, Supervision. **Peter Thorvald:** Validation, Resources, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

Åkerman, M. (2018). *Implementing Shop Floor IT for Industry 4.0* ((PhD).). Gothenburg, Sweden: Chalmers University of Technology.

Åkerman, M., Fast-Berglund, Å., Karlsson, M., & Stahre, J. (2016). Introducing Customized ICT for Operators in Manufacturing. *Procedia CIRP, 41*, 490–495. https://doi.org/10.1016/j.procir.2015.12.074

Andersson, A., & Trogen, W. (2020). *Development and Evaluation of Digital Assembly Instructions: Cognitive Support in Final Assembly.* (MSc.). Chalmers University of Technology, Gothenburg, Sweden. Retrieved from https://hdl.handle.net/20.500.12380/300864.

Asklund, E., & Eriksson, R. (2018). Digital Dynamic Work Instructions in a Variant Driven Industry: An Investigation on the Effects of Dynamic Instructions on Operator User Satisfaction. (MSc.). Chalmers University of Technology, Gothenburg, Sweden. Retrieved from https://hdl.handle.net/20.500.12380/256232.

Bäckström, W., & Westberg, C. (2021). Information Model for Auto-generation of Assembly Work Instructions: Using information from manufacturing preparation by increasing system interoperability. (MSc.). Chalmers University of Technology, Gothenburg, Sweden. Retrieved from https://hdl.handle.net/20.500.12380/302214.

Billskog Johansson, K., & Chowda Shetty, M. (2020). *Digital Visualization of Quality Data in Final Demands Station.* (MSc). Chalmers University of Technology, Gothenburg, Sweden. Retrieved from https://hdl.handle.net/20.500.12380/301532.

Boaden, R., & Lockett, G. (1991). Information technology, information systems and information management: Definition and development. *European Journal of Information Systems, 1*(1), 23–32. https://doi.org/10.1057/ejis.1991.4

Bortolini, M., Ferrari, E., Gamberi, M., Pilati, F., & Faccio, M. (2017). Assembly system design in the Industry 4.0 era: A general framework. *IFAC-PapersOnLine, 50*(1), 5700–5705. https://doi.org/10.1016/j.ifacol.2017.08.1121

Brettel, M., Friederichsen, N., Keller, M., & Rosenberg, M. (2014). How Virtualization, Decentralization and Network Building Change the Manufacturing Landscape: An Industry 4.0 Perspective. *World Academy of Science, Engineering and Technology, International Journal of Mechanical, Aerospace, Industrial, Mechatronic and Manufacturing Engineering, 8*, 37–44.

Carroll, J. B. (1993). *Human Cognitive Abilities: A Survey of Factor-Analytic Studies.* Cambridge: Cambridge University Press.

Case, K., Bäckstrand, G., Högberg, D., Thorvald, P., & Vin, L. D. (2008). *An assembly line information system study*.

Cowan, N. (2000). The magical number 4 in short-term memory: A reconsideration of mental storage capacity. *Behavioral and Brain Sciences, 24*, 87–185.

Creswell, J. W., & Plano Clark, V. L. (2018). *Designing and Conducting Mixed Methods Research* (3rd ed.). Thousand Oaks, California: SAGE Publications.

Delen, D., & Pratt, D. B. (2006). An integrated and intelligent DSS for manufacturing systems. *Expert Systems with Applications, 30*(2), 325–336. https://doi.org/10.1016/j.eswa.2005.07.017

ElMaraghy, W., ElMaraghy, H., Tomiyama, T., & Monostori, L. (2012). Complexity in engineering design and manufacturing. *Cirp Annals-manufacturing Technology, 61*, 793–814.

Endsley, M. (1995). Toward a Theory of Situation Awareness in Dynamic Systems. Human Factors Journal 37(1), 32–64. *Human Factors: The Journal of the Human Factors and Ergonomics Society, 37*, 32–64. https://doi.org/10.1518/001872095779049543

Endsley, M. R., & Kaber, D. B. (1999). Level of automation effects on performance, situation awareness and workload in a dynamic control task. *Ergonomics, 42*(3), 462–492. https://doi.org/10.1080/001401399185595

Evans, J. S. B. T. (2003). In two minds: Dual-process accounts of reasoning. *Trends in Cognitive Sciences, 7*(10), 454–459. https://doi.org/10.1016/j.tics.2003.08.012

Fantini, P., Pinzone, M., & Taisch, M. (2020). Placing the operator at the centre of Industry 4.0 design: Modelling and assessing human activities within cyber-physical systems. *Computers & Industrial Engineering, 139*, Article 105058. https://doi.org/10.1016/j.cie.2018.01.025

Fast-Berglund, Å., & Romero, D. (2019). Strategies for Implementing Collaborative Robot Applications for the Operator 4.0. In: Ameri, F., Stecke, K. E., von Cieminski, G., & Kiritsis, D. (eds.) *Advances in Production Management Systems: Production Management for the Factory of the Future (APMS 2019)*, part of series IFIP Advances in Information and Communication Technology, *566*, 682-689, Cham: Springer.

Fast-Berglund, Å., Li, D., & Åkerman, M. (2018). Creating Strategies to Improve the Use of IT- and IS-Systems in Final Assembly. *Advances in Manufacturing Technology XXXII, part of series Advances in Transdisciplinary Engineering* (Vol. 8,, 177–182.

Fast-Berglund, Å., & Thorvald, P. (2021). Variations in cycle-time when using knowledge-based tasks for humans and robots. In *17th IFAC Symposium on Information Control Problems in Manufacturing* (pp. 152–157).

Flynn, B. B., Sakakibara, S., Schroeder, R. G., Bates, K. A., & Flynn, E. J. (1990). Empirical research methods in operations management. *Journal of Operations Management, 9*(2), 250–284. https://doi.org/10.1016/0272-6963(90)90098-X

Fragapane, G., Ivanov, D., Peron, M., Sgarbossa, F., & Strandhagen, J. O. (2020). Increasing flexibility and productivity in Industry 4.0 production networks with autonomous mobile robots and smart intralogistics. *Annals of Operations Research.*. https://doi.org/10.1007/s10479-020-03526-7

Gorecky, D., Khamis, M., & Mura, K. (2017). Introduction and establishment of virtual training in the factory of the future. *International Journal of Computer Integrated Manufacturing, 30*(1), 182–190. https://doi.org/10.1080/0951192X.2015.1067918

Gorry, G. A., & Morton, M. S. S. (1971). A Framework for Information Systems. *Sloan Management Review, 13*.

Goto, S., Yoshie, O., & Fujimura, S. (2017). Industrial IoT business workshop on smart connected application development for operational technology (OT) system integrator. *2017 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM)*.

Hahn, A. (2016). Operational Technology and Information Technology in Industrial Control Systems. In E. J. M. Colbert, & A. Kott (Eds.), *Cyber-security of SCADA and Other Industrial Control Systems* (pp. 51–68). Cham: Springer.

Hart, M. (2008). Systems for Supporting Marketing Decision. *Handbook on Decision Support Systems 2, nternational Handbooks Information System*. https://doi.org/10.1007/978-3-540-48716-6_19.

Helldén, J., & Karlsson, V. (2020). Digital information presentation in a complex production environment: An investigation into reducing operators cognitive workload. (MSc.). Chalmers University of Technology, Gothenburg, Sweden. Retrieved from https://hdl.handle.net/20.500.12380/301531.

Hellgren, R., & Munge, A. (2018). *Kunskapsdelning inom montering på SAAB Aeronautics.* (BSc.). Chalmers University of Technology, Gothenburg, Sweden. Retrieved from https://hdl.handle.net/20.500.12380/255215.

Hernández, J. E., Lyons, A. C., & Stamatopoulos, K. (2016). A DSS-Based Framework for Enhancing Collaborative Web-Based Operations Management in Manufacturing SME Supply Chains. *Group Decision and Negotiation, 25*(6), 1237–1259. https://doi.org/10.1007/s10726-016-9482-x

Holmgård, K. (2020). Information System management in New Space production: Adapting a low volume-high quality production'sinformation management system. (MSc.). Chalmers University of Technology, Gothenburg, Sweden. Retrieved from https://hdl.handle.net/20.500.12380/300863.

Hu, S. J., Ko, J., Weyand, L., ElMaraghy, H. A., Lien, T. K., Koren, Y., … Shpitalni, M. (2011). Assembly system design and operations for product variety. *CIRP Annals, 60* (2), 715–733. https://doi.org/10.1016/j.cirp.2011.05.004

Huysamen, K., Bosch, T., de Looze, M., Stadler, K. S., Graf, E., & O'Sullivan, L. W. (2018). Evaluation of a passive exoskeleton for static upper limb activities. *Applied Ergonomics, 70*, 148–155. https://doi.org/10.1016/j.apergo.2018.02.009

Johansson, P. E. C., Malmsköld, L., Fast-Berglund, Å., & Moestam, L. (2019). Challenges of handling assembly information in global manufacturing companies. *Journal of Manufacturing Technology Management, 31*(5), 955–976. https://doi.org/10.1108/JMTM-05-2018-0137

Johansson, Pierre E. C., Malmsköld, Lennart, Fast-Berglund, Åsa, & Moestam, Lena (2018). Enhancing Future Assembly Information Systems – Putting Theory into Practice. *Procedia Manufacturing, 17*, 491–498. https://doi.org/10.1016/j.promfg.2018.10.088

Kaasinen, E., Schmalfuß, F., Özturk, C., Aromaa, S., Boubekeur, M., Heilala, J., … Walter, T. (2020). Empowering and engaging industrial workers with Operator 4.0 solutions. *Computers & Industrial Engineering, 139*, Article 105678. https://doi.org/10.1016/j.cie.2019.01.052

Kehoe, D. F., Little, D., & Lyons, A. C. (1992, 27-29 July 1992). Measuring a company IQ. *Third International Conference on Factory 2000: Competitive Performance Through Advanced Technology*, 27-29 July, York.

Knowles, J. (2006). *Theory of Science – A Short Introduction*. Trondheim: Tapir Akademisk Forlag.

Leavitt, H. J., & Whisler, T. L. (1958). Management in the 1980's. *Harvard Business Review, 23*(6), 13–26.

Lee-Post, A., & Chung, C. H. (2008). Systems for supporting operations management decisions. *Handbook on Decision Support Systems, 2*, 371–394.

Li, T., & Chan, Y. E. (2019). Dynamic information technology capability: Concept definition and framework development. *The Journal of Strategic Information Systems, 28*(4), Article 101575. https://doi.org/10.1016/j.jsis.2019.101575

Li, D., Fast-Berglund, Å., & Paulin, D. (2019). Current and future Industry 4.0 capabilities for information and knowledge sharing. *The International Journal of Advanced Manufacturing Technology, 105*(9), 3951–3963. https://doi.org/10.1007/s00170-019-03942-5

Li, D., Paulin, D., Berglund, Å. F., Gullander, P., & Bligård, L.-O. (2018). Supporting Individual Needs for Intra-Organisational Knowledge Sharing Activities in Pre-Industry 4.0 SMEs. In S. Pather (Ed.), *Proceedings of the 15th International Conference on Intellectual Capital, Knowledge Management & Organisational Learning* (pp. 160–170).

Longo, F., Nicoletti, L., & Padovano, A. (2017). Smart operators in industry 4.0: A human-centered approach to enhance operators' capabilities and competencies within the new smart factory context. *Computers & Industrial Engineering, 113*, 144–159. https://doi.org/10.1016/j.cie.2017.09.016

Mattsson, S., Fast-Berglund, Å., Li, D., & Thorvald, P. (2020). Forming a cognitive automation strategy for Operator 4.0 in complex assembly. *Computers & Industrial Engineering, 139*, Article 105360. https://doi.org/10.1016/j.cie.2018.08.011

Osvalder, A.-L., & Ulfvengren, P. (2009). Human-technology systems. In M. Bohgard, S. Karlsson, E. Lovén, & L.-Å. Mikaelsson (Eds.), *Work and technology on human terms* (pp. 463–566). Stockholm: Prevent.

Palmqvist, A., & Vikingsson, E. (2019). *Digitalisation of work instructions, coaching and quality follow-up.* (MSc.). Chalmers University of Technology, Gothenburg, Sweden. Retrieved from https://hdl.handle.net/20.500.12380/257030.

Palmqvist, A., Vikingsson, E., Li, D., Fast-Berglund, Å., & Lund, N. (2021). Concepts for digitalisation of assembly instructions for short takt times. *Procedia CIRP, 97*, 154–159. https://doi.org/10.1016/j.procir.2020.05.218

Panetto, H., Iung, B., Ivanov, D., Weichhart, G., & Wang, X. (2019). Challenges for the cyber-physical manufacturing enterprises of the future. *Annual Reviews in Control, 47*, 200–213. https://doi.org/10.1016/j.arcontrol.2019.02.002

Rasmussen, J. (1983). Skills, rules, and knowledge; signals, signs, and symbols, and other distinctions in human performance models. *IEEE Transactions on Systems, Man, & Cybernetics, SMC-13(3)*, 257–266. https://doi.org/10.1109/TSMC.1983.6313160

Romero, D., Bernus, P., Noran, O., Stahre, J., & Fast-Berglund, Å. (2016b). The Operator 4.0: Human Cyber-Physical Systems & Adaptive Automation Towards Human-Automation Symbiosis Work Systems. *Paper presented at the Advances in Production Management Systems. Initiatives for a Sustainable World*. Cham: Springer.

Romero, D., Stahre, J., Wuest, T., Noran, O., Bernus, P., Fasth, F.-B. Å., & Gorecky, D. (2016a). *Towards an Operator 4.0 Typology: A Human-Centric Perspective on the Fourth Industrial Revolution Technologies*.

Romero, D., Stahre, J., & Taisch, M. (2020). The Operator 4.0: Towards socially sustainable factories of the future. *Computers & Industrial Engineering, 139*, Article 106128. https://doi.org/10.1016/j.cie.2019.106128

Segura, Á., Diez, H. V., Barandiaran, I., Arbelaiz, A., Álvarez, H., Simões, B., … Ugarte, R. (2020). Visual computing technologies to support the Operator 4.0. *Computers & Industrial Engineering, 139*, Article 105550. https://doi.org/10.1016/j.cie.2018.11.060

Skinner, W. (1969). Manufacturing—Missing Link in Corporate Strategy. *Harvard Business Review, 47*(3), 136–145.

Slack, N., & Lewis, M. (2019). *Operations Strategy*. London: Pearson.

Stankovic, J. A. (2014). Research Directions for the Internet of Things. *IEEE Internet of Things Journal, 1*(1), 1–7. https://doi.org/10.1109/JIOT.2014.2312291

Toro, C., Barandiaran, I., & Posada, J. (2015). A Perspective on Knowledge Based and Intelligent Systems Implementation in Industrie 4.0. *Procedia Computer Science, 60*, 362–370. https://doi.org/10.1016/j.procs.2015.08.143

Tsujii, T., & Watanabe, S. (2009). Neural correlates of dual-task effect on belief-bias syllogistic reasoning: A near-infrared spectroscopy study. *Brain Research, 1287*, 118–125. https://doi.org/10.1016/j.brainres.2009.06.080

Wagner, H.-T., Beimborn, D., & Weitzel, T. (2014). How Social Capital Among Information Technology and Business Units Drives Operational Alignment and IT Business Value. *Journal of Management Information Systems, 31*(1), 241–272. https://doi.org/10.2753/MIS0742-1222310110

Weber, B. W. (2008). Financial DSS: Systems for Supporting Investment Decisions. In *Handbook on Decision Support Systems 2: Variations* (pp. 419–442). Springer, Berlin Heidelberg: Berlin, Heidelberg.

Yin, R. K. (2009). *Case study research: Design and methods* (4th ed.). Thousand Oaks, California: Sage.