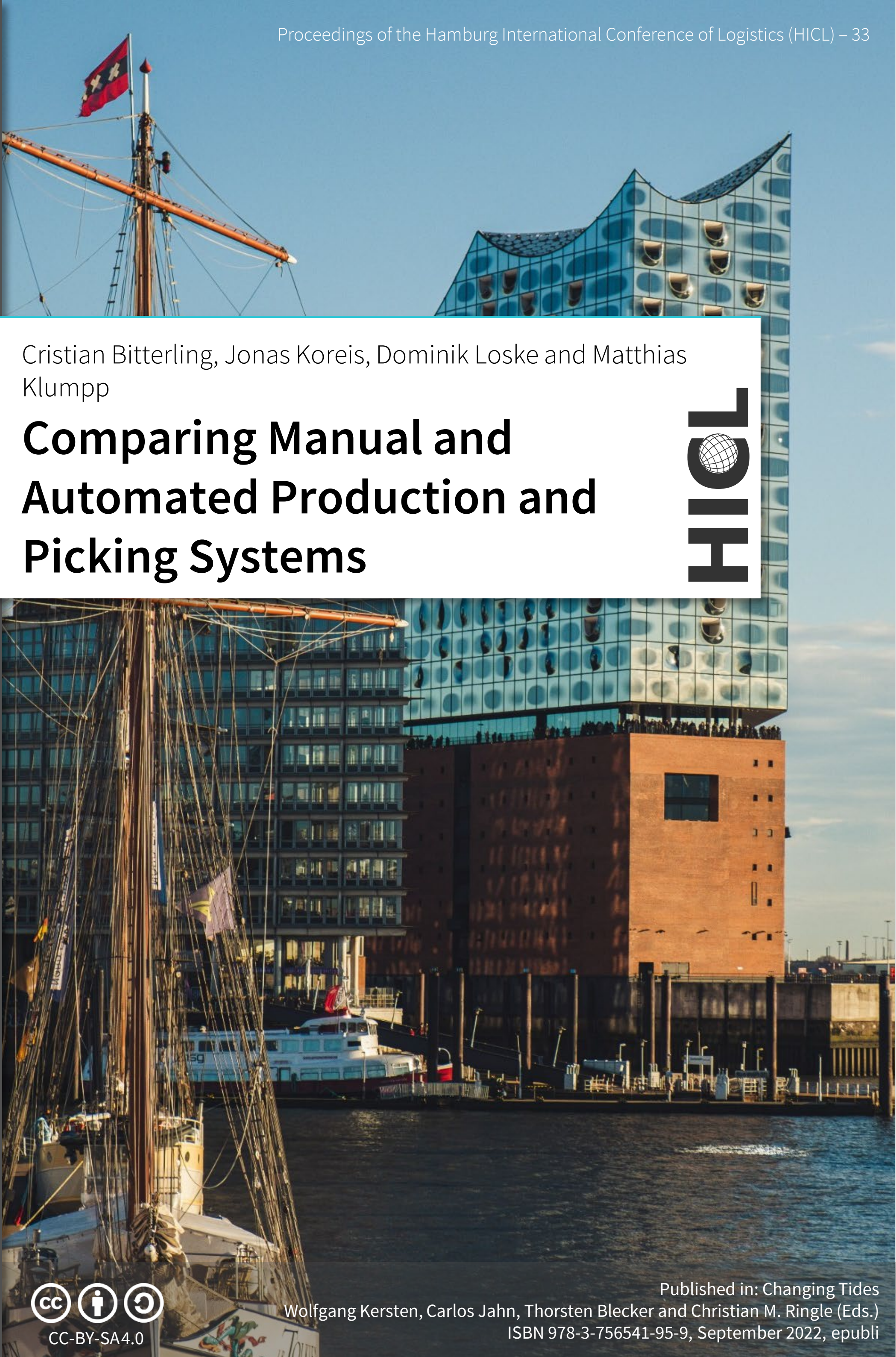
Proceedings of the Hamburg International Conference of Logistics (HICL) – 33



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HICL

Published in: Changing Tides
Wolfgang Kersten, Carlos Jahn, Thorsten Blecker and Christian M. Ringle (Eds.)
ISBN 978-3-756541-95-9, September 2022, epubli

Comparing Manual and Automated Production and Picking Systems

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Purpose: *Automated processes play a crucial role, especially when high product quantities are desired. The automation of manufacturing and order picking processes enables companies to reduce the number of manual transports and order fulfillment time. Nevertheless, manual labor remains relevant. This paper analyses the key aspects that define manual and automated labor and their application in manufacturing and order picking systems.*

Methodology: *We conduct a literature review to analyze manual and automated systems in general and for manufacturing and order picking systems. Using field-based research, we provide several real-world use cases where decisions were made in favor of either concept. Finally, we use morphological analysis to distinguish the key elements of both systematics.*

Findings: *Manual labor cannot be substituted when dealing with highly volatile demands or a high variety of products. Moreover, human adaptability and prestidigitation can, thus far, not be automatized. In conclusion, manual as well as automated labor are not always interchangeable. Further, employing manual as well as automated labor is vital to maximize efficiency in manufacturing and order picking.*

Originality: *While studies exist that deal with automated and manual labor, most are directed at automatization of processes, not considering the advantages of manual labor.*

First received: 10. Mar 2022 Revised: 12. Aug 2022 Accepted: 15. Aug 2022

1 Introduction

This paper aims to compare the processes of manual and automated labor and their application in manufacturing and order picking. Therefore, three research questions (RQ) are proposed: (RQ_1) What are the key elements that define manual and automated labor? (RQ_2) What are the disadvantages of manual labor that drive process planers to favor automated labor and vice versa? Answering these questions provides a framework for the answer of the third research question: (RQ_3) What method can be used to visually compare manual and automated labor? This question is answered using a morphological analysis.

To gain a holistic understanding of both concepts, the following section will be based on a literature review regarding manual and automated labor in general and for manufacturing and order picking systems. Additionally, using field-based research, several real-world examples are presented where decisions were made in favor of each process. In the third section, the literature review and field-based research findings are used in a morphological analysis. The results of review, research, and analysis are presented in the findings section. The paper closes with a conclusion, insights into the limitations of the study and avenues for further research.

2 Literature Review

2.1 Manual Labor

As the name implies, manual labor is physical work done by humans. Characteristics are adaptability and flexibility, dexterity, creativity, and cognitive ability.

- Adaptability is the proficiency to adjust to changes (Ployhart and Bliese, 2006) while flexibility describes the ability to accept changes in tasks, environmental or social features (Tindle and Moustafa, 2021). Although their definition is different, adaptability and flexibility are often used synonymously.
- Dexterity describes the manipulation of the human hand with the goal of manipulating objects. This can be done according to a visual input, also called

eye-hand coordination, or by memory of the desired object's location without visual input (Johansson, et al., 2001).

- Creativity is defined as "the production of novel and useful ideas by an individual or small group of individuals working together". It is described as the "front end of innovation", which can be seen as "the successful implementation of creative ideas within an organization"(Amabile and Pratt, 2016).
- Cognitive ability, often also described as general intelligence, is the capability to "reason, plan, solve problems, think abstractly, comprehend complex ideas, learn quickly and learn from experience" (Gottfredson, 1997).

Additionally, human labor can be divided into two different forms: physical and mental workload. Physical workload is characterized by tasks that require a person to adapt to energetic, biomechanical or environmental demands (Sluiter, 2006). Mental workload is an individual's capability to provide cognitive capacities towards task demands. Generally, the mental workload increases when the demands of the task are high, e.g., when dealing with high amounts of information, and responding capacities are low. Correspondingly, low task demands, and high capacities lead to low mental workload and therefore underload or inattention (Hwang, et al., 2008).

The downsides of manual work are mental and physical limitations, fatigue, and error. Physical limitations are the limits the human musculoskeletal system can endure. Mental limitation describes the human brain's limited capacity to become aware of, hold in mind, and act upon visual information. Some factors affecting the limits of a human being, physical and mental, are exposure to environmental extremes like heat or cold, sleep deprivation or noise (Sadegh and Worek, 2006).

Fatigue can be categorized into mental and physical fatigue. Physical fatigue, also known as muscle fatigue, is a decline in performance due to exercise-induced reduction of the maximal voluntary muscle force. (Wan, et al., 2017). Mental fatigue describes a state of diminished cognitive performance, caused by prolonged cognitive activity (Marcora, Staiano and Manning, 2009).

Human error is a deviation from intention, expectation or desirability (Senders and Moray, 2020). While fatigue and limitations, mental and physical, contribute towards errors, they are not the only reasons for humans to fail. Distractions from systems or other persons or acute causes like illnesses or injuries also influence human performance and error (Rasmussen, 1982). Human error is responsible for about 80% of total product failures (Di Pasquale, et al., 2015).

2.1.1 Manual labor in manufacturing

Modern companies are subjected to more and more complexity challenging their manufacturing sector. Figure 1 illustrates the drivers of manufacturing complexity.

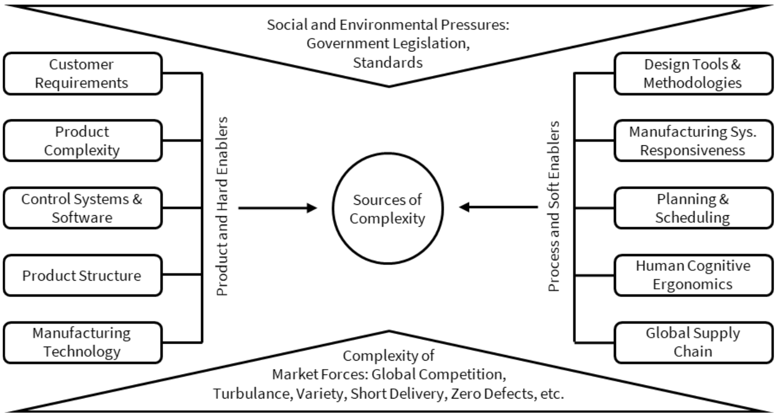

Figure 1: Drivers of Manufacturing Complexity (Elmaraghy, et al., 2012)

Therefore, they rely on manual labor in areas where high flexibility is imperative, or automation is economically unreasonable or technically difficult or impossible. The most typical manual labor tasks are material handling and assembly of products. Manual handling involves the lifting, lowering, pushing, pulling, or carrying loads. Reasons for manual materials handling are the high grade of flexibility and the costs (Lee and Dai, 2011). Characteristic assembly operations consist of joining and handling parts as well as adjusting, controlling and various auxiliary operations (e.g., cleaning, unpacking, printing, oiling). It is estimated that assembly makes up about 45% of the total manufacturing work (Lotter and Wiendahl, 2012).

Manual assembly systems utilize the worker's high flexibility, adaptability and ability to process multiple sources of information and rapidly switch between tasks (Hinrichsen, Riediger and Unrau, 2016).

2.1.2 Manual labor in order picking

Order picking also heavily relies on manual work. As with manufacturing, warehousing is subjected to decreased life cycle and increased product differentiation efforts in industry (Grosse, Glock and Neumann, 2017). Today, warehouses are confronted with

- Small order sizes (Boysen, Stephan and Weidinger, 2018)
- Large assortments, especially in e-commerce (Brynjolfsson and Smith, 2003; Boysen, Koster and Weidinger, 2019)
- Limited delivery time (Yaman, Karasan and Kara, 2012)
- Varying Workload (Boysen, Koster and Weidinger, 2019)

Therefore, warehouses tend to employ manual labor in the order picking process. Companies use the minimum of technological expenditure, the high flexibility in regard of volatile demands and range of goods, the suitability for all kinds of products as well as the possibility of processing rush orders, single orders, partial orders etc. at the same time (Gudehus, 2010).

The most common method is the so-called picker-to-parts system: the requested item, stored in a rack or a bin is manually pulled by a worker travelling along the storage aisles. Estimates show that about 80% of all order processes in warehouses in western Europe are picked manually using the picker-to-parts system (Koster, Tho and Roodbergen, 2007; Grosse, Glock and Neumann, 2017). These systems are able to process a maximum of 10.000 order lines per day (Marchet, Melacini and Perotti, 2015).

The downside of manual order regards the operating expenses of warehouses: picking makes up 55% of the operating cost (Figure 2). Of these 55%, half is used for travel between the aisles and to and from shelves (Tompkins, et al., 2010). As travel is seen as non-value-add labor (Bartholdi and Hackman, 2019), it can be inferred that 27.5% of all costs in warehouses are lost to traveling alone.

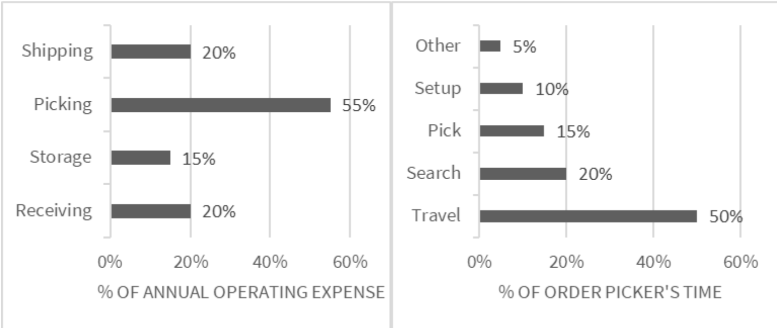

Figure 2: Typical distribution of warehouse operating expenses and order picking time (Tompkins, et al., 2010)

2.2 Automated labor

Automation can be defined as “the technology by which a process or procedure is performed without human assistance” (Groover, 2019b). While humans may observe or participate, the labor in itself is done autonomously and without human intervention (Nof, 2009). Estimates by the World Economic Forum show that by 2025, the share of tasks between humans and machines will be equal (Schwab and Zahidi, 2020).

There are a multitude of reasons to automate labor. These include

- The reduction of labor cost due to reduced cost per unit (Groover, 2019a)
- Increased productivity (Nof, 2009)
- Mitigation of effects of labor shortage (Groover, 2019a)
- Safety, as automation is used in areas either unsafe for human operation (Nof, 2009)
- Improved quality (Groover, 2019a)
- Taking over monotonous or strenuous work (Groover, 2019a)

At the same time, there are different disadvantages of automation. One of the main reasons not to automate a process is that it simply isn’t suited for automation, e.g., when the physical access to the work location is limited or the task demands high dexterity. Another main reason is the cost: not only are automated processes linked to high investment costs, but the research and development cost of automating a process is difficult to predict (Lamb, 2013; Groover, 2019a).

2.2.1 Automation in manufacturing

Automation in manufacturing can be subdivided into three different types: fixed, programmable, and flexible automation. Fixed automation is characterized by a fixed sequence of processing operations with specialized equipment. The disadvantages of fixed automation are the high initial investment costs, especially regarding the specialized equipment, and the poor flexibility. In contrast, it can produce very large product quantities, enabling companies to distribute costs over many units, thus minimizing the cost per unit compared to other manufacturing methods (Gupta, Arora and Westcott, 2016; Groover, 2019b).

In programmable automation, the equipment is designed to accommodate changes in the process to allow the manufacturing and assembly of different parts or products. New programs for different parts can be prepared and easily introduced into the control. (Gupta, Arora and Westcott, 2016; Groover, 2019b).

Flexible automation can be seen as an extension or advancement of programmable automation. The equipment is designed to realize quick changes and therefore manufacture a variety of products with little adaption or reprogramming time. Therefore, changes in the product or new product lines can be introduced quickly, and different products can be produced alternately (Gupta, Arora and Westcott, 2016; Groover, 2019b).

There are two fields of application for automation in manufacturing: manufacturing lines and assembly systems. Manufacturing lines consist of multiple workstations that process parts, connected by a transfer system. Automated assembly systems perform a sequence of automated assembly operations to combine multiple components. A typical assembly system consists of one or more workstations, parts feeding devices, handling systems and, in case of multiple workstations, a part transfer system (Groover, 2019a).

2.2.2 Automation in order picking

Figure 3 shows the different picking systems and the corresponding level of automation. Even in manual picker-to-parts systems, automation is used. For example, automated guided vehicles (AGVS) are used to reduce the amount of manual transport (Boysen, Koster and Weidinger, 2019).

In a picker-to-box system, the picking area is divided into zones connected by a conveyor on which boxes with the manually picked items are placed, each corresponding to a customer order. With this system, up to 120.000 order lines per day can be achieved (Marchet, Melacini and Perotti, 2015).

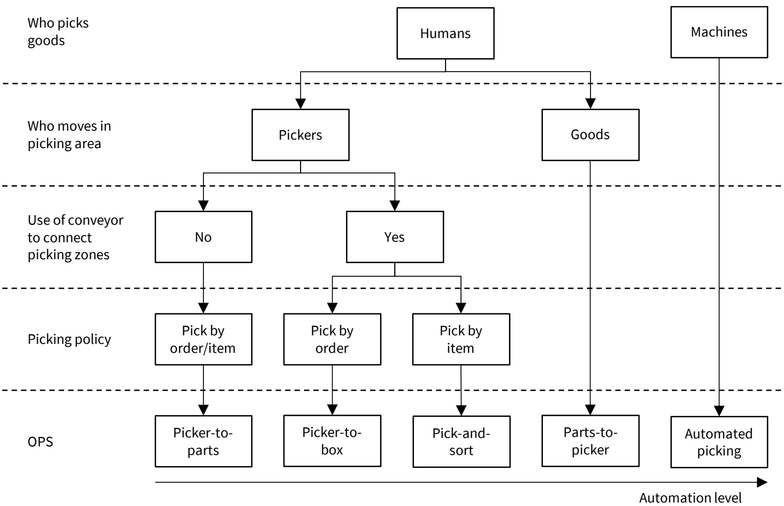

Figure 3: Classification of order picking systems (Dallari, Marchet and Melacini, 2009)

In Pick-and-sort systems, pickers retrieve an amount of a single item resulting from the batching of multiple orders and place them on a takeaway conveyor connected to an automated sorting area, which allots the items to the customer orders. The achievable picking volume can be up to 35.000 order lines per day. Both picker-to-box and pick-and-sort systems are not suitable for bulky, heavy, and fragile items or those with low picking volume (Marchet, Melacini and Perotti, 2015).

In parts-to-picker systems, the items are automatically transported to the human picker from the storage area. The picker selects the required amount of each item and the unit load, if not empty, is transported back to the storage area. Depending on the industry, the picking volume normally reaches a maximum of 10.000 order lines per day (Marchet, Melacini and Perotti, 2015).

Automated order picking systems (AOPS), like the so-called A-frame, completely forgo manual labor in the picking process. Typically, there are four reasons to contemplate the usage of AOPS: high numbers of different items to be picked fast, requirement to pick single pieces, very high flow intensity and minimizing material handling costs (Roodbergen and Vis, 2009).

3 Field-based Research

Additionally, to the literature review, field-based research was conducted. It is a contemporary method in which the researcher has no control, but instead serves as an observer of the phenomena present. This can be achieved by direct or participant observation, interviews of people involved, questionnaire surveys or archival analysis (Snow and Thomas, 1994). Field-based research aims is to gain a holistic overview of real-world events or phenomena. It can either be used to develop theory, e.g., by early exploratory investigations of unknown or little-understood phenomena, or to test and refine existing theories (Yin, 2009), which is used in the paper at hand. Five cases of automation or manual labor decisions are presented. The first four were examined at a company in the electronics industry while the last one was surveyed at a warehouse of a brick-and-mortar business. In all cases, a manual task was studied regarding the potential for automation. The data was acquired through direct observation and archival analysis. As the authors of this paper were directly involved in all projects the cases are based on, they had a holistic insight into all process steps and deliberations that eventually led to the decisions in favor of manual or automated labor.

3.1 Case I

For an injection molding process, several parts must be assembled and the quality controlled. This process was performed manually, which posed capacity problems, as the takt time of the worker (3 minutes) was lower than the mold's closing time (2 minutes) as well as logistics problems, as the manual workstation was spatially disconnected from the molding area and couldn't be moved closer. Using automation, the processing time could be reduced to match the mold's closing time. Further, the automation could directly be added to the molding system, eliminating the transportation need.

3.2 Case II

In this case, the manual completion assembly of the injection molded product of case I was studied. In the process step analyzed, the product is equipped with an actuator. This actuator is manually screwed on and then fastened with a specific torque.

The process poses a few challenges:

- The tip of the actuator, which holds the thread, is spring-loaded and pivoted. Therefore, the torque must be applied to this tip
- The tip is only 6mm long and inserted at least 116.5mm into the casing
- The space between actuator and casing is about 28mm along the entire circumference
- Rework is necessary in 16 percent of all cases

This process was considered for automation. Yet, the expected assembly time was estimated to be higher, with no automated process for disassembly. As the manual process time analyzed yielded ~60 seconds, as well as having the ability for rework, the automation attempt was discarded in favor of manual labor.

3.3 Case III

In this case, the manual final assembly of the switchgears was studied. While the assembly process by itself isn't suited for automation due to order volume, complexity, accessibility, etc., the transport of the switchgears was examined. During assembly, the gear must be subjected to several component tests. For that purpose, it is transported between test stations, buffers, etc. (Figure 4)

		handover station out	buffer 1	test station 1	assembly station	test station 2	test station 3	buffer 2	repair station	handover station out	sum
1	handover station in	0	**6**	0	0	0	0	**6**	0	0	12
2	buffer 1	0	0	**7**	**2**	**6**	0	0	0	**2**	17
3	test station 1	0	**2**	0	**7**	**1**	0	**2**	**1**	0	13
4	assembly station	0	**5**	0	0	**2**	0	**5**	0	0	12
5	test station 2	0	**1**	0	0	0	**10**	**1**	**1**	0	13
6	test station 3	0	**2**	0	0	0	0	**2**	**1**	**8**	13
7	buffer 2	0	0	**7**	**2**	**6**	0	0	0	**2**	17
8	repair station	0	**1**	**1**	0	0	0	**1**	0	0	3
9	handover station out	0	0	0	0	0	0	0	0	0	0
	sum	0	17	15	11	15	10	17	3	12	100

Figure 4: Material flow matrix of the switchgear final assembly for a two-shift day

The evaluation showed that about 100 transports, each lasting up to four minutes, are performed daily. Due to the size of the switchgear and safety regulations, every transport must be conducted by two workers. Considering a two-shift day has about 900 minutes (including breaks), ~44% of the daily working time was lost to transportation. Therefore, AGVs were implemented. With a few layout modifications, these could take over all necessary transports, reducing the number of manual transports to zero.

3.4 Case IV

The outgoing products of the electrical company are either stored in pallet cages or wooden boxes. These boxes were stored in multiple manually operated high racks in the past. Additionally, the material used for manufacturing was also stored in the high racks. Due to high manufacturing rates as well as demands, this resulted in high amounts of transports. Further, the workers needed specific special trainings, for example forklift certifications. Therefore, the materials-handling was automated using a multi-deep automated storage and retrieval system (AS/RS).

3.5 Case V

For the warehouse of brick-and-mortar company, automation was considered for two different areas. In the first area, fruit and vegetables, automation was ruled out. This was due to highly volatile goods issues and demands (+40 percent in demand on 52 days/year) as well as limited keepability of such spoilable wares. In the second area, drugstore goods, automation was implemented, as the number of articles is high while goods issues per article are low, resulting in high amounts of walking time and transports.

4 Morphological Analysis

General morphological analysis describes a heuristic creativity technique developed by Fritz Zwicky. This method aims to gain a holistic understanding of the relationships of multi-dimensional, non-quantifiable, problem complexes (Zwicky, 1967). Each of these problems or complex parameters is then assigned a number of relevant attributes or conditions (Ritchey, 2011). Finally, these parameters and their attributes are then collected in a n-dimensional matrix, also called morphological box. Each cell contains one condition for the parameter, thus visualizing the particular state of the problem complex (Ritchey, 2011). One advantage of the method is the “totality research” (Zwicky, 1967), meaning it provides the means to derive all the solutions of any given problem (Ritchey, 2011). Further, it helps identify relationships and boundary conditions of the given parameters and attributes (Ritchey, 2011). The morphological box finally represents a structured format illustrating all potential solutions to the problems (Kley, Lerch and Dallinger, 2011). Therefore, while historically rooted in engineering and the design of physical products, it is also used in the service design domain, e.g. for business models in the Business to Business context (Lay, Schroeter and Biege, 2009), service for industrial goods (Aurich, Mannweiler and Schweitzer, 2010) or electric vehicle service (Kley, Lerch and Dallinger, 2011).

Based on our findings from field-based research and the literature review, we conducted a morphological analysis to visualize the key elements, or conditions, of manual and automated labor attributes. The performance categories of order picking are time, quality, cost and productivity (Staudt, et al., 2015), as well as flexibility (Koster, Tho and Roodbergen, 2007), operational efficiency (Gu, Goetschalckx and McGinnis, 2010) and human factors (Grosse, Glock and Neumann, 2017). While designed for order picking, the indicators mentioned above are universal. For example, a manufacturing plant aims for high throughput, low cycle or takt times, low cost, high quality etc. Therefore, in the morphological analysis, these categories are used for the comparison.

Figure 5 shows the analysis for labor in the manufacturing area. For manual labor, productivity and quality can be moderate to high, depending on the product and the type of work. This could also be validated in the second case of the field-based research. At the same time, manual labor is the go-to solution when high flexibility is in demand. Further, compared to automated systems, the costs for manual labor are low, especially when the labor is outsourced to low-wage countries. On the downside, manual labor is usually connected to high cycle time and human factors, especially regarding ergonomics.

labor in manufacturing				
performance indicator	manual labor	fixed automation	programmable automation	flexible automation
cycle time	high	low	moderate	moderate
quality	moderate - high	very high	very high	very high
cost	low	moderate – very high	high – very high	very high
productivity	moderate - high	very high	very high	high
flexibility	very high	low	moderate	high
operational efficiency	moderate - high	high – very high	high	moderate - high
human factors	very high	low	low	low - moderate

Figure 5: Morphological Box for labor in manufacturing

Automation is characterized by high productivity and quality, yet at the same time high investment costs. The flexibility of the systems range between low and high. As explained, fixed automations are generally utilized for single products with high demand, and changes in design are difficult and costly to implement. Programmable automation introduces some flexibility by providing the possibility to implement different manufacturing programs and tool changes. The highest, although most expensive, flexibility can be achieved with flexible automation. Yet, all these systems cannot achieve the human flexibility, e.g., dexterity or cognitive flexibility.

The operational efficiency for automation can range between moderate and very high. Due to the very high productivity of fixed systems, the cost per unit usually is very low compared to manual labor. Therefore, the investment cost can be balanced to a certain degree. While programmable and flexible automation are also highly productive, their investment costs dampen the operational efficiency. Human factors normally play a secondary role in automation. Yet, they should at least be considered, e.g., when planning access points or control systems.

In order picking (Figure 6), automated labor is regarded across the whole scope. As can be seen, for picker-to-parts systems, which make up the bulk of OP, order lead time is high and productivity low. This is due to the high amounts of walking and transportation. On the other hand, it is the very high flexibility, e.g., when dealing with highly volatile demands or processing a large variety of products, which makes it the most-popular method of order picking.

With picker-to-box systems, the lead time can be reduced and the productivity drastically increased, due to transportation being taken over by the system. On the downside, the cost is increased as well, due to the investment for the system itself and the needed space. Therefore, these systems are preferred in areas with high number of small-sized items, medium-size flows, and small order sizes. The flexibility is lower, due to the system being unable to process bulky, heavy, or fragile items. As both systems rely on workers moving and picking, as well as high picking quality, they should be laid out as ergonomically as possible.

Pick-and-sort-systems further decrease the order lead times. In addition, they increase the quality of the pick compared to the two systems mentioned so far, as the sorting of items is automated, meaning wrongly picked items are discharged from the conveyor and stored next to the system. The flexibility is moderate, as each new item must be programmed into the system. Additionally, the system isn't suited for bulky, heavy, and fragile items or items with low picking volume. The investment is higher compared to the other systems due to the need for space, conveyors as well as sorting systems, which need mechanical as well as digital (scanners, lasers, cameras etc.) facilities.

Parts-to-picker-systems eliminate the transport part of order lead time by transporting the items directly to the picker. As the system only transports the exact items needed to fulfil the order and the picker only chooses the amount, the picking quality is usually high, with a few errors in counting being a possibility. The worker doesn't have to leave his working area, so the ergonomic design can be restricted to his workspace. As the system is manually loaded and emptied, it can accommodate changes in demands as well as items, therefore working with good flexibility. Downsides are the low productivity, as the picking and sorting is still done manually, and the high investment cost. Therefore, it is only moderately efficient.

labor in order picking					
performance indicator	picker-to-parts	picker-to-box	pick-and-sort	parts-to-picker	automated picking
order lead time	very high	high	moderate	low	very low
quality	moderate - high	moderate - high	very high	high	very high
cost	low	moderate – high	high	very high	very high
productivity (OL/day)	low (10.000)	very high (120.00)	high (35.000)	low (10.000)	very high (750.000)
flexibility	very high	high	moderate	moderate - high	very low
operational efficiency	moderate	high	moderate	moderate	moderate
human factors	very high	very high	high	moderate	very low

level of automation

Figure 6: Morphological Box for labor in order picking

Characteristics for automated systems are very low order lead times as well as very high picking quality and productivity. On the downside, the costs for acquiring and accommodate such a system are very high. The flexibility of such systems is relatively low, so as such systems cannot accommodate changes in unit loads, SKUs, long-lasting changes in order volume, etc., as well as being limited in their ability to pick targets from bins filled with multiple items.

5 Findings

We conducted a literature review to answer the first research question (RQ_1) “what are the key elements that define manual and automated labor?”. We found that research on automation, while extensive, rarely discuss the disadvantages. Further, most research is based on automating manual labor processes. This is especially the case for automation in manufacturing. In order picking, the significance and advantages of human labor are better understood, with researchers focusing more on the human factors and elimination of waste potential.

Regarding RQ_2 “what are the disadvantages of manual labor that drive process planers to favor automated labor and vice versa?”, analyzing the literature and the field-based research, we concluded that manual labor is mainly used in areas with high volatility regarding demands or products, where long-term forecasts can’t be ascertained. Automation on the other hand mostly is used for high demands with little to no variation, as the high investment costs must be balanced by driving down the costs per unit. Partial automation, e.g., in order picking, is used to eliminate waste like transport costs.

For the last research question RQ_3 “what method can be used to visually compare manual and automated labor?”, we constructed a morphological box for manufacturing as well as order picking. This visual presentation is based on the findings of the literature review and the field-based research and can be used to comprehend the strengths and weaknesses of the systems. Furthermore, it can be used when dealing with the design of a workspace or procedure.

6 Discussion

Our findings in the field-based research, as well as the morphological analysis correspond to the findings of the examined literature. Case II, which needed a high amount of flexibility and dexterity for the end assembly of electronic products, and Case V, the brick-and-mortar company’s warehouse with high volatility regarding issues and demands, were chosen to remain manual processes. This corresponds with the findings of Hinrichsen, Riediger and Unrau (2016), who name high flexibility, adaptability and ability to process multiple sources of information and rapidly switch between tasks as the main advantages of manual compared to automated labor, or Lee and Dai (2011), who stated the grade of flexibility and lower cost as main reasons for manual labor.

Additionally our research showed limited automation capability for hard-to-reach, high dexterity product designs, which was ascertained by Groover (2019a).

Automated labor is best suited for tasks that demand high quantities, little or no flexibility regarding products or product design or very high product quality. For Case I, where manual pre-assembly of products for injection molding was deemed too slow to keep up with the mold's productivity, as well as the need for further transportation, automation was deemed the best solution. These advantages are for example supported by Groover (2019a), or Gupta, Arora and Westcott (2016). Another reason for automation is the takeover of non-value-add work like transportation. This could, for example be observed in Case III, where a manual, non-automatable assembly process was supported by eliminating the need for manual transportation, thus increasing productivity while also increasing the safety and reducing the physical load on the workers due to transport systems moving the bulky and heavy products. This usage of automated transportation to support normally manual labor, especially heavy and bulky loads, was also studied by Boysen, Koster and Weidinger (2019).

7 Conclusions, limitations, and further research

Manual labor cannot be substituted when dealing with highly volatile demands or a high variety of products. Moreover, human adaptability and prestidigitation can, thus far, not be automatized. Therefore, it is imperative that manual labor not be left out when considering processes. At the same time, companies shouldn't fear or disregard automation of processes. Automation can be used to increase productivity as well as to reduce the mental and physical workload of workers to manageable and acceptable levels. In conclusion, manual as well as automated labor are not always interchangeable. Further, harmonizing manual and automated labor is vital to maximize efficiency in manufacturing and order picking. Therefore, research regarding collaboration should be focused upon, as well as the field-test of collaborating systems, especially in the industry 4.0 era. At the same time, the human factors should always be regarded, as they are key to the highest possible productivity of human workers.

While the study aimed to include the most recent research as well as current field research, the insight into the application of up-and-coming systems, fall short. The reason is that those are still considered to be in the early stages of development, although the development steps and periods between publications are becoming shorter. For example, using hybrid order picking systems could be a means to combine human flexibility with the productivity and quality of automation, as well as liberating humans from strenuous and challenging labor tasks.

Further research is warranted regarding the collaboration of automated systems and humans, human-centric system designs and sustainable engineering of manufacturing and order picking systems.

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