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Sustainable human-robot co-production for the bicycle industry

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Abstract

Bicycle production has not changed much over the last 100 years, it is still performed mainly by manual labor in mass production. During the global pandemic, the demand for ecologically friendly and customized transport has increased. Hence, customers start to impose the same requirements on bikes as on cars: they want more customized products and short delivery time. This publication describes an approach to transform bicycle manufacturing towards human-robot co-production to enable smaller batch sizes and production on-shoring. We list the challenges of this transformation, our applied methods, and presents preliminary results of the cobot-driven prototypes.

Keywords: Manufacturing, Bicycles, Cobots, Automation analysis, Assembly, Industry 4.0

1. Introduction

Invented in 1817, bicycles have substantially transformed mobility all over the world. The COVID-19 crisis currently even seems to support this boom. The global market for bicycles was estimated at US$29.2 billion in the year 2020 and is projected to reach a size of US$34.6 billion by 2027 [1]. Bicycle production consists mainly of a manual labor-intensive assembly process. Materials and production processes, and production locations have changed since the early days of bicycle production. Original bicycle steel frames produced in Europe, evolved into currently used aluminum frames produced in Asia, and are now further evolving into carbon-fiber structures and 3D-printed frames [2]. But the assembly process still looks very similar to the early days of bicycle production, and requires specially trained, skilled personnel, performing manual tasks that also include heavy loads. Within the EIT Manufacturing-funded project “Robofiets”, the project consortium set out to analyze current bicycle production processes and develop prototype solutions for (partly) robot-assisted assembly. In this paper, we will give an overview of the current analysis process with focus on the applied methodology. The preliminary insights through this research are intended to inspire other industries, that are similarly based on manual labor and expected to undergo a similar journey driven by Industry 4.0 technologies, like human-robot co-production: a certain spectrum of robot assisted technologies which can be summarized as follows according to [3]. In recent years, research on topics related to the digitization of production systems has been growing rapidly. In particular, the use of robot technology in various forms and capabilities to assist human operators in this context has been a major field of focus. While some of this research focuses on the development of better robot-assistants for humans in the manufacturing context [4], on the other end of the spectrum, progress is being made towards a more human-centric way of including humans in highly automated systems [5]. In the middle of this spectrum, development of system and data architectures to enable efficient and safe human-robot task sharing in production environments has been taking shape [6]. This spectrum is called human-robot co-production (HRC). It is important to state that the goal is not the replacement of human workers, but the transformation of the worker into an Operator 4.0 [7], assisted by intelligent robots.

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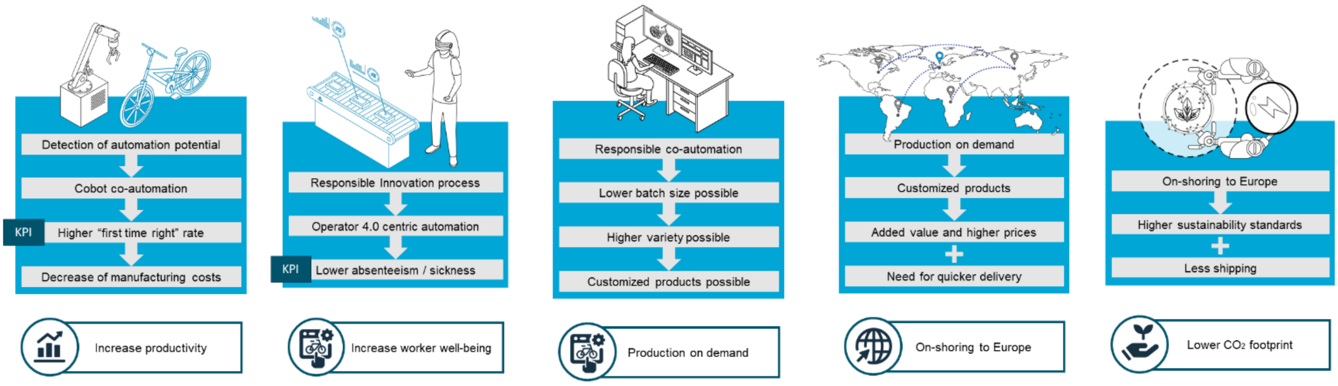

Fig. 1. Goals (a) increase productivity; (b) increase worker well-being; (c) production on demand; (d) on-shoring to Europe; and (e) lower CO_2 footprint.

1.1. Challenges

Given the rapid development outlined above, how can we address the following challenges:

1. *How to introduce innovative technologies in conventional production culture?* Bicycle production has not changed much over the last 100 years, whereas for example automotive industry has continuously innovating the production processes towards Industry 4.0.
2. *How to maintain and develop expertise in an aging society?* Currently, it can be observed that the percentage of absenteeism is increasing (due to older workforce).
3. *How to cope with increasing complexity?* Bikes are highly labor intensive, especially e-bike production is increasingly complex.
4. *How to reduce the ecological footprint of the production?* Mass-market production is mainly carried out in Asia, this results in a larger CO_2 footprint.
5. *How to improve quality by human-robot co-production?* Manual work leads to deviations. The more complex the bikes are, the more precise production needs to be.

1.2. Goals

In order to address these challenges, this project has set several goals, which are summarized in Figure 1. First, the direct impact of automation is displayed (Figure 1a). The automation analysis helps to identify optimization potential of the current production. In addition, a return of invest value is determined for cobot integration. Further, since machines produce a similar level of quality, human errors in production can be reduced, which should lead to a higher "first time right" rate, a KPI (key performance indicator) that is already measured. This will result in lowering of manufacturing costs, thus contributing to increased productivity.

Second, the project will apply a responsible innovation process. This means, that the entire socio-technical system is regarded and worker worries like "Will I be replaced by robots and lose my job?" will be addressed. This step of our approach aims to secure innovation by incorporating the worker's voice into cobot solutions and making sure that they are ready to accept the change. This is why we aim for a human-centric automation, which follows the Operator 4.0 paradigm [7]. This will for example take work ergonomics into account in the production process and can be measured by metrics of decreased absenteeism (KPI) (see Figure 1b).

Third, the above explained responsible co-innovation will enable lower batch sizes and higher variety. Only if this is achieved, customized products with very low batch sizes ("batch size one") is possible. This is not possible with the current assembly process with reasonable costs. If this is achieved, it would be possible to provide production on demand (see Figure 1c).

Customization of products adds extra value and enables higher pricing. But with the offer of customized products comes the need for a quicker delivery and the opportunity for local production. At the same time, automation also leads to better quality, less waste in production, and ultimately lower production costs. It creates an opportunity for companies to bring production back to Europe. Most of today's bicycle production is located in Asia, so in order to come to customized products, production needs to be on-shored to Europe (see Fig. 1d).

Finally, production in Europe, for example in the Netherlands, requires higher sustainability standards apply (for example with regards to pollution from factories, but also for worker rights and working conditions). Furthermore, less shipping of bicycles is required. Both measures will lower the CO_2 footprint of the product (see Fig. 1e). This is why we think that our approach systematically increases the sustainability of the production.

1.3. Structure of the paper

This paper is structured as follows: After the introduction, a summary of the related work is given. The next section introduces a general approach, the iterations which have been done so far, and some of the preliminary results. Finally, the conclusion discusses these findings and the approach so far and gives an outlook to future work.

2. Related work

Multiple studies [8][9][10] show that future productivity within the manufacturing industry (as envisioned by the Industry 4.0 [11] paradigm) will depend on humans working alongside intelligent machines and robots in the factories. The introduction of new technologies, like collaborative robots, Augmented and Virtual Reality but also Artificial Intelligence into the production floor demands for new interactions and new methods and tools in order to be able to design the "future of work" for production workers, who will more and more work in a team including intelligent systems.

The Operator 4.0 is a game-changing paradigm advocating a stronger human factors research within the "Industry 4.0" manufacturing environment [7]. The core idea is to see the human worker as "a smart and skilled operator who performs not only 'cooperative work' with robots, but also is 'work aided' by machines as and if needed, by means of human cyber-physical systems, advanced human-machine interaction technologies and adaptive automation towards 'human-automation symbiosis work systems' [7]. The factory of the future will be designed to leverage intelligent automatic machines as well as the power of human intelligence. The Operator 4.0 paradigm advocates for addressing human-in-the-loop systems, in which technology helps to enhance the physical, sensing, and cognitive capabilities of the worker [6]. At this moment, most literature concern the new technology in industry 4.0. There are also numerous studies on human factors, but hybrid human-robot systems are on the brink of getting more and more attention.

There are several real-life examples for effective combinations of autonomous robots and human workers, together forming a "hybrid intelligence system". [12] show an example from a production environment, in which parallelization of a human and a robot leads to a significant improvement of the overall tact time. Similar examples can be given with different optimization goals. Task allocation refers to ensuring that all tasks have been allocated to a person or a team and that the workload has been distributed properly among the participants (term is mostly used for pilots, process industry and dangerous environments). In addition to task allocation, a precedence graph enables understanding the order of stations and tasks. Function allocation describes if the particular function (or task) will be performed by a person, technology (hardware or software) or a mix between human and technology. This creates resource flexibility and volume flexibility.

There are different strategies for task allocation to which [13] provides a comprehensible overview. These strategies have been developed and discussed over time. Obviously, every project needs to find the approach which works best for their specific application context. First, the so-called comparison allocation or "men/humans are better at, machines are better at" or M/HABA-MABA approach should be mentioned [14]. This presumes that there is a distinct partition between tasks that shall always be done by either the human or the machine. Secondly, there is the "leftover allocation", which automates everything that is automatable and allocates the rest to humans. Third, the cost for automation and the cost for the human worker is calculated and the economically more feasible solution is chosen. Finally, the "Sharing and trading of control" approach considers different levels of automation and determines the appropriate level depending on the task. These different "levels of automation" have been specified for the manufacturing industry [15]. By choosing a task allocation method, the requirement mentioned in [16] should be regarded, e.g. encouraging participative use by end-users.

Next to the levels of automation, there are also the levels of interaction between the robot and the human user. Based on an initial classification [17], a revised classification on human robot systems has been introduced [18], which distinguishes for both human and robot between an active, supportive, inactive, and intuitive role and find the different combinations that are possible for a specific task. Furthermore, the authors differentiate between single, multiple and team application cases for each of the partners resulting in a number of possible combinations.

Especially for the usage of collaborative robots (cobots), the levels of collaboration [19] have been developed - either the robot works separate to the human in a cell, or there is a coexistence in which each actor has his or her own working space, or there is some kind of task synchronization, or some kind of cooperation, or, at the highest level a real collaboration between both partners.

Each chosen task allocation method needs to make sure that the safety regulations are take into account and are monitored appropriately (ISO15066). The safety of a cobot is built by intrinsic and extrinsic facts. The taxonomy from [20] spans the view over the different aspects of failure sources, ordering them according to engineering, human and environment aspects. Although the classification is dedicated to UGVs, it could be applied to collaborative robots. All aspects of engineering and design are intrinsic facts. Once they are considered and validated, they are valid for the robot system exploitation. This is important for the agile application. The intrinsic safety remains in effect independently from the application site. The extrinsic safety is highly dependent on the environment and on the behaviour of the operator as well as on the application (tools, workpiece, workflow, location) itself.

In an operator-centered production design (ISO 9241-201:2010) trustiness of safe usability in a human-robot collaboration mode is the key element. This is why especially in close collaboration scenarios the so-called "soft factors" needs to be taken into account as well – the overview in [21] displays different factors that enable (but also can hinder) the establishment of trust between the human and the robotic system. It distinguishes between human-related, robot-related, and environmental factors and mentions for example (human-related) ability-based factors like operator workload or (robot-related) performance-based factors like predictability.

Robots have changed over the last years due to a large body of research. They have started to acquire complex physical skills for movement and manipulation; perceptual skills to be aware of human behavior and help predict it; collaborative skills needed to physically cooperate with a human worker (for a recent survey on collaborative robots, see [22]); and first steps towards social cognition ([23], [24]). This has also changed the way how we think about industrial robots and the application of robots in general within manufacturing. [25] conducted a recent interview study in order to identify current trends within that area. First, they investigated on the reasons to apply automation. This was primarily due to total cost / return of investment, although additional considerations have been playing a role as well, including ergonomics, an aging workforce and quality control. They highlight, that the worker perspective is critical, as they are an important driver of innovation. Their final point is, that the focus appears to shift toward the increasement of flexibility.

3. Analysis Approach

This section describes the iterative analysis and design approach, that was chosen for the conduction of the project.

3.1. Video-based production process analysis

Luckily, just before the COVID-19 outbreak, the company was visited for two weeks by a research intern who performed a contextual analysis and recorded video material for each production step. Later on, the project was heavily affected by the outbreak of the pandemic and most of the described work needed to be performed remotely. Next to traditional remote communication, video conferences were the only additional tools used to collect and analyze production processes and workers' situation. This approach was introduced to overcome limitations caused by the COVID-10 regulations. This is why the research was limited to a specific bike type and the found results will need to be generalized in a further step.

3.2. First analysis iteration: traditional Toyota approach

Based on the video material a task decomposition was performed and the traditional Toyota approach [26] distinguishing between value-adding and non-value-adding work was chosen. This was conducted on a second-granular analysis of the video footage. In addition, the MOST approach [27] was chosen to characterize the individual movements and compare it to the measurement within the video in order to generalize the measurements. The movements within the different production steps were visualized in Spaghetti diagrams. According to a list of requirements, the main problems were identified, and, on each of these, the "Five Why" method was applied [28] in order to find the root cause of the investigated problem. This analysis served as an overview for the production process as a base for discussion.

3.3. Second analysis iteration: task analysis

The task analysis was refined to enable more in-depth analysis (see following sections), and for logically structuring the tasks in relation to each other, so that they might be able to be reorganized for the integration of robotic tasks. This is why a Hierarchical Task analysis (HTA) was performed [29]. The HTA breaks down the assembly process into hierarchical levels. On the highest levels, the main operations needed to be performed to assemble the bike are listed in terms of their goals. These operations are broken down into sub-levels, where relevant sub-goals are described. The results of this analysis are used to generate a Precedence Graph [30], showing the necessary sequential relations. This analysis showed that there is a high concentration of conditions at assembling the mechanical and electrical drive system of the bike. In the precedence graph, at least three bottlenecks were identified. Based on the precedence graph an upper limit of the lowest PG cycle time (longest path) of 40% was found.

3.4. Third analysis iteration: Physical ergonomics

Based on the task decomposition, the RULA method (Rapid Upper Limb Assessment) [31] was applied to evaluate the physical ergonomics for the workers in the production line. RULA evaluates each step on the ergonomic risks, by scoring each position of the worker. The analysis results in one grand score per assembly step, which differentiates between 1: "Posture acceptable if not maintained or repeated for long periods" and 7 "Investigation and changes are required immediately".
In Figure 2 an overview of the estimated scores is provided. Higher RULA scores are mostly due to extreme twisting/ bending/ tilting of wrists, reaching arms above head, or bending forward to reach a part. In general, the neck is more bent when the task is precise (like tuning brakes) because workers need a closer and more precise look. Also, for shorter workers the RULA scores become higher, due to are more tasks where arms are above head/ eye-height.

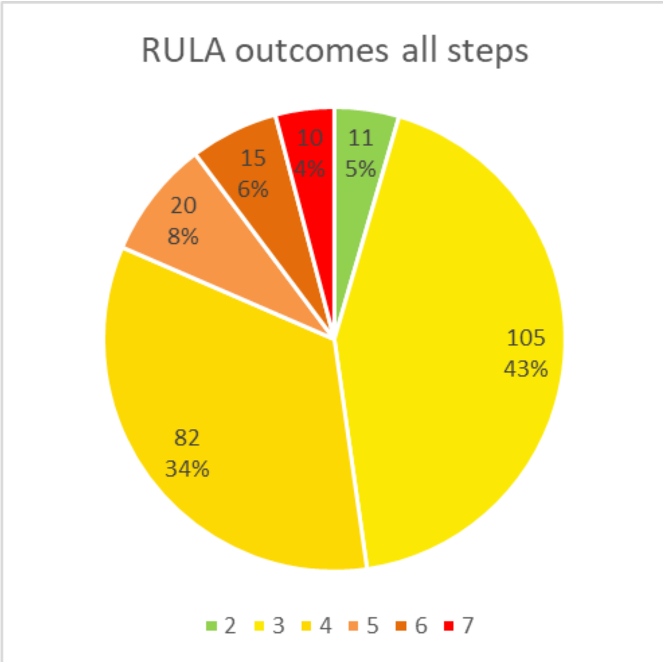

Fig. 2. Overview on the estimated RULA scores

3.5. Fourth analysis iteration: Level of automation

For an assembly system to be robust, flexible, and adaptable, the system must be capable of effectively handling new products, tool changes, and other production disturbances. In order to achieve this effectiveness, it is important to understand how to appropriately balance an assembly system with a proper mix of operators and machines to achieve maximum efficiency without compromising on product quality. To simplify the understanding of achieving a proper balance, the system can be divided into two sections, information handling and physical work. Next step in this process is the allocation each assembly task into a level of automation (LoA). The level of automation is process of allocating physical and cognitive tasks between humans and technology, described as a continuum ranging from totally manual to totally automatic [32].

4. Design for Automation

4.1. First design iteration: Work organization prototype

Based on the first iteration of the analysis several work organization issues have been found that could directly have impact on saving production time without the introduction of any robot. One example of these findings is displayed in Figure 3, in which the grease pot is relocated. The operation in the reconstructed layout situation took 5.5 seconds on average over 10 tests (standard deviation σ = 0.54). The relocation was able to save 1.1 seconds on average (σ = 0.69).

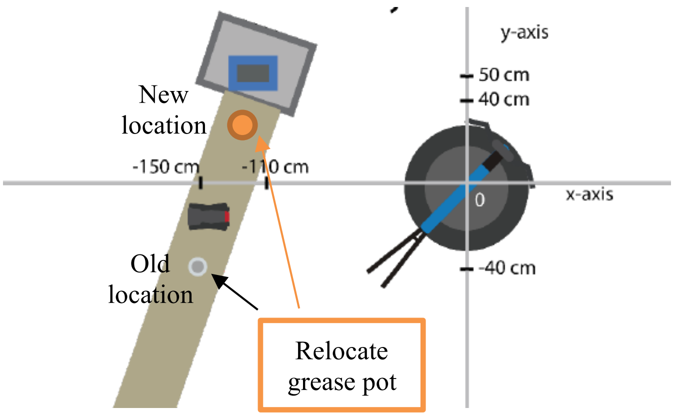

Fig. 3. Work organization prototype

4.2. Second design iteration: Envisioned HTA simulation

Based on the HTA, an envisioned HTA was created in which all of the tasks which have been identified in having a high automation potential, have been rearranged in order to enable a fully automated part of the production. This envisioned HTA in different versions have been simulated with Visual Components and is displayed in Fig. 4.

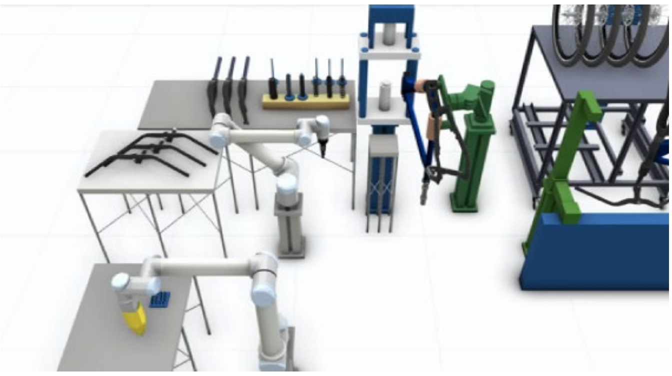

Fig. 4. Part-automation simulation prototype

4.3. Third design iteration: Individual robot prototype

In a third iteration, a specific task has been identified as having a strong impact on the physical ergonomics: The movement of the bike from one of the production line parts to another. As the partly assembled bike needs to be lifted, this has a strong impact on the worker who needs to do this for a longer time. For this specific task, a customized solution was designed.

4.4. Fourth design iteration: Cobot prototype

In order to approach the challenge of human-robot co-production, a cobot prototype was built, which is displayed in Fig. 5. It is currently based on single workcell, in which several assembly steps are performed by one worker and one robot in order. This is also used as a test setup for user studies on task instructions.

Fig. 5. Cobot prototype

4.5. Fifth design iteration: VR-based simulation

Within the discussion with the workforce, it had been apparent that there are a lot of fears connected with the vision of working alongside robots in the future. In order to talk with workers on which specific development they dislike or would encourage, a Virtual Reality representation of a future work setup was built (Fig. 6). It shall be used in order to discuss the desirable future within a scenario-building progress together with the workforce [33].

Fig. 6. Virtual Reality prototype

5. Conclusion and future work

This preliminary research results in this paper provide valuable insights on how modern manual production can be optimized to address challenges from chapter 1. We believe that this could lead to onshoring of production, which would make production more sustainable. Our research explored various methods for analyzing existing situation in manual production and identify innovation opportunities by human-robot co-production. We have applied this set of methods in a case study that aims to improve and automize production of bikes. Our approach aims to integrate process and human-centered analysis with reflections on socio-technical impacts of automation. Though the proposed approach provides sufficient grounding for innovating existing processes as demonstrated in our case study, there is a need for further research to address the following challenges:

- Conducting the cognitive ergonomics analysis (was not possible during the COVID restrictions)
- Conducting further research on task sharing and indication of the shared mental model with Augmented Reality
- Further effort into an in-depth fault / error analysis
- Further research into physical ergonomics and possible reorganization of the production line
- Changing the parts: Conducting a design for manufacturing analysis and change the parts

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