Characterizing the state of the art of Human-Robot Coproduction

Argun Cencen, Jouke Verlinden, Jo Geraedts
Faculty of Industrial Design Engineering
TU Delft
Delft, The Netherlands
a.cencen@tudelft.nl, j.c.verlinden@tudelft.nl, j.m.p.geraedts@tudelft.nl

Abstract— It is expected that soon, systems consisting of a blend of humans and robots be devised in such a way that higher productivities will be achieved. The main enabler for this is expected to be the possibility of collaboration between workers and robots. HRI (Human Robot Interaction) is the field in which such phenomena are studied. A growing number of investigators treat the collaboration of robots and workers (humans) in many contexts, however attention towards the manufacturing industry is predominantly focused on full automation of human tasks. Industrial robots have long been unsafe to work in close vicinity to workers due to their duty to be fast and powerful. However, nowadays, with the drive from emerging technologies, this is changing. Safe worker-robot collaborations are beginning to take shape and the HRI community is beginning to study such scenarios. Despite being a very effective form of interaction, a key research question is whether collaboration is a suitable mode of interaction for manufacturing environments. To be able to address this question, we found a collection of ten worker-robot systems that constitute a first step in outlining coproduction characteristics. This collection allowed us to identify differences in task initiative and product handling and component handling, while we frame coproduction as an extension of man. Challenges that require additional attention are workflow planning and defining proper performance indicators. We conclude with the fact that, although the worker-robot collaboration systems are inspiring and redefine labor, no sufficient knowledge or tools exists to reproduce such qualities in different manufacturing settings. Further work will be focused on modeling and assessing the performance and bottlenecks of systems based on novel robotic systems.
Keywords; Worker-Robot Collaboration, Coproduction, Manufacturing, Robot, Intelligent Manufacturing Systems

I. INTRODUCTION

Looking at the state of the art of robotic technologies around the world, we see that it is possible to create a robotic solution for virtually almost any problem, given sufficient time and resources. As far as current industrial automation technology goes (robots, sensors, software), assuming the availability of key resources (time, money, people), it seems plausible that many tasks inside a manufacturing process that currently include manual work, can in one way or another be robotized. However, knowledge on making true tools out of robots, rather than automated machines, is a domain that is relatively less covered. This forms a barrier for the development of new manufacturing systems that the EU wants to establish, in which humans and robots are seamlessly integrated. The European Union (EU) is working towards a future in which it wishes to put robot-related and manufacturing-related knowledge together to establish advanced manufacturing systems in which humans and robots are able to function side by side by employing novel task divisions and role definitions. By doing so, the EU wants to hold and sustain its competitive position amongst other manufacturing areas of the world.

Following this idea, the integration of the latest advances in several (industrial robots, computer vision, 3D printing etc.) technologies in order to develop the necessary tools for a “rapid-robotization” concept is a task that is the main goal of the European FP7 framework funded Factory in a Day (FiaD) project. As a partner of FiaD we investigate this goal from our field of expertise of Industrial Design Engineering. This perspective focuses to develop a design methodology that is applicable to the design of human-robot coproduction systems.

This paper is aiming at characterizing the state of the art of such human-robot coproduction systems in manufacturing. Initially, we provide some background knowledge on manufacturing and its relationship with robots. Next, a collection of documented cases of worker-robot collaborations are presented and analyzed. This is followed by discussion conclusions, and presentation of future work.

II. BACKGROUND

A. Origins and notions of modern manufacturing

Before the Industrial Revolution all manufacturing was done by hand and tools were an extension of the craftsman’s physical skills [1].

According to Bowen & Youngdahl, in the context of manufacturing, technology combined with a well-defined division of labor, clear rules, and limited span of control results in consistent quality and efficiency [2].

One of the best examples of this combination is the development of mass production, which is an approach that increases overall efficiency, while maintaining product quality. Henry Ford introduced the production-line approach in the beginning of the twentieth century and revolutionized the manufacturing industry [1]. A production line is defined by Groover [3] as a system that consists of multiple workstations and a workstation refers to a location in the factory where a well-defined task or operation is accomplished by an automated machine, a combination of man (worker)-machine or man (worker)-tools. A simple drawing showing the inputs and outputs of a workstation is seen in Figure 1. Currently, in most cases, the worker is extension of the machine / tool.

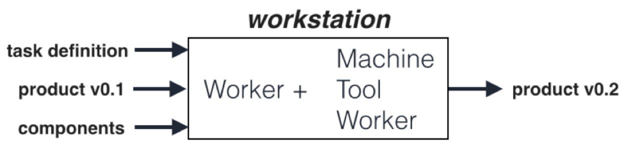

Figure 1. A conceptual display of the inputs and outputs of a workstation.

A U-shaped layout for multi-skilled workers was proposed by Hopp et.al. in order to increase efficiency [4]. Following this idea, Al Zuheri et.al. introduced the idea of the Walking Worker Assembly Line (WWAL) as opposed to Fixed Worker Assembly Line (FWAL) [5] In a WWAL, all workers are multi-skilled and do several assembly operations, following eachother. However, it is known that flexibility is always a trade-off against efficiency [2].

Manufacturing systems can be viewed from several perspectives, e.g., Groover divides manufacturing systems in 4 parts. Production machines, material handling system, computer control system and human resources [3]. On the other hand, from a changeability and reconfigurability perspective, Zaeh et.al. propose manufacturing systems as consisting of 3 parts: the physical system, the control system and the organization of system [6] . The combination of these views provide a good foundation for the positioning of HRC systems.

Nowadays flexibility and changeability became the main enablers for efficient production [7]. In the context of small and medium enterprises (SME), Masood et.al. and Miyake have observed the effect of this trend for SME managers and engineers and their need to enable change capability for the production systems they are responsible for [8]. It is believed that the SME can increase its flexibility while maintaining their productivity through so-called "collaborative frameworks" where workers and robots share a workspace [9] [10] [11].

According to Zaeh et.al., Artificial Intelligence (AI) has helped to improve automated systems, however they can still not cope with unexpected events, therefore the most flexible production system is still regarded as the skilled and experienced human worker [11]. Zaeh therefore proposes that these systems be equipped with artificial cognitive capabilities. Stollnberger gives an example from improved input modalities. Cheng et.al. mention that a virtual robot manufacturing cell is an initial step towards building an actual robot cell and these virtual cells are built and simulated and fine tuned in various software packages like Robcad and Robotstudio [12]. However, they recognize the raised issues between the virtual and the actual world. This gap is addressed by a "teaching' process. Lin et.al have studied improved pendant designs [13].

B. Human-Robot Interaction

Rahimi & Karwowski mention different "robotic systems" in their research on Human-Robot Interaction [14]. The HRI context is framed in Task requirements, user characteristics, robot characteristics, environment, and interactions. According to Stollnberger, the input modality is how a robot is interacted with and controlled; the main input modality for robots is through speech input [15]. It is argued that speech is advantageous because it frees up other modalities such as hands and that also, speech is a familiar modality for humans. Other possible modalities are keyboard and gestures.

Rouanet et.al. have studied several interaction modalities with robots in the execution of a certain type of task, albeit not in the manufacturing context [16]. However, the authors indicate the importance of differentiating between task types and complexity levels. Additionally, the appearance of robot is counted as a factor that effects the interaction. Some researchers have conducted similar research for the manufacturing context. Lin et.al. mentions several areas of use of "industrial robotic arms" and claims that the primary human-robot interface for operating a robotic arm is a teach pendant [13].

C. Towards Human-Robot Coproducion

In 2007, Goodrich and Schultz have produced a survey on Human-Robot Interaction (HRI), providing examples of areas where interaction with robots are to be expected. In this review, manufacturing is not counted in the 6 main categories and is mentioned in the "other applications" category. HRI in the manufacturing context requires the human/worker and the robot to be either in physical contact or in close vicinity to each other. Table 2 identifies the four different roles that the human can have in this coproduction: remote controller, supervisor, co-worker, and teammate.

TABLE I. HUMAN-ROBOT COLLABORATION IN TIME AND SPACE.

Time / Space	Simultaneous action	Sequential activities
Human&Robot in separate area	*Remote controller*	*Supervisor*
Human&Robot in same area	*Co-worker*	*Teammate*

Glasauer et. al. investigates this from an efficiency perspective, and mentions that when workers need to physically interact with a robot, the benchmark for natural and efficient performance is their experience with other humans. Therefore, the study of joint action amongst humans is essential in understanding interactions between humans and

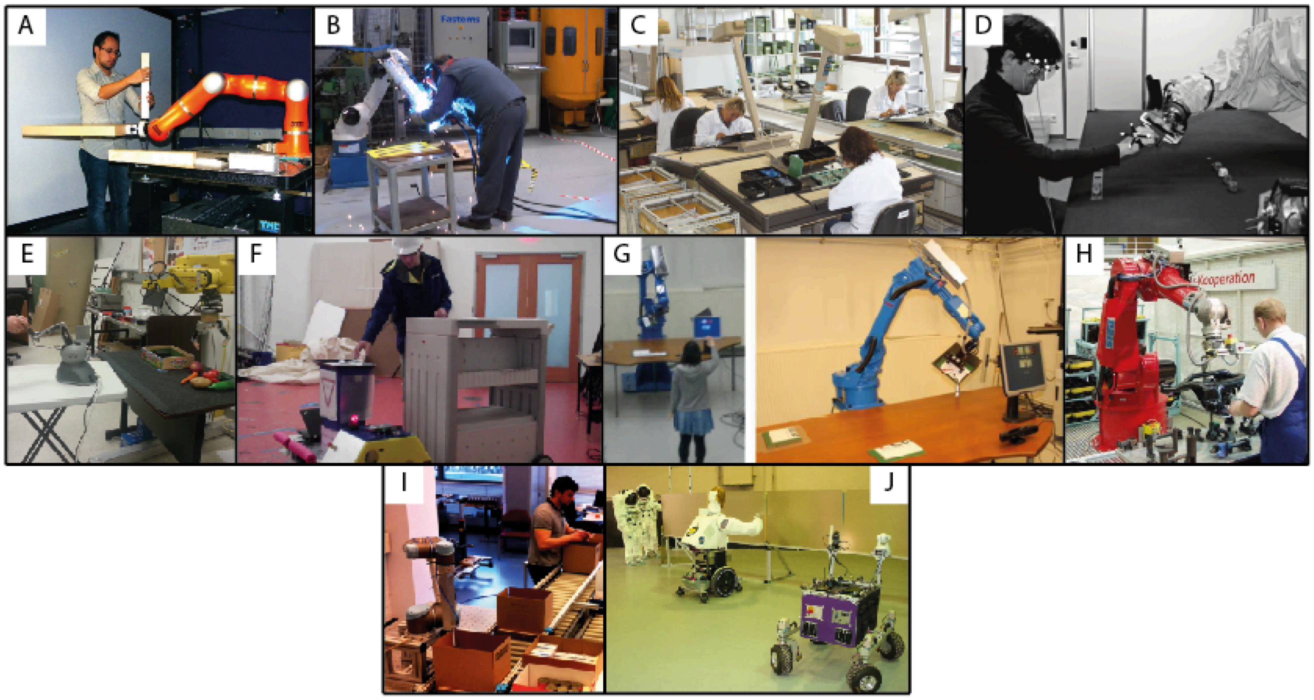

Figure 2. Collection of Human-Robot coproduction applications.

robots. Glasauer describes joint action as a collection of perception, prediction and planning actions [17].
In their 2013 publication, Stollnberger et.al. recognize the increased importance of HRC(Human Robot Collaboration) in various contexts and proposes to address the issues related to this type of interaction through the investigation of the relationships between input modalities and task complexities [15]. They mention that "Due to the strong interdependency of input modality and task complexity, the design process for planning human robot collaborative systems should specifically include the tasks which have to be fulfilled."

D. *Task allocation: worker skills and robot abilities*

From the perspective of the task that is collaboratively being executed,, the distribution of roles between worker and robot within a task requires consideration. When considering task allocation, bringes (Bringes 2013) looks at the whole task and distinguishes parts of a task, followed by the assessment of the most suitable part to put a human in the loop. Traditionally, Fitts studied the functions of humans in complex man-machine systems [18]. In Table 1, tasks where humans and robot outperform eachother are summarized based on [9][19][10]. Furthermore, Cranor argues that humans often fail to fulfill their roles in security-critical situations, with respect to human-in-the-loop systems [20].

TABLE II. ALIGNMENT OF SKILLS AND ABILITIES FROM LITERATURE.

	Human skills	**Robot abilities**
Morato et. al.	- manipulation of a wide range of parts without using special fixtures - natural ability to handle unexpected situations on the shop floor	- welding - component soldering - bolting - packaging - in general, tasks requiring speed
Blume et. al.	Highly adaptable skills	Carry and manipulate heavy goods
Schraft et. al.	Sensory skills Knowledge Skillfullness	Quality of work Increase speed Raise ergonomics of workplace

According to Stork et.al. interaction forms are becoming more complex with the trend of the application of robots in new contexts, such as human-machine interactions in a working environment [21]. These assistive systems need to be flexible and adaptive. Both aim at improvement of performance and reduction of cognitive effort, assuming that cognitive effort is an bottleneck in communication with robots.

III. SURVEY OF HUMAN ROBOT COPRODUCTION SYSTEMS

Human-Robot coproduction as introduced in the previous sections has been subject to several explorative studies. From manufacturing and robotics literature, we have collected ten distinct cases of collaborations between humans and robots, in which the humans act as co-workers of Table 1. Figure 2 depicts these, the common denominator of this set is the element of a production context, each will be summarized below.

A. *Rozo et.al.*

The authors propose a kinesthetically learning algorithm to support an assembly task of a small side-table, which is designed to be assembled by humans [22].The task is conceptualized as follows: a human assembles the legs of the table one by one while the robot holds the top piece of the table in an orientation which is comfortable for the human. Prior to the assembly operation, a human demonstrates the portion of the workflow related to the role of the robot kinesthetically. The robot records haptic data and movement patterns during this demonstration, using a motion capture system with passive retro reflective markers attached to the table parts and six-axis force-torque sensor that is attached between the wrist of the robot and the table. During the execution of the task, the human communicates with the robot through exerting torque or displacement force. This is one of the few systems that demonstrate a manufacturing task, in which the robot arm plays a supporting role by lifting and repositioning the assembly, while the human dexterity and perception-action coupling as described by Gibson are used for the high-precision aspects of the task [23]. Furthermore, communication through haptic channels makes sense in human robot coproduction tasks, designing information exchange between actors implicitly as part of the task at hand. This type of coupling is in line with the Dourish' embodied task coupling in which human and tool become one in a specific action, based on the definition of the phenomenologist construct of "vorhanden" (as opposed to "zuhanden")[24]

B. University of Tampere

As shown in an instruction video, the Finnish researchers propose a robot welding assistant that holds and repositions the assembly that is being welded together by a human welder [25]. The task is conceptualized as follows : The robot picks and holds the first piece of the assembly at a position which is comfortable for the task of the welder. The welder then locates and welds the remaining pieces onto the piece held by the robot one by one, while the robot changes the orientation of the piece it is holding, in order to allow the human to execute the welding task as effectively and ergonomically as possible. The portion of the workflow related to the role of the robot is pre-programmed into the robot prior to the execution of the task. The human communicates with the robot by using gestures that can be tracked through a camera attached to the robot. According to the authors, environmental and process related parameters in real life play a crucial role in the implementation of such systems. This is also addressed by [26].

C. Royonic

In this commercially available Printed Circuit Board (PCB) assembly system, the robot indicates the areas on a PCB where through-hole components need to be placed one by one [27]. Each time, the system also highlights the location of the component to be picked. The human follows the instructions of the robot and executes the picking and placing task. The workflow is pre-programmed into the robot prior to the execution of the task. The human communicates with the robot by pushing an electrical button or a foot pedal. In our selection of collaborations, this is an example of a collaboration in which the task division of physical activity between the robot and human is arranged in an unconventional way. Here, the robot is responsible for the cognitive part of the task. According to Schwerdtfeger, this method for assembly results in an error rate of 0,002% [28].

D. Glasauer et.al.

In this experiment consisting of several stages, the authors aim to investigate the difference in performance between human-human and human-robot hand-over of objects [17]. Two types of hand-overs are distinguished. In the first type, the agent delivering the object also initiates the action, in a second type of hand-over, a so-called "foreman" and "assistant" work together. The assistant needs to deliver the parts just in time for the foreman to assemble the parts onto another part. In the experiment which is executed in order to study the first type of hand-over, a robot has the role of picking of cubes from a table and handing over to a human. The human has the role of receiving the cubes from the robot and placing them on the table again. The workflow is pre-programmed into the robot and communicated to the human prior to the execution of the task. The human communicates with the robot through hand motions that can be tracked and interpreted through a camera attached to the robot. One of the most important conclusions is the increase of performance when the hand-over action performed by the robot is more human-like.

E. Bringes et.al.

The authors have built an experimental setup to investigate the performance of several pick & place scenarios, involving a teleoperated robot manipulator and a human [29]. They predict that a human-in-the-loop will be beneficial to the performance of the system, especially when there is some form of noise in the perception/cognition of the robot. The task in all scenarios is the picking of fruit/vegetables from random locations on a table and placing them inside a container. The robot manipulator is equipped with a gripper that is capable of providing a steady grasp of all object that are needed to be picked. This is the main role of the robot. The human decides on the workflow during operation. The human has the role of targeting each object and communicating their location to the robot, which is done with a haptic-pen device. The system performs best when there is no noise and no human in the loop. However, in the case of noise, the human worker assisting to determine a coarse approach of the stage results in a better performance.

F. Unhelkar et.al.

This experiment revolves around the task of assembling a LEGO-toy [30]. Robots and human assistants are given the task of delivering components needed for the assembly of the LEGO-toy in several steps and. Another human has the task to assemble the LEGO-toy using the components and instructions delivered to him/her at each step. The workflow is pre-programmed into the robot and instructed to the human worker. The workflow is communicated to the assembling worker during the delivery of new parts. The worker communicates with the assistants through accepting and relocating parts that are delivered to him/her. The authors conclude that the performance of the task is better when only humans perform the task. However, they also identify advantages of the inclusion of robots in the workflow, such as the sound that the robot makes while approaching , which can provide a cue for the human working on the assembly.

G. Pieska et.al.

In this work, robot and human coproduction is viewed from the perspective of palletizing products. A robot has the role of picking products from one location and placing them in a stacked format at an other location [31]. The worker has the role of instructing the robot the location of the product to be picked and placed. The workflow is pre-programmed into the robot. The worker communicates with the robot by using gestures that can be tracked through a camera attached to the robot. Prieska et. al. mention that inexperienced users can program and control robots through gestures and dedicated interfaces.

H. Schraft et.al.

This human-robot collaboration focuses on the rearrangement of parts that are needed for an assembly. The robot has the role of picking parts for the assembly task, and bringing them very close to the location where they need to be assembled[10]. The role of the human is to manipulate the orientation of the part that is being held by the robot and insert this into the corresponding destination. The workflow is pre-programmed into the robot. The human communicates with the robot through kinesthetic feedback and by pressing electrical buttons. The safety norms surrounding industrial robots are bottlenecks for increased performance of the type of systems that are the subject of the experiment. In the clauses 5.10 of ISO 10218-1, collaborative operation is allowed, in the most advanced case regarding co-located operation in which case power and force limiting needs to be enforced by inherent design features or control.

I. Cencen et.al.

In this experimental setup, the robot has the role to pick two products from their boxes and place them inside a box that is being transported on a conveyor [32]. The robot also has the task to relocate a filled box by pushing it further on the conveyor. There are several human workers part of the workflow. The role of one worker is to pick three products from their boxes and place them inside a box on the conveyor. This worker also picks a box from a stack of boxes and places it on the conveyor. Another worker in the workflow relocates the filled boxes from the end of the conveyor to another location. The workflow is pre-programmed into the robot and communicated to the humans. The worker with the role of picking the products communicates with the robot by pushing a half-filled box towards on of the sensors of the robot. The results of the experiment point to the fact that there are many product, process and person related unknowns when designing human robot coproduction systems and that these need to be further investigated. Furthermore, the pace of the (human-safe) robot was too slow to engage in an efficient workflow.

J. Fong et.al.

This research reports on the findings from an experiment in which human robot collaborations in lunar environments are being studied. In this setup, one robot has the role of welding, another robot has the role of quality inspection of the weld that is produced [33]. Two astronauts have various roles inside the workflow, ranging from relocating robots to checking the quality of results. The robots can also be teleoperated by a third astronaut. The workflow is determined by the astronauts by interacting with the robots during operation. Similarly, the robots communicate with astronauts by requesting feedback at various intervals. The authors defend that the performance of human-robot collaboration increases if the right software platform is used.

IV. CATEGORIZING HUMAN ROBOT COPRODUCTION SYSTEMS

The presented examples envisage how human-robot coproduction can secure human labor in the future. However, only a few of these are fully implemented while no detailed prescriptions or operational guidelines exist. To aggregate knowledge from these examples, we consider a) definition of robots, b) division of roles between worker-robot, c) interdependency.

A. Robots, Robot manipulator and system with robotic qualities

In our analysis, we looked at systems containing human workers and robots. In these systems, we observed that the physical attributes of what can be called robots were diverse. According to Bartneck, the two foremost definitions of robots written by the Robot Institute of America and International Standard Organization (ISO) mainly talk about a “manipulator” and are describing autonomous or semi-autonomous industrial robots [34]. According to these descriptions, in most of the systems we analyzed, a robot manipulator has been used, which makes it relatively simple to identify the system as a system containing a robot. However, research F, J, and Markstein [27] have used other devices with variant formalities to achieve systems with similar qualities, and performing comparable actions. Therefore, one way of naming these systems would be “systems with robotic qualities”.

B. Division of roles between worker – robot

We consider the aforementioned collection of systems representative of workstations in a manufacturing system. As discussed in section IIA, this is operationalized by delegating tasks to various combinations of worker, machine, tools and/or other workers.

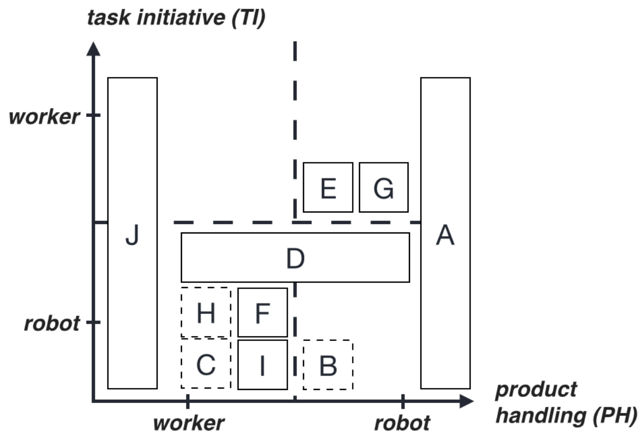

Figure 3. Task initiative versus physical handling in the examples (dashed-lined boxes indicate industrial systems)

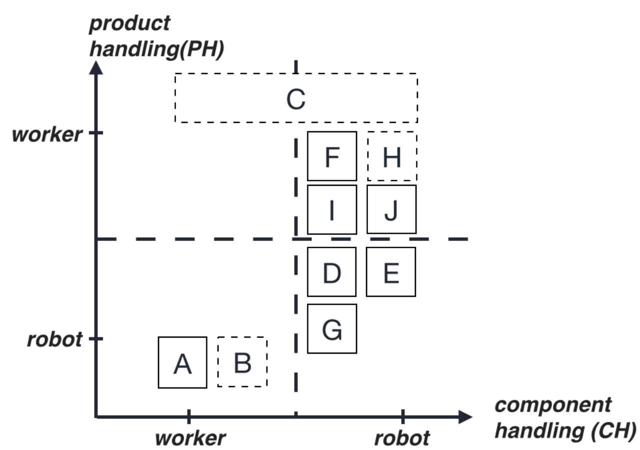

Figure 4. Product handling(PH) versus component handling (CH) in the examples (dashed-lined boxes indicate industrial systems)

One of the defining elements of a workstation is a clear definition of the task that needs to be performed. Looking at a workstation consisting of a human worker and a machine, the task definition, in which an implicit role delegation has already been made, is embedded in the design of the machine and the work instructions that the worker is required to be familiar with. Taking the three inputs mentioned in Figure 1, and translating these to roles which can be delegated to actors of a workstation, an initial categorization was realized as can be seen in Figure 3. and Figure 4. *Task Initiative* (TI)*,* is a role in which the workflow of the task is controlled and monitored. *Product Handling* (PH)*,* is a role in which the role owner is responsible for the main part of the product which is being assembled or manipulated. This can be on the level of the product (e.g., holding and/or positioning the part). On the level of components, this is named Component Handling (CH) (e.g., picking and/or handing over of new parts, welding of parts, placing products/parts in boxes)

At first sight, none of the systems shared both roles between robot and worker. In the six instances where some shared responsibility is seen (A,C,D,E,J,G), this is limited to only one role. In these cases, the remaining two roles are divided between the worker and the robot. Insufficient means of interaction and type of task might play a role in this choice of role combination. When looked at the systems which we consider to be operational in industry (B,C,H), only case C includes a shared responsibility. A reason for this might be the high operational requirements that are considered during the design of the system. In these types of systems, TI is a common role that is delegated to the robot. Only in two instances (E,G), the robot is not part of the TI role.

C. Interdependency and extensions of human capability

Fong mentions that robots are often viewed as tools [37]. Defines tool as a device which performs tasks on command. *"As such, a robot has limited freedom to act and will perform poorly whenever its capabilities are ill-suited for the task at hand. Moreover, if a robot has a problem, it has no way to ask for assistance. Yet, very often, the only thing the robot needs to get out of difficulty and to perform better is some advice (even a small amount) from a human."* Fong mentions that we should therefore not see robots as tools, but rather as partners/peers. This way work will be more meaningful and better results will be achieved.

We believe that this argument is based on the idea that robots are omnicompetent-yet-imperfect machines that need humans in order to operate successfully. On the contrary, the literature and examples from industries and academia show us that in the context of manufacturing, production tasks require minimal interaction, especially between workers, in order to be efficient. Therefore also requiring the tasks to be well-defined. Historically, we know that the relationship between man-tool is very strong in production tasks, which as of today, still forms the core activity of manufacturing. In Figure 5, it is shown that many of the studied research is located on the bottom left corner of the diagram, with some, pointing towards the top. On the right-hand side, system C is considered an unconventional, yet inspiring example of human-tool coproduction. It is worth noting that this system is stated to operate almost with no errors.

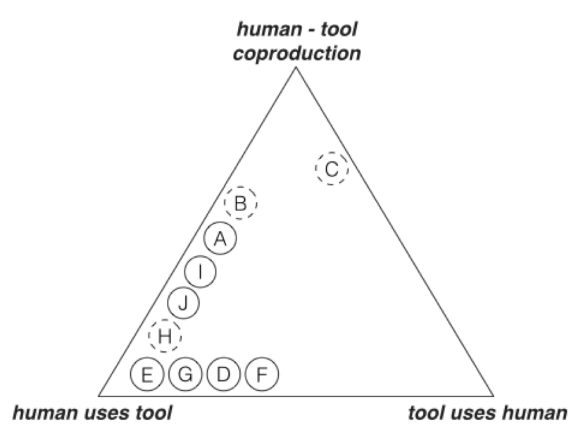

Figure 5. Positioning the studied research in relation to human, tool and human-tool coproduction. (dashed circles indicating industrial systems)

V. Discussion

A. Initial insights

Although a limited set of systems were analyzed, in the roles of task initiative (TI) and physical handling (PH), a dominance in the role of robots are seen. This needs to be further investigated and understood. This knowledge will be essential in supporting the design of such systems. It is notable that shared roles/responsibilities are not integral parts of these systems (yet). This is in line with the idea of efficiency in production lines. However, many examples and trends in literature suggest that notions such as interdependency and collaborative frameworks are the future perspective of worker-robot systems. In order to be able to create operational-worthy systems, we need to understand the performance indicators of these collaborations. These will potentially be different than the regular time/quality/cost paradigm and will move in the direction of flexibility/recovery.Looking at the systems E and G in more detail, we revealed that they fall in the category of teleoperated systems. In such systems, humans have an essential cognitive role in the loop and the performance of the task. It can be argued that in tasks where similar cognitive capabilities are necessary, it can be advisable to implement teleoperative properties.

B. Workflow planning

Factories are organized in discrete tasks that result in minimal interaction between tasks other than input-output. However, moving forward, it is projected that this will be affected by machines that have different working requirements compared to machines of the past. They will require flexibly defined roles that might be subject to change at unexpected times. Which is in contradiction with the prevailing philosophy of a manufacturing environment. Considering the planning of facilities, Jiang et.al. talk about a facility layout planning (FLP) for manufacturing systems [38]. They argue that a well designed layout can greatly reduce total operating costs and mention two approaches towards FLP. Namely, Procedural approaches [39][40] and Algorithmic approaches [41][42].

C. Performance indicators

Pritchard summarizes productivity as “how well a system uses its resources to achieve its goals.” In the context of the surveyed systems, speed and costs of systems are important. Productivity of the whole system is related to the performance of the sub-systems. but also the quality of the products and the quality of work from the workers perspective should be taken into account [35]. Glasauer notes that the timing of interactions in a collaborative tasks is a key element for the efficiency, safety and acceptance of the task itself for the human worker [17]. According to Leroux, picking and placing of an object are seen as fundamental aspects of human motion [36]. Almost in all cases, except A,B and J, we see similar actions as a main or sub-part of the task.

VI. Conclusions and future work

In the past , humans were supposedly only needed because automation could not yet replace them[43]. However , a new generation of experimental systems provide inspiration to prove this wrong. There are still difficulties to operationalize these human-robot collaboration notions in present work. The reasons and actions to be able to achieve this can be summarized as follows;

The presented examples are inspiring and show how future worker-robot systems can provide sufficient work for humans. However, only a few are operational and these examples provide relatively less material for the analysis of the complexity of required interactions in other situations.
As shown in IV-B and IV-C, there is insufficient knowledge on Worker-Robot Collaboration. Although an initial theoretical frame is drawn, when making a qualitative analysis of the investigated systems, these do not fit perfectly inside this frame. Yet, our efforts revealed basic insights in how such systems can be viewed and how what these frames are lacking.

While experimenting with such systems, also operational models of these systems need to be made in order to be able to iterate between various designs and gain more insight in performance related details. Literature on finite machines is worth investigating [46]. We expect that these models, together with dedicated computer-aided-process-planning (CAPP) approaches, will provide a foundation for successful initial industrial implementations. With the avenue of novel robotic systems, such as Rethink Robotics Baxter [44] and Universal Robots UR arms [45], the enabling technologies are progressing at a fast pace. Future research will be directed towards implementing these technologies in combination with Robot Operating System (ROS) and similar novel programming environments in human-tool coproduction manufacturing environments.

I. Acknowledgement

The work leading to these results has received funding from the European Community’s Seventh Framework Programme (FP7/2007-2013) under grant agreement n° 609206

References

[1] D. Hounshell, *From the American system to mass production, 1800-1932: The development of manufacturing technology in the United States. No. 4.* JHU Press, 1985.

[2] D. E. Bowen and W. E. Youngdahl, “‘Lean’ service: in defense of a production-line approach,” *Int. J. Serv. Ind. Manag.*, vol. 9.3, pp. 207–225, 1998.

[3] M. P. Groover, *Automation, production systems, and computer-integrated manufacturing*. Prentice Hall Press, 2007.

[4] W. J. Hopp, E. Tekin, and M. P. Van Oyen, “Benefits of skill chaining in serial production lines with cross-trained workers,” *Manage. Sci.*, vol. 50.1, pp. 83–98, 2004.

[5] A. Al-Zuheri, L. Luong, and K. Xing, “Prediction and analysis impact of operational design of a manual assembly system with walking workers on performance,” *Int. J. Comput. Integr. Manuf.*, vol. 26, no. 6, pp. 540–560, Jun. 2013.

[6] M. F. Zaeh, Æ. M. Wiesbeck, S. Stork, and Æ. A. Schubo, “A multi-dimensional measure for determining the complexity of manual assembly operations,” pp. 489–496, 2009.

[7] H.-P. Wiendahl, H. A. ElMaraghy, P. Nyhuis, M. F. Zaeh, H.-H. Wiendahl, N. Duffie, and M. Kolakowski, “Changeable Manufacturing: Classification, Design, Operation,” *Ann. CIRP*, vol. 56/2, 2007.

[8] T. Masood, R. Weston, and A. Rahimifard, “A model-driven approach to enabling change capability in SMEs,” *Int. J. Adv. Manuf. Technol.*, vol. 69, no. 1–4, pp. 805–821, May 2013.

[9] C. Morato, K. N. Kaipa, B. Zhao, and S. K. Gupta, “Toward Safe Human Robot Collaboration by Using Multiple Kinects Based Real-time Human Tracking,” *J. Comput. Inf. Sci. Eng.*, vol. 14, no. 1, p. 011006, Jan. 2014.

[10] R. D. Schraft, C. Meyer, C. Parlitz, and E. Helms, “Power Mate – A Safe and Intuitive Robot Assistant for Handling and Assembly Tasks,” no. April, pp. 74–79, 2005.

[11] M. F. Zaeh, M. Beetz, K. Shea, G. Reinhart, K. Bender, C. Lau, W. Vogl, M. Wiesbeck, M. Engelhard, C. Ertelt, T. Rühr, M. Friedrich, and S. Herle, “The Cognitive Factory,” pp. 355–371.

[12] H. Cheng, H. Chen, and Y. Liu, “POMDP based robot teaching for high precision assembly in manufacturing automation,” *2013 IEEE Int. Conf. Cyber Technol. Autom. Control Intell. Syst.*, pp. 159–164, May 2013.

[13] H.-I. Lin and Y.-H. Lin, “A novel teaching system for industrial robots.,” *Sensors (Basel).*, vol. 14, no. 4, pp. 6012–31, Jan. 2014.

[14] W. Karwowski, “A RESEARCH PARADIGM IN H U M A N - R O B O T,” vol. 5, pp. 59–71, 1990.

[15] G. Stollnberger, A. Weiss, and M. Tscheligi, “‘ T he Harder it Gets ’: Exploring the Interdependency of Input Modalities and Task Complexity in Human-Robot Collaboration,” pp. 1–6, 2013.

[16] P. Rouanet, J. Bechu, and P.-Y. Oudeyer, “A comparison of three interfaces using handheld devices to intuitively drive and show objects to a social robot: the impact of underlying metaphors,” in *Robot and Human Interactive Communication, RO-MAN 2009. The 18th IEEE International Symposium on,*, 2009, pp. pp. 1066 –1072.

[17] S. Glasauer, M. Huber, P. Basili, a. Knoll, and T. Brandt, “Interacting in time and space: Investigating human-human and human-robot joint action,” *19th Int. Symp. Robot Hum. Interact. Commun.*, pp. 252–257, Sep. 2010.

[18] P. M. Fitts, “Human engineering for an effective air navigation and traffic control system. National Research Council, Washington, DC,” 1951.

[19] J. Blume, a. Bannat, G. Rigoll, M. Rooker, a. Angerer, and C. Lenz, “Programming concept for an industrial HRI packaging cell,” *2013 Ieee Ro-Man*, pp. 93–98, Aug. 2013.

[20] L. F. Cranor, “A Framework for Reasoning About the Human in the Loop.”

[21] S. Stork, C. Stößel, and A. Schubö, “Optimizing Human-Machine Interaction in Manual Assembly,” pp. 113–118, 2008.

[22] L. Rozo, S. Calinon, D. Cadwell, P. Jimenez, and C. Torras, “Learning collaborative impedance-based robot behaviors,” *Proc. AAAI Conf. Artif. Intell. Bellevue, WA, USA, pp. 1422-1428*, 2013.

[23] J. Gibson, *The ecological approach to visual perception*. 2013.

[24] P. Dourish, *Where the action is: the foundations of embodied interaction*. 2004.

[25] “Human robot co-operation welding workcell case study.” [Online]. Available: https://youtu.be/Kxw-SJd-j-o. [Accessed: 29-Mar-2015].

[26] S. Qiu, X. Fan, D. Wu, Q. He, and D. Zhou, “Virtual human modeling for interactive assembly and disassembly operation in virtual reality environment,” *Int. J. Adv. Manuf. Technol.*, vol. 69, no. 9–12, pp. 2355–2372, Aug. 2013.

[27] H. W. Markstein, *The Electronics Assembly Handbook Springer Berlin Heidelberg*. Springer Berlin Heidelberg, 1988, pp. 70–76.

[28] B. Schwerdtfeger, D. Pustka, A. Hofhauser, and M. Garching, “Using Laser Projectors for Augmented Reality,” pp. 134–137, 2008.

[29] C. Bringes, Y. Lin, Y. Sun, and R. Alqasemi, “Determining the benefit of human input in human-in-the-loop robotic systems,” *2013 Ieee Ro-Man*, pp. 210–215, Aug. 2013.

[30] V. V. Unhelkar, H. C. Siu, and J. a. Shah, “Comparative performance of human and mobile robotic assistants in collaborative fetch-and-deliver tasks,” *Proc. 2014 ACM/IEEE Int. Conf. Human-robot Interact. - HRI ’14*, pp. 82–89, 2014.

[31] S. Pieskä, J. Kaarela, and O. Saukko, “Towards Easier Human – Robot Interaction to Help Inexperienced Operators in SMEs,” pp. 333–338, 2012.

[32] A. Cencen, K. Van Deurzen, J. C. Verlinden, and J. M. P. Geraedts, “Exploring Human Robot Coproduction,” 2013.

[33] T. Fong, J. Scholtz, and J. Shah, “A preliminary study of peer-to-peer human-robot interaction,” *Syst. Man Cybern.*, pp. 3198–3203, 2006.

[34] C. Bartneck and J. Forlizzi, “A design-centred framework for social human-robot interaction,” *RO-MAN 2004. 13th IEEE Int. Work. Robot Hum. Interact. Commun. (IEEE Cat. No.04TH8759)*, pp. 591–594, 2004.

[35] R. Pritchard, “Organizational productivity,” *Handb. Ind. …*, 1992.

[36] C. Leroux, I. Laffont, N. Biard, S. Schmutz, J. F. Désert, G. Chalubert, and Y. Méasson, “Robotic grasping of unkown object, description and validation of the function with quadriplegic people,” vol. 00, no. c, pp. 35–42, 2007.

[37] T. Fong, C. Thorpe, and C. Baur, “Collaboration , Dialogue , and Human-Robot Interaction,” no. November, 2001.

[38] S. Jiang, S. K. Ong, and a. Y. C. Nee, “An AR-based hybrid approach for facility layout planning and evaluation for existing shop floors,” *Int. J. Adv. Manuf. Technol.*, vol. 72, no. 1–4, pp. 457–473, Feb. 2014.

[39] A. Shahin, “Facility layout simulation and optimization: an integration of advanced quality and decision making tools and techniques,” *Mod. Appl. Sci.*, vol. 5, no. 4, pp. 95–111, 2011.

[40] T. Yang and C. Kuo, “A hierarchical AHP/DEA methodology for the facilities layout design problem,” *Eur. J. Oper. Res.*, vol. 147, no. 1, pp. 128–136, 2003.

[41] I. Mahdavi, B. Shirazi, and M. Paydar, “A flow matrix-based heuristic algorithm for cell formation and layout design in cellular manufacturing system,” *Int. J. Adv. …*, 2008.

[42] S. Singh and R. Sharma, “A review of different approaches to the facility layout problems,” *Int. J. Adv. …*, 2006.

[43] J. P. Womak, D. T. Jones, and D. Roos, *The Machine that Changed the World: The Story of Lean Production,*. New York, NY, USA: HarperCollins, 1990.

[44] C. Fitzgerald and D. Ed, “Developing Baxter,” 2013.

[45] “Universal Robots.” [Online]. Available: http://www.universal-robots.com. [Accessed: 14-Apr-2015].

[46] M. Minsky, *Computation: finite and infinite machines*. 1967.