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Published in:
Towards Sustainable Customization

DOI:
10.1007/978-3-030-90700-6_27

Publication date:
2022

Document version:
Accepted manuscript

Citation for pulished version (APA):
Hjorth, S., Schou, C., Ribeiro da Silva, E., Tryggvason, F., Sørensen, M., & Forbech, H. (2022). A case study of Plug and Produce Robot Assistants for Hybrid Manufacturing Workstations. In A-L. Andersen, R. Andersen, T. D. Brunoe, M. S. S. Larsen, K. Nielsen, A. Napoleone, & S. Kjeldgaard (Eds.), *Towards Sustainable Customization: Bridging Smart Products and Manufacturing Systems - Proceedings of the 8th Changeable, Agile, Reconfigurable and Virtual Production Conference CARV 2021 and 10th World Mass Customization and Personalization Conference MCPC 2021* (pp. 242–249). Lecture Notes in Mechanical Engineering https://doi.org/10.1007/978-3-030-90700-6_27

A case study of Plug and Produce Robot Assistants for Hybrid manufacturing workstations

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Abstract. In the paradigm of smart factories, flexible and scalable manufacturing resources are essential. The human worker offers great flexibility; however, the operators are often a sparse resource in high-wage countries. Consequently, they are often responsible for several tasks at once and must prioritise the most critical ones. Consequently, the productivity on less critical tasks will suffer in the absence of the operator. In this paper, we present a case study on the effect on productivity when deploying a collaborative robot assistant in a plug and produce fashion to substitute a human worker at manual workstations on a production line. Realistic cycle and changeover times are derived from physical experiments and used in discrete event simulation to analyse two scenarios. The results show that if an operator must abandon his/her workstation, deploying a robot assistant as a substitute reduces the loss of productivity.

Keywords: Plug and Produce, Collaborative Robot, Robot Assistant, Smart Manufacturing, Simulation.

1 Introduction

The smart factories of the future will depend on flexible and reconfigurable manufacturing equipment to cope with the increasing consumer need for product innovation and customisation. This allows the smart factory to introduce new products quickly, produce at batch sizes down to a single product and dynamically scale the capacity as demand varies. For scaling the capacity, the need to scale the automation level is also a preferred capability. In this way, new product variants with low or unknown demand can be initially introduced using manual processes. As demand increases, the manual processes are step-wise replaced with semi or fully automated solutions.

Plug and produce robot assistants (fr om here on referred to as robot assistants) offer the flexibility to handle a multitude of tasks and have become a natural element in the smart factory paradigm. If workstations are prepared for both humans and robots attending it, scaling back and forth between manual labour and automated labour can be done quickly and frequently. Moreover, the robot assistants could also be used as substitutes for the human operators, who often have to prioritise between several tasks for which they are responsible. A likely scenario is an operator is attending a manual workstation close to an assembly line, whilst the operator also has to keep the entire production line running. This entails resolving stops on the line and breakdowns in the automated equipment. In case of a stop, the operator must prioritise it over the manual work at the station. This means the operator leaves the manual station unattended until the stop is resolved. In case the stop requires a prolonged intervention, deploying a robot assistant to substitute the operator at the workstation would retain some of the lost productivity.

As highlighted in our review of related research presented in Sec. 2, realising robot assistants comprises several technical challenges, which have attracted most of the research attention until now. However, in recent years we have seen real-world demonstrators and implementations of robot assistants; thus, indicating that the technology has reached a Technology Readiness Level (TRL) of seven or above on the EU TRL scale [1]. With the maturation of the technology, research into the implications on production operations when applying such robot assistants becomes relevant.

Considering this, we investigate the operational potential of robot assistants. We base our work on the following hypothesis: "*In a production environment with high task variety, deploying plug and produce robot assistants to aid the human operators will increase the productivity.*" Our investigation into this hypothesis is based on a case study that mixes the use of human operators and robot assistants. We investigate the scenario of deploying a robot assistant as a substitute for the human operator for short periods in an industrial-like lab setting containing multiple workstations and tasks. We determine how long an operator should leave the production line before deploying a robot assistant is favorable in terms of productivity.

2 Related Research

The plug and produce paradigm represents the idea of a quick and seamless connection of production equipment with minimal or no setup needed. Derived from the term plug and play from the IT domain, plug and produce was first mentioned by Arai et al. [2]. Current research in plug and produce primarily addresses the technical challenge of adding and removing components instead of the implications and benefits from an operations perspective [3–8]. Schleipen et al. [4] present a comprehensive overview of the requirements and technical challenges in implementing plug and produce. In particular, the challenge of modelling and sharing the necessary equipment and product information is pointed out. The use of AutomationML and OPC/UA is proposed as a solution. Focusing on plug and produce for robotics, Schou and Madsen [8] propose a roadmap to enable shop floor operators to reconfigure industrial collaborative robots easily and quickly. The roadmap highlights the need for modularity in both hardware and control systems, and the need for intuitive tools supporting the configuration task for the operator. Maeda et al. [9] developed and conducted a feasibility test on a multi-robot setup. Three fixed manipulators were amended with a plug and produce movable robot for assembly tasks. Both Antzoulatos et al. [5] and Michalos et al. [10] propose the use of an agent-based architecture for configuring plug and produce assembly systems.

Michalos et al. [10] combine the agent-based architecture with ontologies for knowledge capturing in managing the production resources. Schou and Madsen [8] propose an architecture and control framework allowing commercial robotic components to be adapted into plug and produce components for building industrial robot setups. The framework introduces a generic function layer, abstracting away from specific vendor syntax and implementations. Wojtynek et al. [6] present a scheme promoting robot autonomy for the robot to self-adapt to a given task context in a modular production system. Hence, the task of the human operator only includes plugging the robot in and omits any complicated setup and installation. Zimmer et al. [7] see plug and produce enabled resources as a key to decreasing the ramp-up time of assembly systems. Looking at the operation of plug and produce resources, Colledani and Angius [3] propose a methodology for combined planning of both operation and reconfiguration tasks for modular plug and produce systems. The method optimises batch completion time and batch sequence for maximising the system utilisation.

In a final reflection, Schleipen et al. [5] highlight the need for research on how production plants can benefit from plug and produce solutions. Despite a significant body of research within the paradigm of plug and produce, we have not been able to find research explicitly evaluating the operational benefits of using plug and produce collaborative robots in a dynamic production setting.

3 Methodology

As aforementioned, this paper investigates the effect on productivity when using a robot assistant to cover for an absent operator. For that, the following approach was used. In order to obtain realistic data on the productivity when the robot assistant and the human operator are attending the same tasks, physical experiments were conducted. The physical setup included a modular production line in a lab setting and a robot assistant. The latter was composed of a movable platform equipped with a collaborative robot and a tool changing mechanism, enabling the manipulator to adapt to different tasks autonomously. A plug and produce interface between the robot assistant and the production line was implemented. The data obtained from the physical experiments were used as input to a discrete event simulation, simulating several different staffing compositions. Based on these results, a breakeven time was computed. The breakeven time reflects the duration an operator must be absent before it is favourable to deploy the robot assistant.

4 Case Study

In the case study, we use a modular, industrial-like production line called AAU Smart Production Line (AAU SPL) situated in the AAU Smart Production Laboratory at Aalborg University [11, 12]. We use a movable collaborative robot assistant equipped with a tool changer and a variety of tools.

4.1 AAU Smart Production Line

The AAU SPL is a modular manufacturing line based on the FESTO Didactic Cyber-Physical Factory concept. It consists of eight standardised transportation modules, each with two slots on top for processing equipment. The product produced is a customizable dummy smartphone consisting of a back cover, a PCB, fuses and a front cover. In total, 1632 different variants of the product are currently possible. The products are transported on pallets incorporating RFID chips which store the individual product's recipe and specification. The process equipment on AAU SPL is a feeding unit for the back cover, a caged robot assembly unit for mounting PCB and fuses, a quality control unit for checking the PCB and fuses, an automatic assembly unit for mounting black front covers, and two manual stations; one station for mounting blue and white front covers and packaging, and one station for adding fuses and dispensing glue to waterproof variants of the product. The manual stations are an integral part of the process flow, and thus the production flow will halt if they are not attended. For an illustration of the robot tending the two manual stations, see Fig.1.

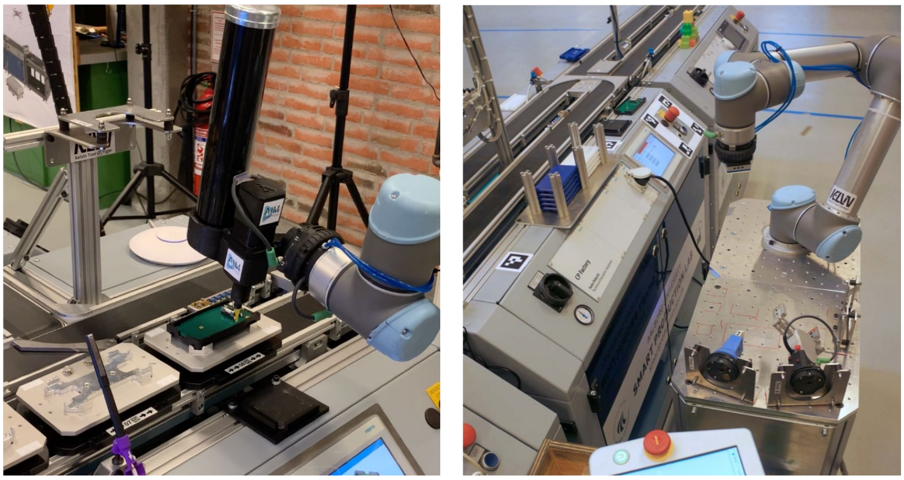

Fig. 1. The robot assistant tending the two manual workstations at AAU Smart Production Line. The robot carries generic tools on its platform, see right-hand picture. The robot also makes use of station specific tools available at the stations, see left-hand picture.

4.2 Plug and Produce Robot Assistant

The robot assistant hardware components and plug and produce interface are described in this section.

Robot hardware
The robotic platform used for the physical implementation was derived from the Little Helper family of robot assistants [13] (see Fig. 1). It consists of a: movable platform

on wheels, Universal Robots UR5, Kelvin Tool Changer, and four task-specific tools. The movable platform was designed in such a way that it could hold all the necessary hardware as well as being able to be maneuvered easily between stations. The UR5 is mounted on top of the movable platform, equipped with the Kelvin Tool changer at its end-effector. The Kelvin Tool Changer enables the robot to change its tools autonomously, consisting of a mounting plate at the robot's end-effector and a counter plate that holds the tools. The mounting plates are connected with a mechanical locking mechanism and are equipped with a pass-through for pneumatic states and electronic signals to the tool. Lastly, the four tools used are: a calibration-block, an OnRobot RG2 v1 gripper, a 4TECH pneumatic gripper and an AIM Robotics Glue dispenser.

Plug and Produce procedure

A plug and produce concept entails that the robot is deployed for different predefined tasks at various stations on a production line. The main challenge regarding implementing such a system is to reduce the time needed to set up the platform at a given station. By introducing a specific calibration point at each station at which the robot can be accurately calibrated once deployed, the manual positioning of the movable cart only requires centimeter accuracy and can thus be done rather quickly. The individual steps of the deployment procedure are the following:

- **Step 1**: Place the robotic platform within a marked area at one of the plug and produce enabled stations.
- **Step 2**: Connect the robot to stations dedicated power and Ethernet circuit.
- **Step 3**: Equipped the UR5 with the Calibration-block.
- **Step 4**: Hand-guide the UR5 to the station’s dedicated calibration point.
- **Step 5**: Confirm the station and the UR5s calibration position.

After these steps are completed, the robot will autonomously exchange the calibration tool with a task-specific tool depending on the Task-ID. These Task-IDs are stored on the RFID chip and hold all the information relevant for the products assembly. Whenever a new product arrives at the station, the information is transmitted to the robot via a MODBUS connection to the MES of the production line. This connection enables the robot to carry out different task variations depending on product variant. Whenever the robot receives a new task, it acknowledges the received information before either starting immediately with the assigned task or changing its tool before proceeding with the task. The latter happens when the robot has executed a task with a different operation.

4.3 Production Scenarios

Following the motivation for this paper, we address the setting of a highly dynamic production environment where the human operators are responsible for multiple tasks at once. Consequently, an operator might need to leave one task to solve another with higher priority, e.g., resolving a stop on an automated line nearby. Specifically, to our case, we consider a scenario where initially two operators are tending the two manual stations shown in Fig. 1. Due to a critical event elsewhere, one operator must leave his/her station for a period, resulting in two scenarios: #1 The remaining operator must tend both tasks, or #2 the remaining operator deploys a robot assistant as a substitute. The left-hand image in Fig. 2 illustrates the two scenarios. In scenario #1, the changeover is immediate, leaving no production gap. In scenario #2, the remaining operator must spend time plugging in the robot, leaving a period with no production. In scenario #2, once the leaving operator returns, he/she must spend time unplugging the robot before he/she can resume work. The scenario has a duration of three hours, with one operator leaving after one hour. The duration of the away time is the variable of interest.

5 Results

To simulate the productivity in scenarios #1 and #2, we first need to determine the cycle times for both the robot and the operator, and the plug-in and plug-out time for the robot. To do so, multiple physical experiments using the AAU SPL and the robot assistant were carried out. The experiments included running the production at each manual station for both a human operator and the robot. Furthermore, the experiments include the plug-in and plug-out procedure at each of the two stations for the robot assistant. The time for each task is the average resulting of 25 trials to avoid bias (see Table 1). The operator is in all tasks quicker than the robot assistant. The reasons for this are (1) the robot's velocity is limited due to safety, and (2) the task was originally designed for human labour, see Table 1. For the plug-in and plug-out procedure (see Sec. 4.2), the robot was idle and located 15 meters from the AAU SPL.

Table 1. Average cycle times of Physical Experiment.

Task	Operator [s]	Robot [s]
Dispense Glue	30	42
Add fuse	12	37
Mount cover and package	8	45
Plug-in	-	187
Plug-out	-	62

To study the outcome of scenario #1 and #2 described in Sec. 4.3, we first need to determine the productivity when the line is 1) operated by two operators, 2) a single operator that must travel between the stations, and 3) one operator and one robot. In this effort, a discrete event simulation has been made using the Enterprise Dynamics software. The simulation model is based on a previous study, where a digital twin of AAU SPL was designed. The robot assistant is added to the digital twin of the AAU SPL, and a production scenario of three hours is simulated. For the results of the simulation see Table. 2.

Table 2. Results of the discrete event simulations. Op = operator; Rob = robot assistant.

Station 1	Station 2	Total productivity [s]	Products per hour[s]
Op1	Op2	134.2	44.7
Op1	Op1	109.6	36.5
Op1	Rob1	132.4	44.1
Rob1	Op1	133.0	44.3

From these results and the results of the physical experiments, see Table 1, we can now compute the productivity of scenario #1 and #2 as a function of the time the operator is away. The graph on the right-hand side of Fig. 2 shows the productivity of both scenarios and highlights the breakeven time.

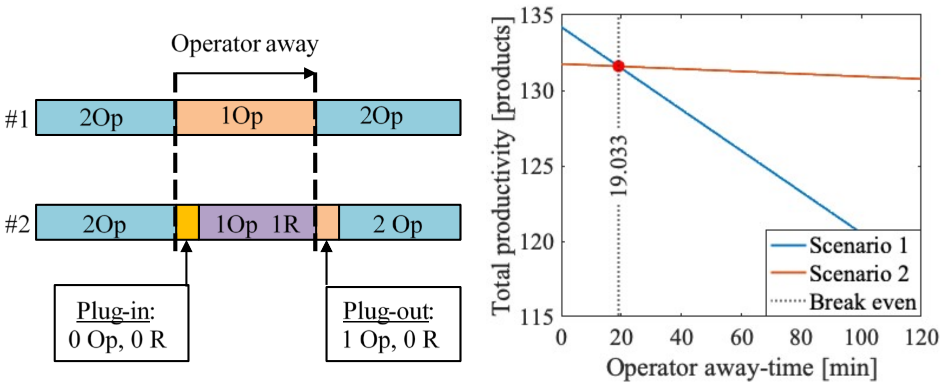

Fig. 2. The left-hand graphical illustration shows scenarios #1 and #2. The robot plug-in is done by the remaining operator, and the plug-out is done by the returning operator. Op = operator, R = robot. The right-hand image plots scenarios #1 and #2 as a function of the time the operator is away. If the operator needs to leave for longer than the breakeven time, a productivity increase will be gained from investing time in deploying the robot assistant.

The breakeven time is found to be approximately 19 minutes. Thus, if the operator needs to be absent for longer than 19 minutes, the highest productivity is obtained by scenario #2; hence, spending the time on deploying the robot assistant. If the operator is away for less than 19 minutes, the highest productivity is obtained by continuing with just a single operator.

6 Conclusion

We have in this paper investigated the operational potential of deploying plug and produce robot assistants in an ad-hoc manner to substitute for human operators. With offset in the hypothesis that: *"In a production environment with high task variety, deploying plug and produce robot assistants to aid the human operators will increase*

the productivity", we have studied an industrial-like scenario of an operator leaving a manual station for a short period of time and deploying a robot assistant as a substitute. We have used the real-world timing of cycle- and changeover times combined with discrete event simulation to estimate its productivity.
Our study found that if the operator is away for more than 19 minutes, the robot assistant should be deployed. Although the breakeven time is unique for this specific scenario, the approach used to determine it will be applicable to other scenarios.
In future research, we are investigating the applicability of the above-described approach in a real industrial setting. Additionally, we explore how combining the approach used in this study with key production-related features could be used to evaluate the applicability of plug and produce robot assistants for a given scenario.
Lastly, it is relevant to investigate what effect the maturing of technology regarding collaborative enabled manipulators and their control strategies have on the field of such robot assistants.

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