A COLLABORATIVE ROBOT IN THE CLASSROOM: DESIGNING 21ST CENTURY ENGINEERING EDUCATION TOGETHER

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ABSTRACT

A new industrial robot found its way to the Dutch manufacturing floor: the collaborative robot (cobot). For the first time, production workers can directly interact with an industrial robot. Such human-cobot collaboration creates opportunities to improve production system productivity and flexibility. However, it raises the question how we should prepare production workers and engineers for human-cobot collaboration. The aim of this paper is to research what engineering education could prepare future production workers and engineers for human-cobot collaboration.

Since it is unclear what criteria engineering education should meet to prepare future production workers and engineers for human-cobot collaboration, we researched what knowledge, skills, abilities, and other characteristics (KSAOs) are relevant for creating and maintaining human-cobot collaboration. We used the O*NET Content Model to search 60 interviews on cobot implementation in Dutch industry for cobot-related KSAOs. We discovered how 31 KSAOs were relevant for the design, programming, operation, and reparation of human-cobot collaboration and how these were divided amongst production workers and engineers. The repair KSAOs were mastered by both production workers and engineers. Most of the design and programming KSAOs were mastered by engineers. The operation KSAOs were mastered by production workers.

Based on these results and the effort of two community colleges, three manufacturers, a system integrator and two research groups, a 240-hour vocational education course on human-cobot collaboration was designed. In the discussion section, we illustrate how engineering education can be kept up-to-date when educators, scientists, and practitioners unite in a community of practice and design education together.

INTRODUCTION

European manufacturers are experimenting with a new type of industrial robot: the collaborative robot arm (cobot) [1-3]. The cobot is smaller, weaker, and shorter than other industrial robots. Nonetheless, it is more accurate and easier to program [4]. Manufacturers use cobots to load and unload machines, pack boxes, glue and weld objects, and assemble products [5-7]. These cobots execute simple and repetitive tasks, often around the clock. Although they are used as (semi) autonomous robots, production workers and engineers still play an important role in the production system.

Production workers are increasingly responsible for operating the cobot next to their other production tasks [8]. They provide the cobot with products, activate it, and process the products handled by the cobot. Furthermore, they solve small cobot errors. Engineers, on the other hand, are often responsible for installing the cobot, integrating it into the production system, and solving errors that could not be solved by the production workers. To prepare their production workers and engineers for the creation and maintenance of such ‘human-cobot collaboration’, manufacturers organize different types of facilitating conditions. These conditions vary from info sessions, to formal and informal training and workplace assistance. Knowing how manufacturers prepare their production workers and engineers for human-cobot collaboration is not only helpful to other manufacturers who want to implement cobots. Engineering education could benefit too. The question our local engineering educators are having is: what engineering education prepares future production workers and engineers for human-cobot collaboration?

Until recently, cobots could not be found in the engineering education of our local community colleges and university of applied sciences. However, the number of cobots in industry is rising [9-10]. To prepare their students – the next generation of production workers and engineers – for human-cobot collaboration, these educators want to include cobot education into their curricula. Currently, they are creating cobot education. They, however, have trouble finding relevant content, are unfamiliar with the cobot technology and lack clear best practices from industry. Furthermore, the cobot research oversteps the capability requirements human-cobot collaboration comes with [11].

To achieve our goal, research what engineering education could prepare future production workers and engineers for human-cobot collaboration, we must have a clear understanding what knowledge, skills, abilities, and other characteristics (KSAOs) current production workers and engineers need to create and maintain a human-cobot collaboration [12-13]. Knowledge refers to all procedural and declarative facts and information one memorizes [14]. Skills reflect all work-related and general behaviours one could enact [15]. Abilities are one’s physical, mental and perceptual capacities to enact and sustain a particular skill [16]. Other characteristics refer to actor-related traits, such as personality and interests [17]. We formulated the following research question: *which KSAOs do production workers and engineers in Dutch industry need given their responsibilities for creating and maintaining human-cobot collaboration?*

METHODOLOGY

To discover the KSAOs relevant for creating and maintaining human-cobot collaboration, we used the data from our prior research on human-cobot collaboration in Dutch industry [8]. The study included 21 manufacturers having working experience with cobots. Using a semi-structured interview protocol, we asked engineers (N=29), line managers (N=11), and production workers (N=20) what their human-cobot collaboration looked like and how these collaborations were implemented. The interviews were recorded and converted into verbatim transcripts.

The O*NET Content Model [18] was used to code the transcripts. The model captures a number of theories, such as Theory of Work Adjustment [19], to describe occupations and workers. We considered the O*NET Content Model comprehensive and suitable for this research as it was used for describing over 1,000 occupations and its workers both inside and outside industry. In this research, we focus on the model’s worker-oriented descriptors: worker characteristics and worker requirements – we excluded worker experience since we had insufficient data to determine interviewees’ experiential backgrounds. The work characteristics and worker requirements descriptors comprise eight variables (e.g., knowledge), 30 sub-variables (e.g., Manufacturing and Production), and 70 indicators (e.g., production and processing).

Since the KSAO variables, sub-variables, and indicators were provided by the O*NET Content Model, we used a deductive coding method [20] to analyse the data. Prior to the analyses, a coding structure was created using the above-mentioned variables, sub-variables, and indicators. In the structure, a distinction was made between production worker KSAOs and engineer KSAOs. The coding structure was imported into the coding software tool Atlas.TI. In total, three researchers used the coding structure to analyse a part of the transcripts. They mainly coded the tasks production workers and engineers executed to create and maintain a human-cobot collaboration. In line with thematic analysis [20], the transcripts were analysed in three steps. First, the variables under study were used to deduct relevant quotes from the transcripts (e.g., "… production workers should have basic understanding about the cobot's movement" was linked to "Knowledge"). Second, per variable, the quotations were linked to the sub-variables (e.g., 'Engineering and Technology'). Third, per sub-variable, the quotations were linked to an indicator (e.g., 'Mechanical Knowledge'). The researchers compared their outcomes to determine the production worker KSAOs and engineer KSAOs. Since the deducted KSAOs clustered around a part of the human-cobot collaboration, four characteristic groups we created.

RESULTS

In total, we found 31 KSAOs relevant to the creation and maintenance of human-cobot collaboration. We clustered these into four characteristics groups: design characteristics, program characteristics, operate characteristics, and repair characteristics. Table 1 (page 4) provides an overview.

Cluster 1: Design characteristics

This cluster captures all KSAOs to create a human-cobot collaboration design. Engineers used their *production and processing knowledge* and *operations analysis skills* to thoroughly analyse the production system the cobot would be implemented into. Furthermore, they used their *engineering and technology knowledge* to understand cobot and accompanying tooling specifications and how both could be used in practice (e.g., by searching for online use cases). Based on the analyses, engineers used their *ability of originality* to come up with feasible human-cobot collaboration designs. They used their *equipment selection skills* to select the cobot tooling most suitable to their designs. Once the design was ready, engineers presented the designs to the production workers using their *speaking skills* (e.g., through images or videos). Production workers were asked to review the design and propose alternatives. Production workers used their *ability of fluency of ideas* to come up with a number of preferred human-cobot collaborations. Engineers used their *active listening skills* to understand the production workers' input.

Cluster 2: Program Characteristics

This cluster captures all KSAOs to install and program the human-cobot collaboration. Since only engineers installed the cobot and wrote the necessary programs, this cluster appeals to engineers exclusively. Engineers used their *engineering and technology knowledge* about the cobot hardware and machine programming to install and program the cobot. By using their *installation skills*, they unboxed the cobot, its transformer and controller, and assembled these onto the workstation. Next, they attached the tooling to the cobot, wired it to the cobot and transformer, installed the software, and centred the cobot. Once installed, they wrote the program underlying the cobot application using their *programming skills*. During the installation and programming, complex cobot errors occurred (e.g., miscommunication between the cobot and a CNC machine). Engineers had to use their *complex problem-solving skills* and the *ability of inductive reasoning* to give meaning to these errors, search for their cause, and come up with a solution. Once programmed, engineers trained production workers for their role (Cluster 3) in the human-cobot collaboration using their *instructing skills*.

Table 1. Overview of Characteristic Clusters and KSAOs

Cluster 1: Design Characteristics			
KSAO	*Sub-Variable*	*Relevant to Engineers*	*Relevant to Production Workers*
Knowledge	Production and Processing	X	-
Knowledge	Engineering and Technology	X	-
Skills	Operations Analysis	X	-
Skills	Equipment Selection	X	-
Skills	Speaking	X	-
Skills	Active Listening	X	-
Abilities	Originality	X	-
Abilities	Fluency of Ideas	-	X
Cluster 2: Program Characteristics			
KSAO	*Sub-Variable*	*Relevant to Engineers*	*Relevant to Production Workers*
Knowledge	Engineering and Technology	X	-
Skills	Complex Problem Solving	X	-
Skills	Installation	X	-
Skills	Programming	X	-
Skills	Instructing	X	-
Abilities	Inductive Reasoning	X	-
Cluster 3: Operate Characteristics			
KSAO	*Sub-Variable*	*Relevant to Engineers*	*Relevant to Production Workers*
Knowledge	Mechanical	-	X
Skills	Operation and Control	-	X
Skills	Time Management	-	X
Abilities	Reaction Time	-	X
Abilities	Visualization	-	X
Abilities	Problem Sensitivity	-	X
Abilities	Spatial Orientation	-	X
Abilities	Manual Dexterity	-	X
Other Characteristics	Self-Control	-	X
Cluster 4: Repair Characteristics			
KSAO	*Sub-Variable*	*Relevant to Engineers*	*Relevant to Production Workers*
Knowledge	Engineering and Technology	X	-
Knowledge	Mechanical	-	X
Skills	Complex Problem Solving	XX[2]	X
Skills	Troubleshooting	XX[2]	X
Skills	Repairing	XX[2]	X
Abilities	Reaction Time	-	X
Abilities	Deductive Reasoning	-	X
Abilities	Inductive Reasoning	X	-

[2]XX = Engineers should master this KSAO in a more advanced level compared to production workers.

Cluster 3: Operate Characteristics

This cluster captures all KSAOs to operating the human-cobot collaboration and preventing it from falling into a standstill. In contrast to the program capacities, the operate characteristics appeals to production workers exclusively. They used their *mechanical knowledge* to operate the cobot, supply the it with parts, and determine what a well-functioning cobot looks like (e.g., movements, appearance). They used their *ability of manual dexterity* to precisely place parts for the cobot to handle in a designated pick-up area. Once handled, the production worker used the same skill to collect the products from the drop-off area. Using their *operation and control skills*, production workers switched-on the cobot, used the controller to select one of the prewritten programs, and press the start button. Since most cobots under study used one of a few programs, production workers had to changeover rarely.

To prevent the cobot from falling into a standstill, production workers had to timely load and unload the cobot using their *ability of reaction time*. Furthermore, they used their *ability of spatial orientation* to prevent themselves from colliding with the cobot and causing it to stop. To monitor the performance, they used their mechanical knowledge, operation and control skills, and *ability of visualization* to create a mental image telling them when the cobot functions well. Their *ability of problem sensibility* helped production workers to predict if the cobot would run into a standstill. In addition, since most production workers ran parallel tasks when the cobot was running its program, they had to use their *time management skills* to plan when they would execute their cobot and parallel tasks without letting the one overshadowing the other. Finally, production workers had to have the *self-control* to work with the cobot. They had to perceive it as a tool that would help them to do a better job and not hinder or destruct it.

Cluster 4: Repair Characteristics

This cluster captures all KSAOs to reactivate the cobot once fallen into a standstill. Production workers used their *ability of reaction time* to troubleshoot and, when possible, repair the cobot as soon as an error occurred. They used their *mechanical knowledge* to follow the prescribed troubleshooting and repair procedures. With their *troubleshooting skill* they would visually inspect the state of the cobot, the tooling, and parts being handled. Their *ability of deductive reasoning* and *complex problem-solving skills* allowed production workers to define the cause of the basic issue and apply standardized repair duties accordingly. The production workers' *repair skills* knew two degrees of freedom: rebooting the cobot using its power switch and reselecting the program. In case these repair efforts did not solve the issue, the engineers would be called to the scene and took over.

The engineers would use their in-depth *engineering and technology knowledge* about the cobot's hardware and software to troubleshoot and solve cobot errors that could not be solved by the production worker. Engineers would not only inspect the scene visually but also digitally (e.g., reading the history on controller and checking the program). Since engineers faced a wide variety of more complex errors that could go beyond general rules, procedures, and guidelines, they had to highly rely on their *ability of inductive reasoning* to solve these. In addition, the complexity of the errors also required the engineers to have more complex problem-solving and repair skills compared to production workers.

CONCLUSION & DISCUSSION

In this study, we asked ourselves the question what engineering education prepares future production workers and engineers for human-cobot collaboration. Since it is unclear what KSAOs production workers and engineers should master to create and maintain a human-cobot collaboration, we used the O*NET Content Model [18] to analyse 60 transcripts about cobot implementation in Dutch industry. We found 31 KSAOs relevant to the creation and maintenance of human-cobot collaboration. We were able to group the KSAOs into four categories and connect these to production workers, engineers, or both. Our results revealed a classic distinction between production worker and engineer responsibilities: the engineer (together with management) determines the machine's application, implements the machine, and solves complex errors; the production worker operates the machine and solves errors using detailed instructions [21-23].

Cobot education provided to future production workers should develop them into *cobot operators*. These operators are willing to work with the cobot, can think along with engineers about its application, can prepare and maintain the cobot and its workstation according to instructions, can solve and communicate cobot errors, and are able to manage multiple production systems. The operators should learn the following: the use of the cobots' control panel, cobot (dis)functioning, loading and unloading, and basic cobot troubleshooting.

Cobot education provided to future engineers should prepare them to become *cobot programmers*. These programmers are able to determine which cobot application and tooling are best given the state of the production system, build accompanying programs from scratch, integrate the cobot with other machines and devices, develop the social skills to engage and instruct cobot operators, and solve complex cobot errors. The cobot programmers should be educated about the following: the cobot and tooling specifications, the programming language, cobot input and output management, and expert cobot troubleshooting. In addition, they should learn how to thoroughly analyse a production system and conduct professional conversations.

Designing 21st Century Engineering Education Together

In the latter part of our contribution, we illustrate how we used our results to develop engineering education that prepares vocational education student, the next generation of production workers, for human-cobot collaboration. We used the educational design model [24] to structure the development process. The model uses an *iterative* process consisting three stages, namely: 1) exploration, 2) design, and 3) evaluation.

In order to translate the needed KSAOs for cobot operators, as mentioned before, we formed a *community of practice*. The community of practice comprised the following members: six vocational education teachers from two different community colleges with different technical backgrounds (mechatronics, ICT, laser technique), four researchers from two research groups specialized in HRM, industrial design, and mechatronics, two educational designers, three practitioners from technical companies, and a cobot integrator. The diverse expertise in this community of practice allowed us to embed all required KSAOs in our engineering education and align it with industrial practice.

Phase 1: Exploration of the Current Situation

During the first meetings with the community of practice, we reflected on the 16 KSAOs relevant to production workers working with a cobot. We asked the members to elaborate on two questions: how do these KSAOs match the prior knowledge of students and how should we, as a community of practice, educate the missing KSAOs? We asked educators how they wanted to embed the cobot education into their engineering education system. Since creating a completely new course and redesigning the community colleges' engineering education programs were considered too time-consuming by the educators, we picked an existing 240-hour elective module called Working with an industrial robot. The elective module came with two advantages. First, the elective module was already certified and came with clear-cut learning goals and exam criteria which allowed us to place more focus on developing course content. Second, the elective module's learning goals and exam criteria were in line with the KSAOs relevant to production workers working with a cobot. This alignment allowed us to build course content that could prepare students for human-cobot collaboration without violating the elective module's goals and criteria.

Phase 2: Designing Cobot Education Content

Based on the insights obtained in the exploration phase (phase 1), we created the content for our elective course. Since we found both knowledge and practical KSAOs, a hybrid learning environment was considered optimal. A hybrid learning environment is authentic and situated [25]. It combines the advantages of school-based and workplace learning arrangements by binding these intersecting practices together, without losing the strength of either. A hybrid learning environment combines two learning dimensions. The first dimension is about the learning processes that are to be embedded in vocational education and varies from *acquisition* (knowledge is considered as a commodity that can be acquired, transferred and shared) to *participation* (learning as growing into becoming a full member of a professional community). The second dimension is about the conditions under which the learning process can take place in vocational education and varies from *constructed* (near work exercises like cases and simulations) to *realistic* (how novices participate in authentic work).

The dimensions of a hybrid learning environment were used to structure our elective module, as shown in Table 2. In part A, students' learn about cobots and their applications in a class setting (e.g., images, video's, MOOCs, story-telling). Part B takes place in the workshop and the classroom. In the workshop, students will witness educator-lead demonstrations to experience the cobot's functionalities, programming, and safety measures. In the classroom, the students will work on online cobot programming assignments. In part C, taking place in the workshop, students will apply and improve their cobot KSAOs by working together with a cobot in a mock-up assembly line.

Table 2. Content and corresponding aspects of hybrid learning in the course.

Part A: An introduction to human-cobot collaboration	**Part B: Functionalities of a cobot**	**Part C: Working with a cobot in experimental set-ups**
Basic knowledge of the (kinds of) cobots, introduction to smart industry, differences of a robot/cobot, ethical questions and impact of work	Basic knowledge about working with a cobot, types of cobots and components, basic of programming (computational thinking),	Working with human-cobot collaboration in realistic situations, experimenting with self-designed cobot applications, and recognize

	safety and applications of the cobot in business contexts	and correcting malfunctions with cobots
Constructed acquisition Illustrating theoretical concepts; contextualization of concepts in the form of examples in textbooks by using pictures of video's. *Example: e-learning about the knowledge needed, i.e. parts of the cobot.*	**Realistic acquisition** Learning processes under realistic conditions, to make wok process knowledge explicit (reflective practice). *Example: small assignments about programming a cobot, in which theory is translated to practice.*	**Realistic participation** Learning through work experience or on-the-job learning; at school grounds or at the workplace. *Example: final assignment based on a realistic example of the workplace or short internship; solving a problem in human-cobot collaboration.*
Constructed participation Elements of the rich reality of the professional practice are present, but not entirely. Parts are for example left out , simplified of simulated. *Example: (digital) simulations to practice working with a cobot or semi-structured assignments.*		

Phase 3: Improving the design

Designing an elective course on human-cobot collaboration was an iterative process and relied heavily on the members in the community of practice. The network meetings served as great moments to reflect on what was designed and compare it to new experiences in work and experiments with students. During the design process, five vocational education students tested the designed content, assignments and applications with cobots. We did this to gain a first understanding on how vocational education students deal with the course content and to learn what support they needed from their educator. It seemed that – most of the time – the students found it quite simple to work with basic aspects of the cobot (e.g., activating a program). Furthermore, the occurrence of cobot-related errors showed to be a great opportunity for students to translate their learned knowledge about cobots into practice and use it for troubleshooting. It also stimulated their the fluency of ideas as they provided suggestions for optimizing their human-cobot collaboration.

Another aspect which seemed to be very important, is to have a digital platform that is accessible to all member in the community of practice. Such a platform was in our case needed to share expertise and course content across institutions. The design process resulted in long-term partnerships between education, practice, and science.

With this study, we contributed to the engineering education community and industrial practice by specifying the KSAOs production workers and engineers need to work with a collaborative robot. Furthermore, together with two community colleges, three manufacturers, a system integrator and two research groups, we developed a 240-hour vocational education course on human-cobot collaboration. Co-creating education and a pioneering mindset proved to be of great value and a necessity to keep engineering education up-to-date. We are looking forward to launching our cobot education in the Fall of 2021 and report upon our findings in a follow-up contribution.

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