Idea Lab: Bridging Product Design and Automatic Manufacturing in Engineering Education 4.0

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***Abstract*—Industry 4.0 calls for new multidisciplinary skills, and universities have an essential role in supplying this competence. Engineering Education 4.0 has therefore been introduced as a means of meeting the demands of Industry 4.0, by making technology accessible in a pedagogic environment. This paper introduces an Industry 4.0 Idea Lab for bridging design and automatic manufacturing in Engineering Education 4.0. The Idea Lab is presented within the Learning-Factory-Curriculum-guide, including lab facilities and overview, teaching modules, and specific student development projects. Evaluation of the role of the Idea Lab with respect to design for automatic manufacturing is evaluated with a survey. It was found that a low entry level to the lab is important for students' learning, and that the lab facilities tightens the interactions between local industry, students and university.**

***Index Terms*—Industry 4.0, Engineering Education 4.0, RoboDK, Product Design, Automatic Manufacturing**

I. Background

The new Industry 4.0 era calls for new cross-functional roles with different knowledge and skills that combine several domains [1], [2]. Moreover, Industry 4.0 technologies have become crucial for the development of competitive manufacturing systems, and industrial companies now need new knowledge to compete in a globalized market [3]. Universities have an essential role in developing knowledge and competencies to support this through state of the art engineering education [2]. Universities should now educate multi-disciplinary engineering teams that have the right knowledge and skills needed for such a transformation, and furthermore enable next generation manufacturing concepts.

Industry 4.0 technologies, such as advanced product design tools, cloud-based computing, simulations with digital twins, autonomous robots, internet of things (IoT), big data statistics, and additive manufacturing, requires knowledge within multiple domains. This requires a higher level of collaboration among personnel with different fields of specialization. Prieto et al [4] emphasises that multidisciplinary knowledge must be promoted in academic contexts in order to strengthen the teaching-learning process towards Industry 4.0.

To meet the demands of the new Industry 4.0, Ramirez-Mendoza et al. [5] introduced the Engineering Education 4.0 curriculum. They highlight that a success criterion for Engineering Education 4.0 is making sufficiently mature technology accessible to students, adapting it naturally in a pedagogic environment. Here, active learning techniques, such as problem based learning [6], are used to ground the learning process in a reality-based situation. In addition to technical skills, they highlight several general skills, such as virtual collaboration, design thinking, and transdisciplinary skills as important.

Onar et al. [1] proposes three topics as crucial for engineering education in Industry 4.0. The first is educational content, which involves data and computing technologies, value added automated processes, innovation and entrepreneurship. The second is e-learning technologies, including virtual- and augmented reality, gamification, and learning analytics, and the third is working in interdisciplinary teams. They also point out that a key question for universities is how the structure and content of engineering programs should change for a new era. Tisch et al. [7] suggest that one of the most important pillars in adapting engineering education to Industry 4.0 will be the foundation of a "Visual Production Lab", where computer-aided design and manufacturing (CAD/CAM) with enterprise resource planning (ERP) are carried out, materials and logistics determined and 3D printed factories generated. They define a learning factory as:

> *"(...) a dedicated facility that mimics real production processes and environments and is used to develop competencies of present and future industry personell."*

Based on the Learning-Factory-Curriculum-Guide (LFC-Guide) [8], Tisch et al. [7] present three levels of a competency-oriented learning factory design, namely; i) Macro Level: Design of the Learning Factory infrastructure including the production environment as well as fundamental parts of intended learning processes, ii) Meso Level: Design of teaching modules including the explication of specific sub-

Fig. 1. The Idea Lab facility at NTNU Aalesund, with an AGV, laser cutter, delta robot-conveyor cell, and collaborative robots.

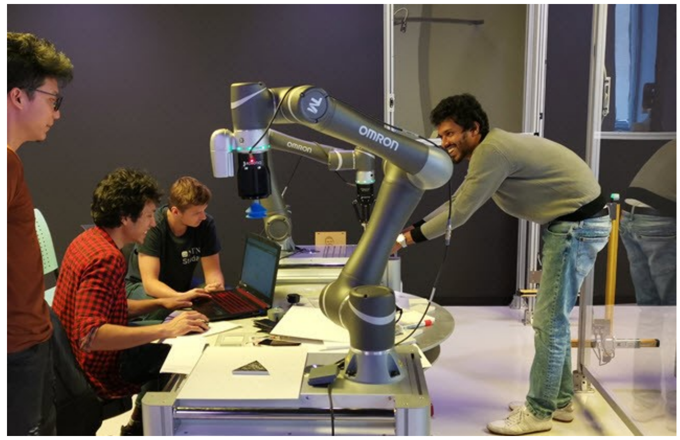

Fig. 2. Students working on a collaborative robot cell in the Industry 4.0 course.

competencies and the definition of general teaching-learning sequences, iii) Micro Level: Design of specific teaching-learning situations. Considering Biggs' Structure of the Observed Learning Outcome (SOLO) taxonomy, the learning factory design goal is to increase student learning from multi-structural to extended abstract [9].

Manulab is a national infrastructure for research on manufacturing engineering with laboratories located at Gjøvik, Trondheim and Aalesund. The project consists of 11 labs, and is funded by the Norwegian research council with contributions from partners [10], [11]. As a part of the Manulab network, we present a novel approach towards Engineering Education 4.0, which includes a state of the art Industry 4.0 Idea Lab concept [12]. Our Idea Lab is presented within the LFC-Guide; i) macro level: design of the lab infrastructure, ii) meso level: design of teaching modules, and iii) micro level: design of specific teaching-learning situations. The lab concept is evaluated with a survey. The Industry 4.0 Idea Lab concept was designed and implemented in June 2019 and has been in operation for 18 months. This paper is based on the experiences we have had teaching of approximately 50 students, within two semesters.

II. Idea Lab: An Industry 4.0 Lab

A. Macro Level: Industry 4.0 Idea Lab

The Idea Lab is specially designed for education, research and innovation within low volume automatic manufacturing with high variety in products. It is a complete mini factory, integrating product design and automatic manufacturing, and contains advanced manufacturing cells. There is ongoing work connecting the mini factory to a web shop for automatically manufacturing customized products. The Idea Lab mindset is based on collaborative learning between industry and university [13]. The lab facilities are open for students at all hours, and the following Industry 4.0 topics are emphasized:

- Advanced CAD product design tools and full integration with the manufacturing cells
- Use of collaborative robots with vision, sensors, fixtures and grippers
- Use of mobile robots for flexible manufacturing

The Idea Lab manufacturing cells consist of two 3D-printer racks, one laser cutter, three collaborative robot cells and two advanced industrial robot cells. All cells are fully equipped with advanced machine vision and sensors. The transport system consists of two mobile robots with platform carriers and one mobile robot with a collaborative robot arm. The products that can be manufactured in the Idea Lab are generally limited to the size of 400x400x400 mm, but larger sizes can also be made in the assembly process. The Idea Lab can manufacture plastic components in the 3D-printer racks, and plastic and wood in the laser cutter. Other components can be sourced from suppliers, such as special components for the products, and more general components like screws.

The Idea Lab includes advanced cloud based CAD systems (Siemens NX and others) and Simulation Software (Robodk and Ansys) for product design, which is closely integrated with the automatic manufacturing systems. One example is the integration of the CAD systems and the 3D-printer factory. The parts designed for 3D-printing can be sent to the printer queue with one click in the CAD program. These parts are automatically checked before they are allowed space in the 3D-printer factory que. Another example is CAD design of automatic manufacturing cells, where the designed components can be transferred directly to RoboDK. There is an ongoing work to develop a complete digital twin of the Idea Lab.

The Idea Lab integrates multiple engineering disciplines such as industrial product design, advanced manufacturing, automation and intelligent systems, as well as information- and communication technology. We aim for low barriers to start working with automatic manufacturing cells in the Idea Lab. We have observed that components can be made in the 3D printer factory, that collaborative robots can be programmed by the students after an hour or two of training, and that mobile robots can be operated after three to four hours of training. Furthermore, we aim to facilitate entrepreneurial learning. Researchers and students can explore and test business models dedicated for Industry 4.0 and put them into live operation to

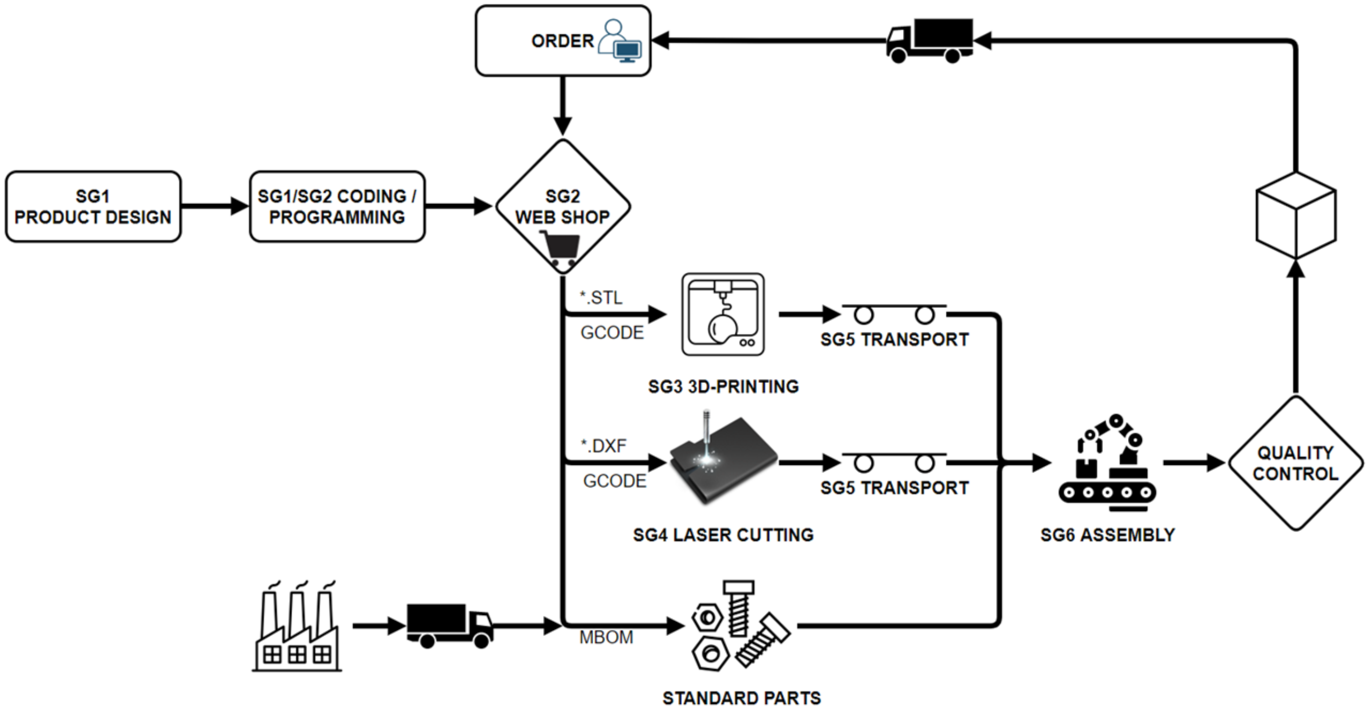

Fig. 3. Industry 4.0 factory flow chart and Idea Lab concept.

reveal challenges and opportunities. Finally, our aim is that the Idea Lab should facilitate transforming theoretical knowledge into practical skills. We have observed that practical skills seem to have a strong impact on the motivation and performance of the student teams.

The regional industry uses the Idea Lab for proof of concept, and research and innovation on automatic manufacturing concepts that they want to implement in their factories. Regional industry also participates in education through the use of industrial cases. Technology providers to Idea Lab contribute with course modules for their respective equipment in teaching. Engineers from the regional industry are also included in review boards for final course presentations.

B. Meso Level: Teaching Modules

The core academic concept for Engineering Education 4.0 comprises an Industry 4.0 course (7.5 ECTS), a 3D-modelling and simulation course (7.5 ECTS), a Mechatronics course (7.5 ECTS) and a bachelor thesis (20 ECTS). The courses are held during the third and final year (fifth semester), and the bachelor thesis as a capstone project during the sixth semester.

The 3D-Modelling and Simulation course is focused on training the students in using 3D-modelling as a design tool (CAD/CAE/PDM), and how to work with these tools in engineering teams. The course is open for product design, ship design and automation engineers. The 3D-Modelling course covers four main topics. The first topic (i) is design databases and PDM-Systems. In the course, a design database is set up with Teamcenter as the backbone. Training students in the use of PDM-systems is crucial to preparing them for real life work

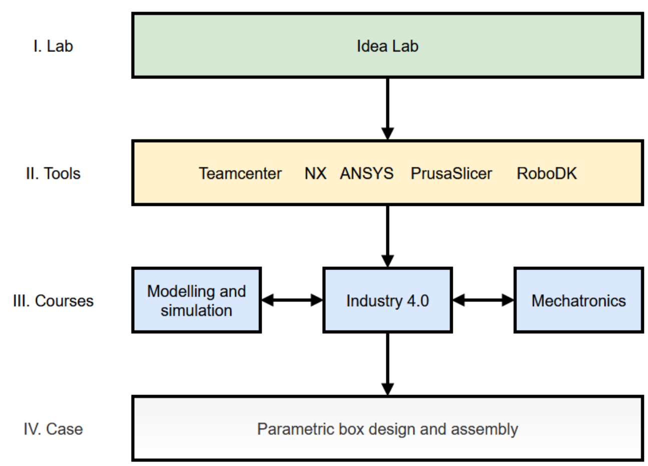

Fig. 4. Engineering Education 4.0 Idea lab concept framework, including courses, tools, lab and case.

experience and and connecting design and manufacturing. A well configured PDM-system gives students access to component libraries and enables students to seamlessly share design data among team members, across the university campus, courses and as well re-use and improving 3D-Models from year to year. The second topic (ii), 3D-Modelling, is to create and modify 3D-geometry (CAD). Here, Siemens NX is used as a design tool in tight integration with Teamcenter. Siemens NX is an extensive software package with modules for CAD, CAM and CAE. However, plugins are configured to enable loading of design data into more specialised software packages like ANSYS, RoboDK and PrusaSlicer for design verification, optimization and manufacturing simulation, which is the third topic (iii). Topic four (iv) is multidisciplinary engineering, and introduces the students to system engineering and solving more advanced design tasks in engineering teams. The design platform and software portfolio is is described in detail in another paper [14].

The Industry 4.0 course has an activity-based learning methodology, which is a combination of problem-based learning and problem-oriented learning. The course is open for product design, ship design, information and communication technology, as well as automation students. The goal of the course is learning how to design products for Industry 4.0 manufacturing in the Idea Lab. A selected product is designed with Siemens NX and can be optimized using ANSYS. The assembly process can be simulated using RoboDK. The physical manufacturing consists of 3D printing and laser cutting, transportation by mobile robots, and assembly by collaborative robots. Vision systems are used in all processes to support the robot operation. Grippers and fixtures are to some extent made by the students. In the project, a 'Box Concept' serves as the product, where the student groups define the customer and an application. A requirement is that the 'Box Concept' should have at least five different variants, or it should be a parametric design. The Industry 4.0 course has eight teaching modules and ten assignments which support the overall aim of the course, namely design and manufacturing of a product in the Idea Lab. The course is interconnected with an industrial research and innovation project on design for flexible manufacturing, which is executed in the Idea Lab. Several of the students participating in the course are also given the opportunity to work in the research and innovation project. This sets the agenda for entrepreneurial activities in the research and innovation project, and this also creates entrepreneurial activities and entrepreneurial learning in the course. The Industry 4.0 course is also offered on masters level under the name 'Digital Manufacturing'.

The Mechatronics course is open to product design, ship design and automation engineers. The course is an introduction to mechatronic systems, robotics, software and control, and supplements 3D-Modelling and Simulation and the Industry 4.0 courses. The focus is on designing and building machines, and digs deeper into the control system, software and mechanics. The course enables students to design and build their own electro-mechanical products with software and control such as robots, grippers and flexible fixtures for use in the lab. The teaching consists of an introduction to theory, concepts and assignments, followed by a multidisciplinary project with focus on building physical prototypes of machines and robots.

Finally, the bachelor project gives students the opportunity to refine and develop skills and tools gained in 3D-Modelling and Simulation, Industry 4.0 and Mechatronics courses. A larger project with a multidisciplinary team consisting of 2-4 students is staged to solve more advanced problems in the lab and for local industry.

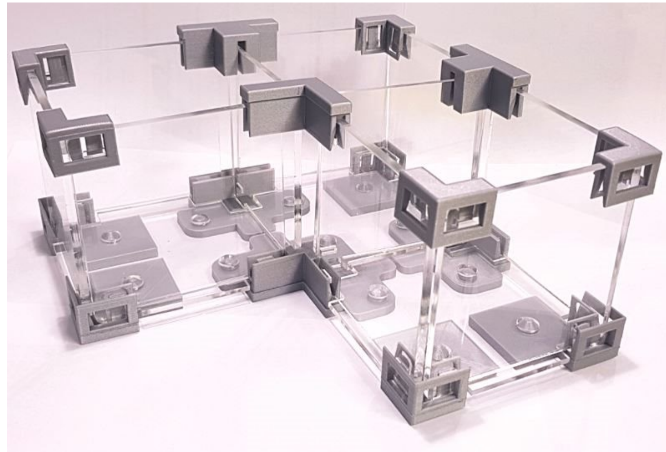

Fig. 5. Parametric box for storage

C. Micro Level: Student Development Project

We use a student development project in the Industry 4.0 course as an example to showcase specific teaching-learning situations. In the project, students were given the task to design a customizable storage box for automatic assembly. An example is shown figure 5. The exercises were carefully developed to include real world manufacturing problems with respect to the capacity of the participants. This creates a scenario where activities has to be performed to achieve the learning goals. As shown in the LFC-Guide, a mix of theory-push and problem-pull were used as learning process strategies [8] [7]. The students were already familiar with 3D-modelling and product design, so this was taught using a theory-push approach. For the automatic assembly part, a problem-pull approach was taken since course participants had no prior knowledge of robot programming. Students also entered a collectivisation mode with self-organised learning and reflection-first approach towards the end of the project [7].

Theory push: An introduction to parametric modelling, product configurators and available manufacturing methods at the lab enabled students to establish a preliminary design. 3D-printed parts were identified as the long lead item with several hours of printing time for each component. Laser cut parts had significantly shorter lead times than 3D-printing. Lead times were reduced down to a few minutes and were well suited for handling product variations in size and appearance such as length, width, height, thickness, color, transparency and engraved custom text and logos.

Problem-pull: Students received weekly on-demand robot training. When working with the mini factory for box production, students identified benefits and disadvantages with different manufacturing and assembly methods. Bolts and screws were replaced by snap fit connections, dove tail joints and interlocking plates. Students learned that 3D-printed parts had to be carefully designed to 1) use as little support materials as possible, 2) achieve correct stiffness for snap-fit connections and 3) to be compatible with available grippers. Most of the teams designed custom jigs and fixtures to help assemble their products. This was especially useful with snap fit connections and joints requiring a force from the robot to lock parts together. Students also designed jigs with "open" ends and motor driven jigs to handle variations.

Reflection-first: As the project progressed, seven student teams shared one robot cell. Therefore, they went into collective mode to avoid bottlenecks and to reduce change-over time similar to an industrial setting. Kitting of parts and jigs came up as a solution. Most of the teams started with absolute coordinates when programming the robots which required calibration of robot positions. Students avoided this by using vision and QR-codes to automatically calibrate robots and real-time adjust the robot program. After safety training, students were allowed to work in the lab at all hours. Students spent night hours programming the robot cell and issues with vision programming and different lightning were identified. Students learned that vision programs created during nighttime are not guaranteed to work during day time with variable light conditions.

III. Evaluation of Idea Lab

A. Survey

A survey was distributed to two student groups participating in the affiliated courses "Industry 4.0" and "Digital Manufacturing" to assess our Industry 4.0 Idea Lab. A Norwegian version was distributed to the students attending "Industry 4.0", and an English version was distributed to the students attending "Digital Manufacturing". The aim of the survey was to assess how the Idea Lab facilities contributed to the students' understanding of design for automatic manufacturing, as well as barriers they encountered in using the lab equipment. The students were asked to describe on a five point Likert scale how much they agreed with a set of statements.

B. Participants

A total number of 13 participants doing industry 4.0 coursework were asked to complete the survey, of which 10 were male and 3 were female. A total of 16 students followed the courses during the relevant semester, resulting in a participation rate of 75 %. Of these paticipants, 54 % were aged 18-25, 38 % 25-30, and 8 % above 30. All of the participants (100 %) were mechanical engineering students. The survey was anonymous.

C. Results

Fig. 6 shows selected results from the survey. When asked about about technical entrance barriers to using the Idea Lab, such as network communication between robots and programming environments, one participant strongly disagreed, five disagreed, four were neutral, one agreed, and one strongly agreed. Additionally, one participant had prior experience with robot programming, two had some experience, while 10 had no experience. However, only one participant reported that he/she had not been able to use equipment (collaborative robots, AGV's, 3D-printers, laser cutter) at the Idea Lab.

Furthermore, there was a clear trend towards the benefits of including the Idea Lab in teaching. All participants agreed that project work increased their understanding for connecting design and manufacturing, that they learned skills they would not have learned in traditional classroom teaching through the use of machines and equipment in the Idea Lab, and that the lab facilities made it easier to solve cases and assignments related to Industry 4.0 courses.

IV. Discussion

In this paper, we have presented a lab concept for teaching Industry 4.0 to engineering students. The Idea Lab is presented as macro level in the LFC-guide. Further on, we present courses on the meso level and a case with a parametric box design on the micro level. The findings demonstrate that the LFC-guide is an adequate framework to describe our Engineering Education 4.0 Concept.

In courses, students have been trained in using design software, programming robots, automatic manufacturing and building electro-mechanical machines. All these skills have been applied on the parametric box design and automatic production of the box in the Idea Lab. Our experience from the lab with respect to the students, courses and case work indicates that design for automatic manufacturing is best learned when students try, test and tune their own designs in the lab. These steps brings the students through several levels of Biggs' SOLO taxonomy. The Idea Lab, tools, courses and case enable students to learn and master design for automatic manufacturing and all components are connected as shown in the framework in Figure 4.

The student survey confirms that the students had a satisfactory learning process in the teaching modules, and that they were prepared for working in the Idea Lab. This is evident from the survey where students reported that they acquired skills in the lab that they would not have learned otherwise in traditional classroom teaching. Further, very few of the students had robot programming experience prior to the courses, but after course completion the vast majority were able to program the robots. Results from the survey also indicate that students have improved their understanding of the impact product design has on the automatic manufacturing of products. This was also observed from the evolution of box- and jig designs in the student projects, as shown in Fig. 5.

More advanced manufacturing labs exist around the world, but we believe the low barriers for using the lab and unrestricted access is crucial for the students to take ownership of the lab. This supports the findings of Ramirez-Mendoza [5], which is that a success criterion for Engineering Education 4.0 is the adaption of technology to a pedagogic environment. It is our impression that students now continuously monitor technology advances and participate in online communities to get new ideas, solutions and methods to improve the lab. They are also collaborating across study programs, engineering disciplines and study levels to design and develop new machines, methods and equipment to further improve the lab.

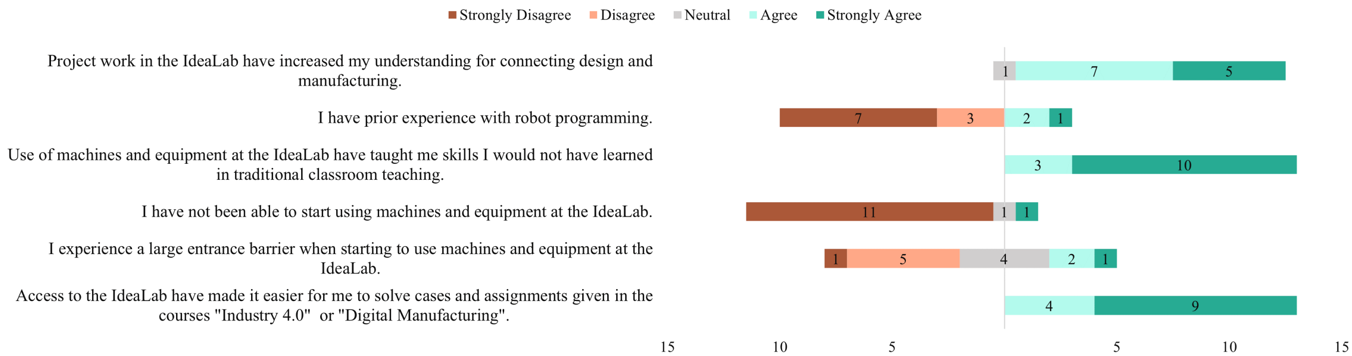

Fig. 6. Selected results from survey with 13 participants (10 male, 3 female).

Observations made during the teaching modules, supported by survey results, shows that product design for automatic manufacturing can be efficiently taught using a problem-based and problem-oriented learning approach. We have observed that students understand that challenges that occur in automatic manufacturing can, in many cases, be solved by improvement in the product design. This also includes design changes of jigs, fixtures and grippers.

V. Conclusion

We have presented a lab where students can learn and test Industry 4.0 technology. The research work demonstrates that the LFC-guide provides an adequate presentation of the Idea Lab. The feedback from students is positive, and we have found that a low entry level to the Idea Lab is important for students' learning. Local industry is also using the lab as proof of concept testing for their own products. Consequently, the Idea Lab and its Industry 4.0 facilities tighten the interaction between industry, students and university. We believe that product design should be an integrated part of Industry 4.0 education. Our lab aims to facilite product design as a means of improving automatic manufacturing performance. Finally, we believe the Idea Lab concept can provide local industry with engineers capable of speeding up the implementation of Industry 4.0.

References

[1] S. Cevik Onar, A. Ustundag, Ç. Kadaifci, and B. Oztaysi, "The changing role of engineering education in industry 4.0 era," in *Industry 4.0: Managing The Digital Transformation*, ser. Springer Series in Advanced Manufacturing. Cham: Springer International Publishing, 2017, pp. 137–151.

[2] S. Coşkun, Y. Kayıkcı, and E. Gençay, "Adapting engineering education to industry 4.0 vision," *Technologies*, vol. 7, no. 1, 2019.

[3] E. Abele, J. Metternich, and M. Tisch, "Overview on the Content of Existing Learning Factories," in *Learning Factories : Concepts, Guidelines, Best-Practice Examples*, E. Abele, J. Metternich, and M. Tisch, Eds. Cham: Springer International Publishing, 2019, pp. 263–287.

[4] M. D. Prieto, Á. F. Sobrino, L. R. Soto, D. Romero, P. F. Biosca, and L. R. Martínez, "Active Learning based Laboratory towards Engineering Education 4.0," in *2019 24th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA)*, Sep. 2019, pp. 776–783, iSSN: 1946-0759.

[5] R. A. Ramirez-Mendoza, R. Morales-Menendez, H. Iqbal, and R. Parra-Saldivar, "Engineering Education 4.0: — proposal for a new Curricula," in *2018 IEEE Global Engineering Education Conference (EDUCON)*, Apr. 2018, pp. 1273–1282, iSSN: 2165-9567.

[6] H. S. Barrows and R. M. Tamblyn, *Problem-based Learning in Health Sciences Education*. U.S. Department of Health, Education, and Welfare, Public Health Service, National Institutes of Health, National Library of Medicine, National Medical Audiovisual Center, 1979, google-Books-ID: Nm1LAQAAIAAJ.

[7] M. Tisch, C. Hertle, E. Abele, J. Metternich, and R. Tenberg, "Learning factory design: a competency-oriented approach integrating three design levels," *International journal of computer integrated manufacturing*, vol. 29, no. 12, pp. 1355–1375, 2016.

[8] M. Tisch, C. Hertle, J. Cachay, E. Abele, J. Metternich, and R. Tenberg, "A Systematic Approach on Developing Action-oriented, Competency-based Learning Factories," *Procedia CIRP*, vol. 7, pp. 580–585, Jan. 2013.

[9] J. B. Biggs, A. J. Edward, and K. F. Collis, *Evaluating the Quality of Learning: The SOLO Taxonomy (Structure of the Observed Learning Outcome)*, ser. Educational Psychology S. Academic Press, 2014.

[10] K. Martinsen. Department of manufacturing and civil engineering: Manulab. [Online]. Available: https://www.ntnu.edu/ivb/manulab

[11] ——. Manulab: Laboratories. [Online]. Available: https://manulab.org/laboratories/

[12] P. S. Kleppe. Idea lab. [Online]. Available: https://www.ntnu.no/blogger/ihb/manulab/

[13] O. J. Mork, I.-E. Hansen, K. Strand, L. A. Giske, and P. S. Kleppe, "Manufacturing Education- Facilitating the Collaborative Learning Environment for Industry and University," *Procedia CIRP*, vol. 54, pp. 59–64, Jan. 2016.

[14] P. S. Kleppe and Ø. Bjelland, "Implementation of Virtual Concurrent Engineering Tools in Engineering Education," in *2022 IEEE Global Engineering Education Conference (EDUCON)*, Apr. 2022.