Andreas Knudsen Sund

Improving Mechatronics Education with Design Thinking

Masteroppgave i Produktutvikling og Produksjon
Veileder: Amund Skavhaug
Juni 2022

Masteroppgave

NTNU
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Kunnskap for en bedre verden

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Preface

0.1 Personal Motivation

This is my master thesis at NTNU, where I have studied mechanical engineering. I have selected a hybrid of two specializations: *Advanced Product Development* and *Robotics and Automation*, which has proved as a fitting synergy for this work. The subject matter and involved technologies fall under automation, while the manner in which the work was conducted and information was gathered is strongly informed by knowledge of product development methodologies.

Throughout my studies, I have had multiple positions as a trustee in the student democracy, and in 2021 I worked full-time as the leader of the NTNU Student Parliament, which is the reason for the one-year delay between this master's and the previous project thesis that served as a pre-study for this work. This has been both informative and strongly motivational for this work. It has allowed me to speak to many students and see the negatives and positives of their studies. I have also been able to get a more structural understanding of the underlying problems preventing educational content from reaching the desired quality and some of the ways this might be remedied. It has also put me in contact with many academic staff members, allowing me to see these issues beyond the student perspective. For the same reasons that I pursued these positions, it is deeply motivational to use my master's thesis to work towards improving the educational content at NTNU, thus giving back to both the co-students that have given me so much. It has also been very valuable to merge these curricular and extracurricular activities in this work, as they can, in fact, strongly inform each other.

In the last few years of my studies, I have been particularly interested in user-centered product development, specifically Design Thinking and its implementation. I have experience with this methodology from courses such as *TMM4220: Innovation By Design Thinking* and *TMM4245: Fuzzy Front End*, along with applying it in my pre-masters project thesis. However, I have also found benefits in applying DT principles in other curricular and extracurricular work and will likely continue to find use for it in my work life. The motivating idea behind these theses was that it would be interesting and useful to apply them in the development of educational activities. Throughout my years at NTNU, I have encountered a broad specter of learning activities of widely varying quality. It is then interesting to explore why some assignments succeed, and others do not, how students best learn, and what stands in the way of achieving this. The ones who know this best are the users themselves, namely students. Using a user-centered methodology such as Design Thinking should then help uncover exciting ideas and insights to improve the educational content.

I have also carried a large interest in mechatronics, which I have been able to pursue both in university courses and playing with micro-controllers at home. I have also been a student and a teaching assistant in courses such as *TPK4125: Mechatronics* and *TPK4128: Industrial Mechatronics*. These courses are among those that interest me the most. However, they have problems as well, particularly the latter. It is frustrating when a course such as this does not live up to its high potential, a view that many of my co-students share, but this is then additionally motivating when working towards improving it.

0.2 Thanks and Acknowledgements

First and foremost, I would like to thank my supervisor Professor Amund Skavhaug. Thank you again for your valuable advice, for giving me the freedom to explore my own interests and intuitions, and for making yourself available for meetings or swiftly answering my questions whenever I required it. While this thesis is occasionally harshly critical of the course work in your course TPK4128, I think you should be applauded for seeking to improve it by suggesting this subject for my thesis. As I also stated in the acknowledgments of my project thesis: even though two thirds of the meetings went to digressions, the last third was triply effective. When I think back, I suspect it is actually closer to three fourths, but for me, it has been enjoyable to be able to speak about other things than my thesis as well.

Again, huge thanks to Nejc Ilc and Uroš Lotrič at the University of Ljubliana for being helpful in answering questions and allowing me to use their FTsim virtual lab. I would also like to thank Federico Lozano for helping me with the design thinking part of the project, for valuable input on my needfinding process, and for giving me helpful tips for testing. Lozano also put me in contact with Matthew Lynch and Uladzimir Kamovich, who I would like to thank for helping me navigate the uncertain terrain that is design thinking literature and finding the nuggets that are viable for citation in scientific writing. Thanks to Niklas Wik at Siemens Trondheim and the student guild Elektra for lending me PLCs, without which I would be unable to complete this work. Thank you to all the students who willingly participated in testing, interviews and much more

throughout this work, your contributions have been incredibly insightful and interesting, and this thesis would be worthless without it.

As previously mentioned I've been involved in a lot of student organizations throughout my time at NTNU. These extracurricular activities have truly been the part I've enjoyed the most about my time here, and likely what I've learned the most from as well. I would like to give my thanks to the Student Parliament, Studentrådet IV, Norsk Studentorganisasjon, A/F Smørekoppen and Studentersamfundet. There is something truly magical about Trondheim as a student city, that has given me incredibly much and I will deeply miss it as I soon leave it behind. More importantly, a huge thanks to all the co-students I've met along the way. I am deeply honored to have been able to spend my time here with so many incredibly kind, funny and intelligent people[1] Thank you to my family, particularly my sister and parents, I would be nothing without your love and support and this is something I can never fully repay.

Free access to higher education is a human right, and this along with the other aspects of the social safety net provided by the Norwegian state have been essential for me to get this opportunity, thank you to the comrades and labour movements who have fought hard for these rights throughout the years. These rights are currently under pressure, and are not in place for most of the worlds people, who are exploited and oppressed by western nations and other powers. The fight must go on to ensure a world free of oppression, where everyone has the same rights and opportunities that I have.

This thesis partly contributes to automation. The added productivity of replacing humans with machines can be used to create better and more meaningful lives for all. However, when automation is actualized in an unjust system we then see that it only further enriches billionaires and corporations at the expense of now-unemployed people.

If any future reader has any questions or wants to discuss the contents of this text, don't hesitate to contact me[2]. This particularly holds true for whoever will continue this work with TPK4128. I have also provided Amund with a google drive with additional materials that will be helpful in this regard.

[1] Except for some, you know who you are.

[2] Email: andreas.k.sund@gmail.com Telephone: 45297450

Summary

This is a master's thesis written by Andreas Knudsen Sund in the spring semester of 2022, as part of the 5th year of the Mechanical Engineering program at NTNU. It studies how practical laboratory assignments in higher education can be designed to provide the desired learning outcomes while inspiring intrinsic motivation and deeper learning. In particular, for the course TPK4128 Industrial Mechatronics, for which a new assignment has been created and user-tested using a Programmable Logic Controller and a factory training model, in addition to suggestions for how the course as a whole can be improved. This work is a continuation of the author's previous work on this subject in the pre-master specialization project *Teaching Automation with Training Models: A Pre-study using Design Thinking methodology*. Both works are based on the product development methodology Design Thinking, in which extensive user interviews, observation, and testing are used to inform the process and evaluate the result. Furthermore, the theses serve as a general examination of the applicability of these methods in creating educational content.

This thesis shows that the students are generally unsatisfied with the current course work in TPK4128 and generally satisfied with the new assignment designed with the training model. This assignment should be adopted in future course iterations and further integrated with other assignments. If correctly designed and presented, practical assignments can push students to high levels of mastery, efficiently teach them new concepts and motivate them for further learning. However, there are many pitfalls that can make them frustrating and unproductive. By basing it on the user-centered product development activities performed in this work, the produced assignment can play to the strengths of practical educational activities. The thesis can thus serve as a useful example of how course work can be improved in general, even beyond this course. This also shows that the core activities of Design Thinking and similar user-centered methodologies are valuable in creating educational content.

TPK4128 shows high potential for improvement, and many of the changes proposed in this thesis are straightforward to implement. However, there are several structural issues caused by external factors that prevent laboratory course work from reaching the desired quality. Labour is required to design,

maintain and oversee such educational activities. This necessitates human and monetary resources that are not sufficiently in place for the course, and many of the issues affecting TPK4128 stem from overworked educational staff. It is essential that the Department of Mechanical Engineering (MTP) changes its priorities regarding educational resources, as good practical assignments provide significant value, but this is difficult to achieve under the conditions currently imposed.

Sammendrag

Dette er en masteroppgave skrevet av Andreas Knudsen Sund våren 2022, som del av 5. klasse ved sivilingeniørstudiet i Produktutvikling og Produksjon ved NTNU. Oppgaven undersøker hvordan praktiske laboratorieøvinger i høyere utdanning kan bli designet slik at de oppfyller læringsmålene samtidig som de inspirerer indre motivasjon og dypere læring. Den ser spesielt på faget TPK4128 Industriell Mekatronikk, hvor en ny laboratorieøving har blitt laget og brukertestet med Programmerbar Logisk Styring (PLS) og en fabrikk treningsmodell, i tillegg til anbefalinger for hvordan faget som helhet kan forbedres. Dette er en fortsettelse på forfatterens tidligere arbeid med temaet i prosjektoppgaven *Teaching Automation with Training Models: A Pre-study using Design Thinking methodology*. Begge oppgavene er basert på produktutviklingsmetodologien Design Thinking, hvor omfattende brukerintervjuer, -observasjoner og -testing blir brukt til å informere prosessen og evaluere resultatet. Videre fungerer begge oppgavene som en generell undersøkelse av anvendbarheten til slike metoder i utviklingen av undervisningsinnhold.

Oppgaven viser at studentene generelt er misfornøyde med det eksisterende øvingsopplegget, men fornøyde med den nye øvingen laget med treningsmodellen. Denne øvingen bør videreføres i fremtidige utgaver av faget, og bør videre utvides til andre øvinger også. Praktiske laboratorieøvinger kan, hvis riktig utviklet og presentert, effektivt lære studenter nye konsepter, drive dem til en høy grad av mestring og motivere dem for videre læring, men det er også mange fallgruver som kan gjøre dem frustrerende og unyttige. Ved å basere den på de brukersentrerte produktutviklingsaktivitetene utført i dette arbeidet, lever den fremkommende øvingen opp til styrkene ved praktiske undervisningsaktiviteter, og kan dermed stå som et verdifullt eksempel for hvordan øvingsopplegg kan forbedres, også utover dette faget. Dette viser også at kjerneaktivitetene i Design Thinking og lignende brukersentrerte metodologier har stor verdi i å lage undervisningsinnhold.

TPK4128 viser et stort potensial for forbedring, og mange av de foreslåtte endringene i denne oppgaven er forholdsvis ukompliserte å implementere. Det er riktignok flere strukturelle problemer forårsaket av eksterne faktorer som forhindrer laboratorieøvingsopplegg fra å oppnå den ønskede kvaliteten. Slike

øvinger er arbeidskrevende å produsere, vedlikeholde og veilede. Dette nødvendiggjør menneskelige og monetære ressurser, som ikke er tilgjengelig i tilfredsstillende grad for emnet, og mange av problemene i TPK4128 er forårsaket av overarbeidet undervisningspersonell. Det er essensielt at Institutt for Maskinteknikk og Produksjon (MTP) prioriteter undervisningsressurser i større grad. Gode praktiske øvinger gir stor verdi, men er vanskelige å oppnå under rammevilkårene instituttet gir per dags dato.

Contents

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Acronyms

DT Design Thinking. 2, 7, 29, 30, 36, 41, 89

ILA Indexed Line Assignment. 5, 29–31, 36, 38, 45–47, 49, 51, 57, 59, 67, 76–81, 85, 86, 92, 97, 98

ILW2MS Indexed Line with Two Machining Stations training model from FischerTechnik[1]. 47, 85

LD Ladder Diagram. 21

OCW Other Course Work. 5, 29–31, 35–37, 40, 45, 46, 49, 51, 55–57, 59, 62, 66, 67, 74, 77, 81, 85–87, 92

OPC UA OPC Unified Architecture. 23, 27, 30, 38, 74, 77–79

OpenCV Open Source Computer Vision Library. 23, 74, 77

PLC Programmable Logic Controller. 15, 16, 23, 24, 28, 30, 31, 85, 86, 97

SA Scientific Assistant. 34, 53, 84

SFC Sequential Function Chart. xv, 38, 61, 63, 64

TA Teaching Assistant. 34–36, 52, 66, 69, 74

Chapter 1

Introduction

1.1 Background and Motivation

As the world continually moves towards increasing automation and Industry 4.0[2], it is paramount that there are enough engineers with the requisite knowledge and skills. This necessitates providing students with an understanding of the automation environment, the equipment and processes involved, the embedded control systems, and the IT systems that allow them to communicate[3]. This involves learning the requisite theory and current state-of-the-art through lectures and learning resources. However, it is also desirable that the acquired skills are practicable in real-life contexts, necessitating that students do practical work where they interact with the equipment they learn about.

Education can be viewed in terms of the product developer being the ones who devise and deliver the learning activities and the user being the students attending a given course or education. Inherent to this context is a large variance among the users. Individual students learn differently and have idiosyncratic backgrounds and knowledge bases. There is also a large gap between the providers (largely educators) and the users (students), both in terms of knowledge and experience and in terms of predispositions and preferred ways of learning. The landscape of university education is fast changing. Age cohorts have cultural differences from one another. Technological developments influence both the way students learn and what they need to learn. This raises the need of continuously evaluating, reevaluating and evolving the content and execution of the education. Moreover, it means the educator will be unable to understand the needs and learning methods of the users without leaving their desk to interact with them. One framework for doing this is Design Thinking. It is a product development methodology containing a set of methods ensuring that the product fits its intended users.

There is much published work about how to teach Design Thinking[4][5][6], but little to be found about applying it in the creation of educational content.

This was explored in the author's pre-masters project thesis, "Teaching Automation with Training Models: A Pre-Study using Design Thinking methodology" (Appendix B), which stated:

> "This serves as an interesting frontier for exploration, and the hypothesis of this text is that Design Thinking is indeed valuable for this purpose. This thesis contributes by exploring how educational activities of this kind can fulfill the desired learning outcomes by better understanding users and the problem at hand."

This hypothesis was to a significant degree confirmed, and it was suggested that user-centered methodologies see continued use in future work with the subject. DT is indeed used in this master's thesis, with an extended selection of activities employed to further this exploration.

The project thesis also served as a pre-study for creating an assignment for the course TPK4128 Industrial mechatronics[7] using an Indexed Line with two Machining Stations training model from FischerTechnic[1]. In this master's thesis, this assignment is created and tested with students. However, working as a teaching assistant in the course, it quickly became evident that many of the insights gained in developing this assignment were generalizable to similar assignments and that the remaining course work had significant room for improvement. This led to an expansion of scope to provide tools to improve the course work in TPK4128 as a whole. It is more conducive to overall educational quality to look at the entire course context and not assignments individually, considering that all elements of the course work interrelate to create a nexus of student learning outcomes.

While the previous project thesis explored whether Design Thinking could produce interesting results and applied those results in making suggestions for educational activities, it has little discussion on whether this corresponds to theory. This master thesis thus explores relevant literature on the factors influencing engineering students learning approach and motivation. The assumption is that the course should instill intrinsic motivation in the students, as this is conducive to a deep learning approach[8]. In the ever-changing world of industry, the students must have the requisite knowledge foundation and the impulse to continually renew this knowledge. Practical assignments like the course work herein discussed have been found to entice this motivation if properly employed[9].

1.2 Problem Description

In general terms, the goal of this master's thesis is to provide a foundation for improving the course work in the course TPK4128 Industrial Mechatronics[7].

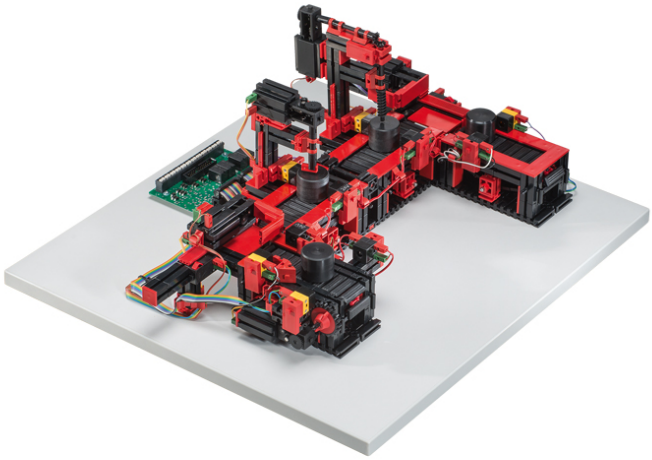


Figure 1.1: The Indexed Line With Two Machining Stations from fischertechnik GmbH[1]

Initially, the scope was limited to creating a new laboratory assignment(s) using a factory training model based on the author's previous work in the project thesis, see Appendix B. However, the nature of this product development method entails that the problem description, requirements, and implementation components constantly evolve throughout the project period, in fact, this is where its strength lies.

The objectives of this master's thesis are to:

- evaluate the course work in the course TPK4128 Industrial Mechatronics, and explore how it can be improved.
- use Design Thinking principles and methods in this process.
- extract insights and user information from user interviews, testing and field observations as a teaching assistant.
- informed by the Design Thinking process and previous work (Appendix B) create a new assignment using the "Indexed line with two machining stations" training model from fischertechnik[1](Figure 1.1) and Siemens Simatic S7-1500. The resulting assignment should provide students with the desired learning outcomes concerning teamwork and competence with automation, PLC control and industrial computer systems. It should be engaging while doing so and inspire further learning. It should also answer faults identified in the other assignments of the course.
- evaluate the success of this assignment through extensive user testing with students, exit interviews and a questionnaire. Describe how the as-

signment can be further improved and how it can be implemented in practice in future iterations of the course.
- describe strengths and faults in the existing course work, and give suggestions as to how it can be changed, and prospective avenues for future work.
- serve as a general exploration of what makes practical assignments educational and motivating. Where possible, make suggestions generalizable to designing other similar assignments.
- identify structural roadblocks preventing the implementation of course work as desired.
- serve as an evaluation of whether Design Thinking is a viable framework for creating educational activities.
- discuss possible shortcomings of the performed work and identify what remains to be done.

1.3 Thesis Structure

Chapter 2 introduces Design Thinking, learning approaches, the course contents, previous work, and the technology used.

Chapter 3 details the development process, the methods used, and how they were executed.

Chapter 4 describes the implementation of the assignment and provides suggestions for how the remaining course work can be improved. Additionally, it explains the basis of this implementation, the testing results, user feedback and insights from the Design Thinking process.

Chapter 5 evaluates the work, its viability, and external factors that can affect it. Finally, it includes a conclusion.

Chapter 6 provides possible actions of future work in a separate chapter to make it readily accessible.

Appendix A contains iterative versions of the assignment designed and tested in this work.

Appendix B includes the author's previous work in the project thesis, "*Teaching Automation with Training Models: A Pre-Study using Design Thinking Methodology*".

As this master's thesis is a continuation of this work, some of its contents are reused. In particular, parts of the text about Background, Design Thinking, Programmable Logic Controllers, Indexed Line, and Previous Work in Chapter 2, along with parts of the descriptions on Design Thinking activities in Chapter 3 and some of the points in the above problem description. Individual sentences are sporadically reused for the remainder of the text but will generally be referred to in quotations. The supervisor has approved this reuse of material.

While it might certainly be helpful in getting a comprehensive understanding of this work, the reader is not required to read the project thesis to understand this master's thesis, as relevant information will be quoted when necessary.

The assignment designed with the Indexed Line and the other course work in the course is often discussed simultaneously. To prevent confusion, two main designations will be used. Indexed Line assignment (often abbreviated ILA) denotes the new assignment being made with the training model from Fischer Technik. Other course work, current course work, or remaining course work (abbreviated OCW) will be used to denote the course work currently in the course in its current or changed form, excluding the ILA. The words assignment and exercise will be used interchangeably to refer to a set of tasks making up a deliverable for the students. Course work denotes a set of multiple such assignments, making up the sum of deliverable work in a course.

Chapter 2

Theory

This chapter provides the background information about Design Thinking, learning approaches, TPK4128, previous work and technologies necessary to understand the work in this thesis.

2.1 Design Thinking

In traditional product development, it is common to start at the solution stage. Most of the time is spent implementing the technical solution to a problem. This is acceptable in cases where the problem and user requirements are well-established. However, the developers may have preconceived notions of the users and problems that are incorrect. Furthermore, when traditional product development teams engage in user research, they often employ methods like surveys and focus groups, which are suitable for selecting among preexisting solutions. However, these inflexible quantitative methods are unfit for acquiring the unspoken needs that customers are unaware of or that do not yet exist[10]. Design Thinking is a methodology of User-Centered Product Development that addresses this. By observing, interviewing, and testing with users and then analyzing this qualitative information, DT ensures that one reliably acquires a correct understanding of the user needs and the problem at hand. It also increases the probability that the team will come across innovations.

In a Design Thinking process there will be sequential iterations of convergent and divergent stages, as shown in Figure 2.1. The divergent processes expand on the solution space and explore. The convergent processes take into account boundaries, limitations, and values and narrow down[11]. In Figure 2.2a Beckman and Barry [12] describes the innovation process as first gathering user information, making sense of it, identifying the needs to be addressed, then creating potential solutions. Figure 2.2b further expands on the activities inherent to these stages and their respective suitable learning styles. The Stanford d.school process proposes five essential activities of design thinking, these

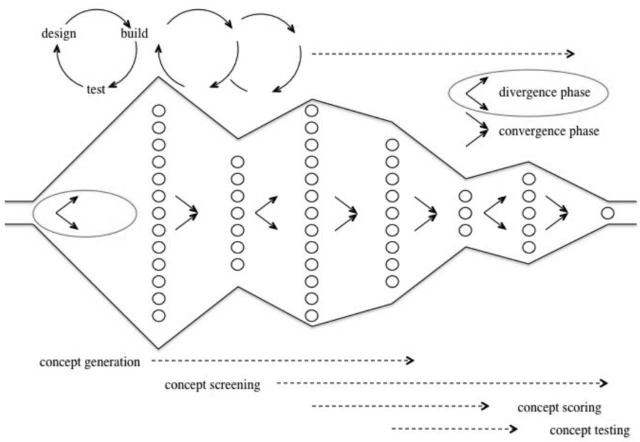


Figure 2.1: Design process as iterative cycles of divergence and convergence steps[11]

being "Empathize, Define, Ideate, Prototype, Test"[4][13]. Beckman's description is more rigorous than the Stanford d.school description of the process, which is more practicable for in-field application of the methods. They both have their strengths and will be discussed in parallel.

2.1.1 Needfinding

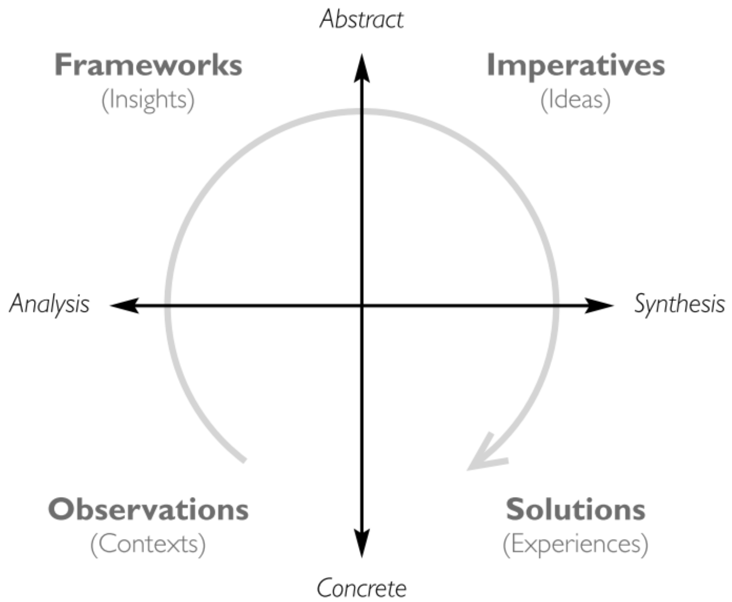
Needfinding is a central concept to Design Thinking. This is the activity of actively seeking to find and characterize the needs of potential users. The best way of solving something is clearly understanding the nature of the problem and the needs it gives rise to. While never specifically mentioning Design Thinking, *Needfinding: The Why and How of Uncovering Peoples Needs* by Patnaik and Becker perfectly encapsulates a lot of the principles and activities central to it while also providing the reasons for using them[10]. They list the central principles of Needfinding, some of which are:[10]

- Look for needs, not solutions
- Go to the customer's environment
- Look beyond the immediately solvable problem
- Let the customer set the agenda
- Iterate to refine the findings

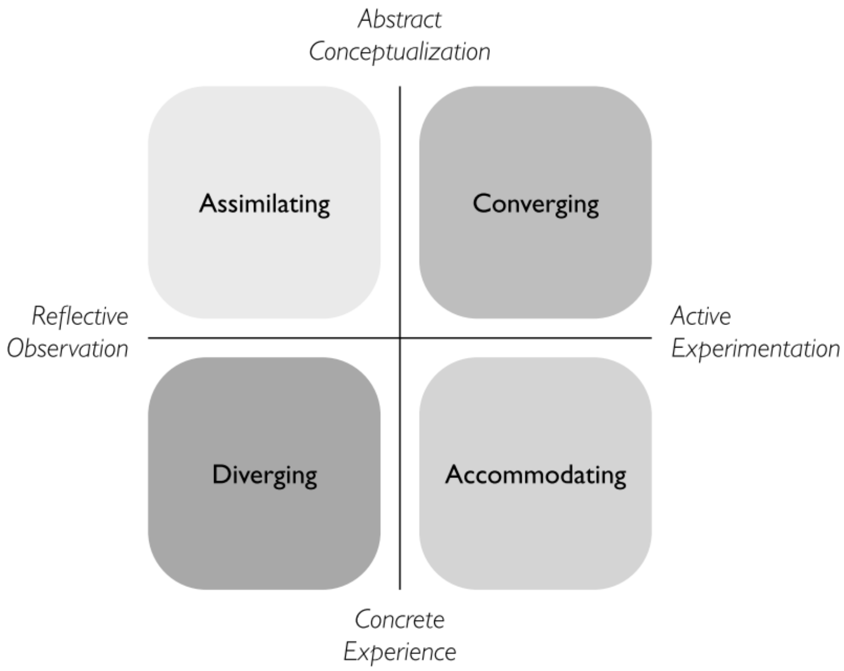
These principles and the activities they warrant will be part of the basis for the work done in this thesis.

2.1.2 I: Observation

In Design Thinking, getting a deep understanding of your users, how they would use your product, and the context in which they engage with it is para-



(a) Innovation process [12]



(b) Learning Styles [12]

Figure 2.2: The innovation processes of design thinking and corresponding learning styles[12]

mount. It is important to engage a wide variety of users[1]. This is a divergent process, respectively described as **Observations** and **Empathize** by Beckman and Stanford d.school. A plethora of different Needfinding activities can be conducted in this phase, consisting of participant and non-participant observation, interviews, and more. One should strive to get at the contradictions between what people say and do, subconscious actions they are unaware of, and information about the context of use that would appear illogical or non-obvious without getting into the field. This entails asking "why" of yourself when observing and the user when conducting interviews. Beckman and Barry [12] state the importance of understanding user needs at the levels of "use, usability and meaning", suggesting that meaning-based needs are the most important for radical innovation and writing: "*Those meaning-based needs are only uncovered as the researcher continues to probe, deepening his or her understanding of the user's thinking about the innovation and its use context.*"[12]. Stanford d.school [13] and Kelley and Kelley [14] describe tools and methods for this which will be applied in Chapter 3.

2.1.3 II: Sense-Making

After collecting sufficient information about users and use context, the next step is to create **Frameworks** or **Define**. Important insights are extracted from the user information. Framing is done by identifying patterns, idiosyncrasies, and interesting nuggets and putting them in system. Most importantly, the innovator identifies the faults, lacks, and pain points from this framework, giving rise to needs that lay out the possible areas of innovation and improvement to expand upon.

2.1.4 III: Synthesis

At this point, the identified framework should be synthesized into a value proposition or a set of **Imperatives**. This entails converging on the goals and needs to be met by the innovation. The stages in the d.school model do not map one-to-one with the Beckman and Barry model of Figure 2.2a. **Define** spans both **Frameworks** and **Imperatives**. **Ideate** is at the junction between **Imperatives** and **Solutions**, when the team diverges upon potential solutions.

2.1.5 IV: Solutions

Moving into the final quadrant, **Solutions**, various concept generation techniques should be employed to create answers to the imperatives. The concepts are narrowed down to a few avenues of exploration one finds valuable to **Test**.

[1]Including extreme users. Users on the outskirts of the bell curve will have amplified needs that are easier to identify and often translatable to the average user or provide possible niches for innovation[10][12][13][14]

In order to conduct a test, a **Prototype** is needed. The prototype is not required to be a near-complete implementation of the product[2], but should be tailor-made to test specific uncertainties that the team has identified[16]. In the words of IDEO's David Kelley "*Prototypes are designed to answer questions*"[15]. After testing with users, the insights can be used to refine the solution further. Elverum and Welo [17] propose the concepts of directional and incremental prototyping, the former assessing major design choices for the type of solution, the latter continuously addressing sub-problems once a decision has been made based on the first.

2.1.6 Innovations Teams and Learning Styles

Design Thinking literature often states the benefit of working in teams, ideally inter-disciplinary ones[4][5][6][12]. Beckman and Barry [12] stresses the importance of different learning styles being present in the team[3]. The learning styles are provided in Figure 2.2b and relate to corresponding quadrants in Figure 2.2a. The dominant learning abilities for the individual styles are the bordering axes. For instance, abstract conceptualization and reflective observation are the activities of the assimilating style. It is suggested that all members take part in every phase, but that the team member with the fitting learning style takes the lead[12]. The key takeaway is that having different perspectives and predispositions is valuable to an innovation team and that one should play to the strengths of individual team members in the befitting sub-processes.

2.1.7 Additional Comments

The stages described for Design Thinking are not meant to be followed strictly in order like in, for example, the waterfall method. Instead, it is a set of processes and activities that aid product developers in identifying and meeting user needs. Different situations necessitate different measures. More time might be spent in some stages than others, the stages might be taken in a different order, and so on. However, Beckman states that teams who only go through one-or-two stages generally perform worse than those who progress through all. Furthermore, teams that go through the stages several times perform even better[12]. The process often entails iterative cycles of repeating the stages[11].

[2]Furthermore, Schrage [15] point out the many pitfalls of having prototypes of too high fidelity. This takes more time, prohibits some experimental activities, and can, in organizations, cause conflict between departments.

[3]It is possible to do design thinking alone, albeit not as effectively. It is unlikely for a team of one to possess all learning styles, meaning that a one-person project might be lacking in certain phases

2.2 Quality in Learning: Deep and Surface approaches

It is generally accepted that it is desirable for students to acquire an integrated understanding that enables them to view the involved concepts and ideas as a whole and independently reflect on them beyond rote memorization of the subject matter. This has been shown to provide a greater degree of long-term recall of the subject matter and inspire further learning after the course is finished, ensuring that acquired knowledge is useful in further studies and work-life. This has been described by Gibbs [8] and others as a **deep approach** to learning, writing "*the student attempts to make sense of what is to be learnt, which consists of ideas and concepts. This involves thinking, seeking integration between components and between tasks, and 'playing' with ideas.*".

Contrary to a deep approach is the **surface approach** to learning, where "*The student reduces what is to be learnt to the status of unconnected facts to be memorized. The learning task is to reproduce the subject matter at a later date (e.g., exam)*"[8]. While a surface approach to learning is viewed as less desirable, it is by a large margin the one most commonly taken by students, partly because of assessment systems not rewarding a deep approach and other factors which will be discussed below[18][9]. Rowe [19] also describes a **strategic approach**, which is similar to surface with the addition that they are motivated to earn the highest possible grades, tailoring their education around this. As they are largely overlapping, they will be collectively be denoted by surface throughout this text.

2.2.1 Intrinsic and Extrinsic motivation

Central to this dichotomy is the manner in which students are motivated. How mode of motivation is related to the learning approach as framed by Savage *et al.* [9] is shown in Figure 2.3. **Extrinsic motivation** is typically related to a surface approach in that students pursue success in external assessment criteria, performing the learning activities in the manner they view as conducive to achieving these goals. **Intrinsic motivation** on the other hand, is deeply connected to a deep approach in that students are, to put it plainly: motivated by the desire to learn. Similar to the complementary approaches, extrinsic motivation is more common. However, there is much that educators can do to foster intrinsic motivation and thus a deep learning approach in students, with positive outcomes in student ability[20][18][19]. Students can have both extrinsic and intrinsic motivation simultaneously, and this can be positive[21]. Extrinsic motivation will always be there because students will be motivated to finish their degrees, but the intrinsic motivation must be fostered. The challenge is then to increase intrinsic motivation without simultaneously increasing extrinsic motivation[18].

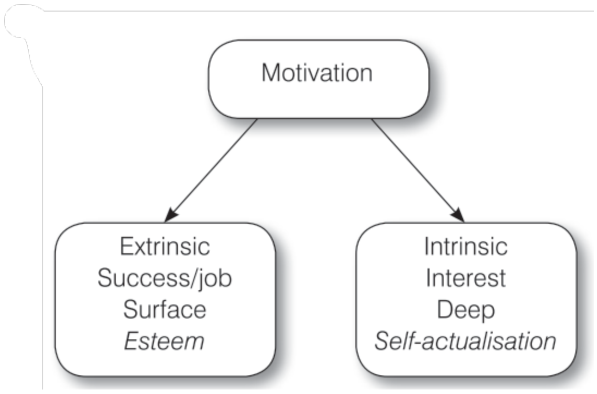


Figure 2.3: Framework for motivation as it relates to learning approaches from Savage *et al.* [9]

2.2.2 Course characteristics influencing learning approach

Based on a wide variety of studies, Gibbs [8] identifies six course characteristics commonly associated with surface approaches, as seen in Table 2.1. The degree to which these characteristics will produce negative consequences is likely based on other contextual factors, meaning that a course with one or more of these characteristics is not inherently unable to produce a deep approach. Points 1-3 speak to overloading the capacity of students, which leads them to focus on what is necessary to pass, not allowing time to reflect on the material. Points 4-5 speak to how the course provider constructs the course and what opportunities they provide. The final point speaks to the assessment system, which has generally been found to be the main driving force behind the surface approach as it is by nature an extrinsically motivating factor.

Table 2.1: Course characteristics associated with a surface learning approach[8]

1. A heavy workload
2. Relatively high class contact hours
3. An excessive amount of course material
4. A lack of opportunity to pursue subjects in depth
5. A lack of choice over subjects and a lack of choice over the method of study
6. A threatening and anxiety provoking assessment system

In addition to avoiding course design that promotes a surface approach, the course should additionally be designed to promote a deep approach. Biggs [22] suggests four elements that determine the degree to which educational activities are likely to produce a deep approach, which can be seen in Table 2.2.

Table 2.2: The four key elements suggested by Biggs [22] to promote deep learning.

1. Motivational Context:	Intrinsic motivation is necessary to foster deep meaning. The course should be designed such that students have independence to chose how and to an extent what they learn (ownership). The surrounding context is also important, including the culture and climate of the class and the degree to which experienced pressure from assessment systems and time constraints is limited.
2. Learner activity	The students need to be active. Quoting Gibbs [8] interpretation: "If the learner is actively involved, then more connections will be made both with past learning and between new concepts. Doing is not sufficient for learning, however. Learning activity must be planned, reflected upon and processed, and related to abstract conceptions."
3. Interaction with others	The student need to discuss the meanings of ideas and solutions through interaction with fellow students.
4. A well-structured knowledge base	Students can not learn new concepts without relating them to existing concepts. This speaks to the need for learning the course material in integrated manner, not with individual concepts viewed in isolation, which requires that the subject matter is well structured in order to display it holistically.

Based on these key elements, Gibbs [23] provides 9 strategies for fostering a deep approach[4], which are exemplified by case studies throughout the book:

1. Independent learning
2. Personal development
3. Problem-based learning
4. Reflection
5. Independent group work
6. Learning by doing
7. Developing learning skills
8. Project work
9. Fine-tuning[5]

These strategies are somewhat overlapping, meaning that employing one neither necessitates nor excludes the others. All strategies contain one or more of the key elements. Another thing most of them have in common is that they entail practical work. Savage *et al.* [9] also finds that practical assignments are important to instill intrinsic motivation and thus a deep learning approach in students, further stating the need for these assignments to be viewed as "relevant to the real world". Vansteenkiste *et al.* [21] further finds "*Presenting tasks that are consistent with satisfaction of basic psychological needs (whether via the content or context of the task) led to positive learning-related outcomes.*", indicating the importance of learning activities to engage with the student on a human level, through being profound, experienced mastery, playing to their interests or simply being enjoyable to perform.

[4]NB! Gibbs and Biggs are two different authors, something that might be easy to miss considering the similarity of their names.

[5]"Fine-tuning" refers to the idea that these strategies do not necessitate radical changes to taught courses, and that moderate modifications can have a significant effect in inspiring a deep learning approach, particularly changes pertaining to increased motivation.

This indicates that the practical course work which will be analyzed throughout this thesis is conducive to inspiring a deep approach. However, including the key elements in Table 2.2 or Gibbs' strategies does not automatically produce deep learning outcomes. It is entirely dependent on how they are implemented, the surrounding context, and other elements which might antithetically inspire surface learning.

2.3 Programmable Logic Controllers (PLC)

Programmable Logic Controllers (PLCs) are ruggedized, single-processor, computer-based devices that are frequently used in production settings[24][25]. Their high reliability in controlling industrial equipment in harsh environments has made them central to modern production facilities and automation. With multiple PLCs working together or along with other computerized equipment, it can be used to control a whole automation system. They are highly modular, lending themselves to be adapted to different environments, for example, a higher temperature range or a large number of inputs. They are efficient in sequential control and have many opportunities for fault detection and diagnosis. PLC can be programmed with accessible logic control languages, which means it does not require advanced programming knowledge from operators. The main architecture of a typical PLC-system is given in Figure 2.4. The central processing unit (CPU) is the most important part containing the programming instructions, interpreting input signals, and executing control actions based on these and the programming. The power supply unit converts AC mains power to DC, supplying the CPU and the I/O modules. These are typically connected to the same rack, working as a mounting mechanism and supplying backplane power.

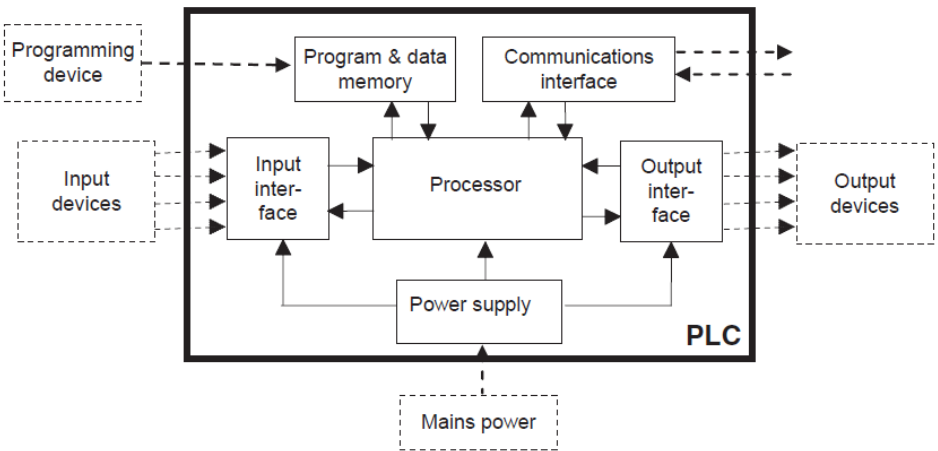


Figure 2.4: The PLC-system [25]

2.3.1 PLC for Indexed Line assignment

The PLC used for this assignment will be a Siemens Step 7 1500 series[26]. In addition to the main CPU and power supply, a combined I/O module or individual output and input modules are required. These should supply 24V DC to operate on the same voltage as the training model[1], and have a minimum of 9 and 10 ports, respectively. Programming will be done through the Siemens Totally Integrated Automation (TIA) Portal V17, uploading on the Profinet protocol by Ethernet from a PC[6]. Newer editions of the S7-1500 contain support for the OPC Unified Architecture (OPC-UA) Protocol[7]. The PLC used in the master's thesis period is provided in Figure 2.5, as seen in the device view of TIA portal and marked in post with exact model numbers for the components.

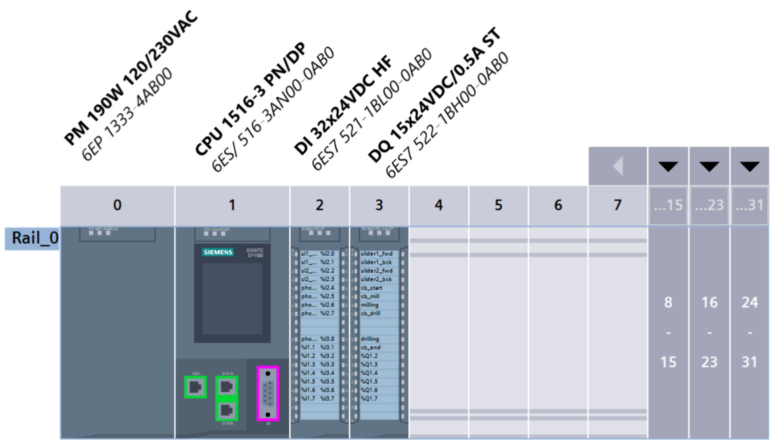


Figure 2.5: The Siemens Programmable Logic Controller used in this masters thesis, with a power supply, S7-1500 CPU, digital input and digital output modules[26]

2.3.2 Siemens TIA Portal

The world of PLCs has become more and more proprietary, meaning that you are required to use Siemens' software, TIA portal V17, to interface with the equipment. Using other PLC programming software such as Codesys or GX-Works[28] is not possible. The Totally Integrated Automation (TIA) portal provides the necessary tools to program Siemens PLCs with corresponding modules, safety functionalities, and much more. Furthermore, it can simulate virtual PLCs using the PLCsim software[29].

[6]Profinet (Process Field Net) is a standard for industrial data communications over Ethernet[27]

[7]Actually, it is the firmware that decides whether or not it is supported, but older models can not update to the newest firmware.

2.4 Indexed Line With Two Machining Stations

The *Indexed Line With Two Machining Stations* is part of a series of miniature educational factory-line training models from *fischertechnik GmbH*, see Figure 1.1. It features a U-shaped factory line with conveyor belts and pushers to provide translation, pushbuttons, and phototransistors to measure position, and a milling and drilling station to simulate the processing of the workpiece[1].

The Indexed Line requires a 24V power supply, although there exists a 9V version as well[1]. It has 9 digital inputs consisting of 5 NPN phototransistors and 4 pushbuttons[8]. There are also ten 24V outputs, all DC motors, controlling a milling station, drilling station, 4 conveyor belts, and the backward and forwards operation of two sliders. The location of the inputs and outputs is given in Figure 2.6 with reference to Table 2.3.

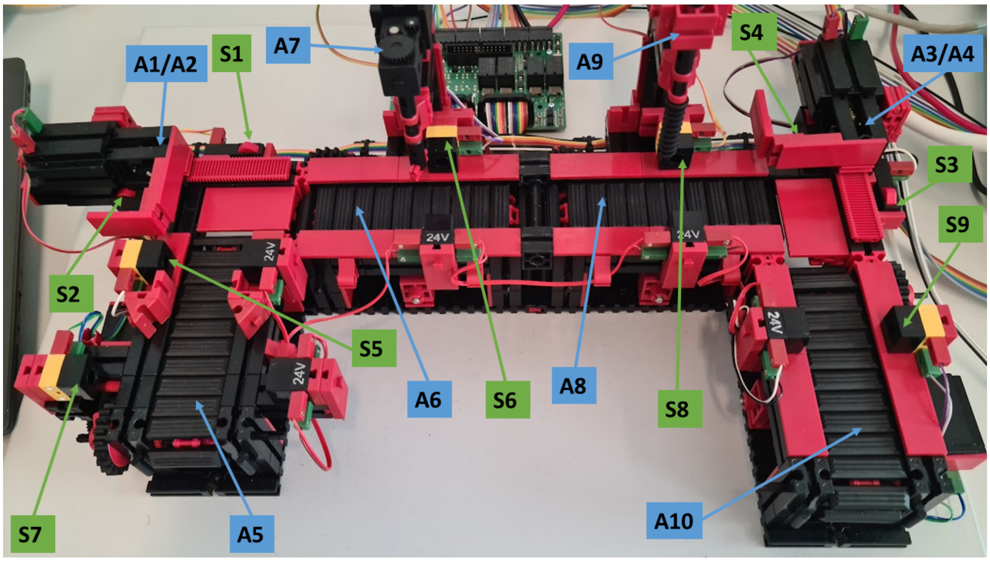


Figure 2.6: Inputs and Outputs of The Indexed Line With Two Machining Stations[1], with reference to Table 2.3

[8]Pushbuttons can operate in both normally-closed (NC) and normally-open (NO). Phototransistors are NC.[1]

Table 2.3: Terminals of the Indexed Line With Two Machining Stations Stations training model from FischerTechnik[1]

Terminal No.	Function	Input/Output
1	Power supply (+) actuators	24V DC
2	Power supply (+) sensors	24V DC
3	Power supply (-)	0V
4	Power supply (-)	0V
5	Push-button slider 1 front	S1
6	Push-button slider 1 rear	S2
7	Push-button slider 2 front	S3
8	Push-button slider 2 rear	S4
9	Phototransistor slider 1	S5
10	Phototransistor milling machine	S6
11	Phototransistor loading station	S7
12	Phototransistor drilling machine	S8
13	Phototransistor conveyor belt swap	S9
14		NC
15	Slider 1 forward	A1
16	Slider 1 backward	A2
17	Slider 2 forward	A3
18	Slider 2 backward	A4
19	Conveyor belt feed	A5
20	Conveyor belt milling machine	A6
21	Milling machine	A7
22	Conveyer belt drilling machine	A8
23	Drilling machine	A9
24	Conveyor belt swap	A10

2.5 Previous work

2.5.1 Project thesis

This master thesis is a continuation of the author's project thesis *Teaching Automation with Training Models: A Pre-Study using Design Thinking Methodology*, from the autumn semester of 2020. The project thesis can be viewed in its entirety in Appendix B. References will be frequently made to it, and some text in this master thesis is adapted from it.

Scope

The original task for the thesis was to make an assignment with the Indexed Line. However, delivery delays meant that no models would be available for the project duration. This led to a pivot to a more conceptual pre-study, aiming to serve as a foundation for how such an assignment could be made. A design thinking methodology was adopted, aiming to gain an understanding of the students and how best to engage them and promote learning. It also explored the viability of Design Thinking as a framework for creating educational activities in general, aiming to make whatever insights, results, and suggestions discovered generalizable beyond the Indexed Line assignment. Concluding that:

> "The application of Design Thinking methodology in finding user needs and generating ideas for a laboratory assignment has been largely successful. A substantial gap between the product developer (educator) and user (student) is inherent to higher education, and thus measures need to be taken to bridge that gap, ensuring an understanding of what best provides students with the desired learning outcomes. Design Thinking is one possible framework for this, and the process therein has been described in this text such that it can be applied in future work with this assignment as well as by others wishing to create educational content pertinent to how their students learn. Regardless of design thinking, a bare minimum of testing with students is decidedly beneficial."

The activities performed consisted mainly of design thinking interviews, testing with the FTsim tool (described below), and various other needfinding methods. As there was a one-year hiatus between the theses, it was unsure who would continue the work with the Indexed Line assignment, so it was ensured that it was written so that any student, educator, or Ph.D. with sufficient background knowledge could finish the work.

Derived suggestions

This process resulted in a set of suggestions for further progression with the assignment, which are provided below. The project thesis is not required reading to understand this thesis. However, reading the descriptions for these suggestions in the results chapter of Appendix B is recommended.

Suggestions for the general structure, context, and execution of the assignment:

1. Introduce with a simple "Hello World"
2. Make it analogous to actual factory situations
3. Make causality apparent
4. Errors should be personal errors
5. Make it foolproof
6. Continue employing design thinking methods, preferably as a team
7. Don't introduce too many concepts at once
8. Limit group size to at most three, preferably two

Suggestions pertaining to the assignment text, and the theory provided in it and the surrounding course.

9. Introduce the relevant concepts and background theory beforehand
10. Ask the students to prepare, but in moderation
11. Provide required actions in a step-by-step structure
12. Include a feedback option
13. Provide a list of common errors

Additional possibilities for the implementation, depending on whether or not it is feasible based on both available time for the implementer and the students capabilities in the allotted time for the assignment:

14. Look to other modes of logic control
15. Have two training models interact
16. Create a virtual lab/digital twin
17. Control the training model remotely
18. Store the equipment in a proprietary container
19. Install stop-button and indicator-lights on the training model
20. Extend the monitoring data

NB! In later chapters, these suggestions will be frequently referenced. This will be done by relaying them in bold and italic. An example: "A decision was made to delay this to a later assignment in order to focus on the main concepts at hand. ***7) Don't introduce too many concepts at once(Section 2.5.1)***".

2.5.2 Work by others

There are other examples of using the Indexed Line or similar equipment in higher education. Gil *et al.* [30] describes the use of the Indexed Line to teach Industrial Automation students at the University of Zaragoza. Along with a physical lab where students interact with the Indexed Line, they create a virtual lab in which students interact with a digital copy. The aim is to teach students

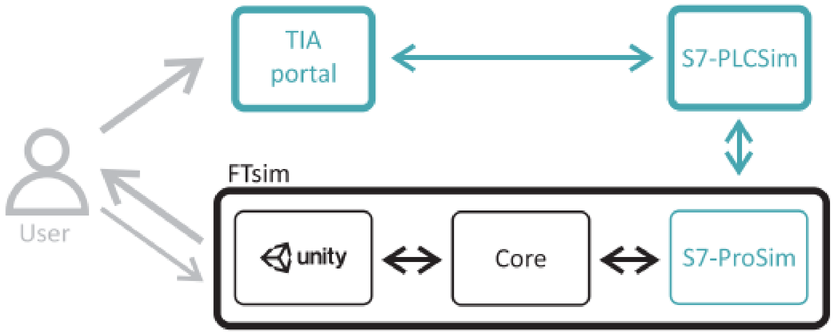


Figure 2.7: The architecture of FTsim, the virtual lab training model by Ilc and Lotrič [32]

Ladder Diagram (LD) control with PLC. They write "*The main conclusion is that the developed VL allows online students do the same practical training than face-to-face students.*" However, they admit that they have not yet tested it, but they plan to do this for future work. Gensheimer *et al.* [31] use several different FischerTechnik training models in concert in order to teach object orientation, reporting high student satisfaction and suggesting the equipment should be expanded to further use.

FTsim Ilc and Lotrič [32] have created the 3D simulator FTsim which mimics the behavior of three distinct FischerTechnik training models, including the Indexed Line. They use the Fischertechnik equipment in a course teaching process automation and control, and state that "*The main idea of the course is to familiarize students of computer science with concepts of automation with a focus on PLC programming and integration with the higher-computer science with concepts of automation with a focus on PLC programming and integration with the higher-level systems.*" They observe that the use of the training models additionally motivates the students, all though limited time with the physical training models produces the need for the digital simulators such that students will have enough time to learn PLC control properly. The student feedback for the FTsim and the physical lab has been positive, leading them to conclude that this is a valuable learning resource. The architecture of FTsim is given in Figure 2.7. The students set up their PLC and programming blocks in TIA Portal, simulating the PLC with PLCSim, the S7-ProSim interface creates Component Object Model (COM) objects, establishing communication between PLCSim and the C# scripts underlying the Unity-based[9] FTsim executable (Figure 2.8).

[9]Unity is a widely used video game engine.[33]

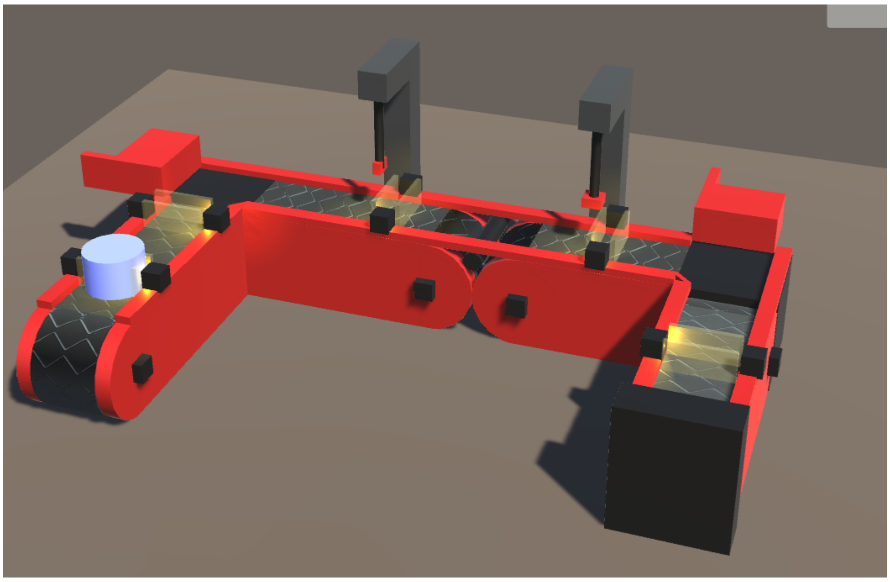


Figure 2.8: FTsim, the virtual lab of the training model by Ilc and Lotrič [32]

2.6 Course Work background theory

In Section 2.7.2 the existing course work in the course TPK4128 will be presented, which will be discussed in detail later. It is then necessary to provide a brief overview of the technology involved.

2.6.1 Raspberry PI

Raspberry PI (RPi) is a collection of lightweight single-board computers, popular for professional, hobby, and educational uses[34]. As they are small, low-cost, and highly modular while still providing extensive functionality. The models range from the main series (including the RPi 4 used in this course), providing full computer functionality with HDMI and USB ports and 4-8GB RAM, to the more minute and cheaper RPi PICO with 264KB RAM intended for physical computer systems. The Raspberry PI Foundation and many third-party vendors produce a variety of software and accessories, giving the RPi extended functionality such as sensor boards, cameras, additional inputs, operating systems, and more.

2.6.2 Linux

Linux is an open-source Unix-like operating systems kernel, originally developed by Finnish programmer Linus Torvalds in 1991, that gives host to a family of many different operating systems[35]. These operating systems are normally provided along with a package management system and named Linux distributions. Because of its flexible and open-source nature, there are a wide variety of Linux distributions tailored for different uses and systems, from home computers, to embedded computer systems in cars, smart refrigerators, factory automation, and more. Popular distributions include Ubuntu and Debian.

VirtualBox

In this course, students will typically not install a Linux Distribution directly on their personal computers but instead run it through a virtual machine with the VirtualBox software from Oracle[36]. This allows them to emulate a virtualized Ubuntu Linux distribution, making it easier to perform operations with C in the terminal than in Windows/macOS and abstracting the consequences of memory leaks from their programming.

RaspberryPI OS

Raspberry PI OS is an operating system based on the Debian Linux distribution[37]. It is made by the Raspberry PI Foundation and tailor-made for the RPi, giving it the functionality of a desktop computer, running smoothly and easily installed with the Raspberry PI Imager. It was formerly known as Raspian. While students will be using RPi OS in TPK4128, it is fully possible for users to create custom Linux kernels as well.

2.6.3 OPC UA

The Open Platform Communications Unified Architecture (OPC UA) is an open-source information model defined by the IEC62541 standard and developed by the OPC foundation[38]. It is used for data exchange in industrial applications between a large variety of different hardware platforms and operating systems, acting as servers and clients. By serving as a common language, it simplifies interfacing these different systems. For example, a central computer can seamlessly communicate with multiple in-field PLCs, computers, and sensors from different manufacturers using different fields-busses.

OPC UA has available application programming interfaces (API) for a variety of different programming languages. Common examples include C/C++, Java, .NET, Python, and tickle/tcl. In the current version of TPK4128, students will use topcua, which binds tcl to the C-based opensource OPC UA implementation Open62541[39]. However, if they are to interface Siemens PLCs with OPC UA, this will likely be done with .NET programmed in C#.

2.6.4 OpenCV

Open Source Computer Vision Library, commonly known as OpenCV, is an open-source programming library originally created by Intel[40]. It provides various tools primarily aimed at aiding computer vision and is commonly used for this purpose. While OpenCV is originally written in C++, there exist bindings to other languages such as Python, MatLab, and Java. The Python OpenCV package is the implementation used in the course work of TPK4128.

2.6.5 ROS

Robotics Operation System (ROS) is an open-source programming suite, originally developed by Open Robotics along with Stanford[41]. Contrary to its name, ROS is not an operating system but instead middleware providing tools and software libraries beyond the capability of the underlying OS it is installed on, aimed at software development for robotics. The most commonly used version is ROS2, having significantly extended functionality from the original ROS1. In TPK4128 ROS2 is used and written in Python.

2.7 TPK4128 Industrial Mechatronics

Industrial Mechatronics (TPK4128) is a course taught primarily to Mechanical Engineering students at the Norwegian University of Science and Technology (NTNU).[10]. The lab assignment(s) discussed in this text are intended to be used in this course, with the possibility of a slightly altered form being used in the introductory course Mechatronics (TPK4125).

2.7.1 Desired Learning Outcomes

The desired learning outcomes, as stated on the university website, are provided in Table 2.4

Table 2.4: Desired learning outcomes of TPK4128 Industrial Mechatronics as stated on the university website[7]

Knowledge	Design and programming of PLC, single board computers and other computer systems for use in industrial computer control systems, as well as in embedded- and mechatronics system in general.
	Methods for interconnecting systems and components using networks, bus systems and electronics.
	Specification and use of interfaces and protocols. Sensors, actuators, power supplies and motor drives.
Skills	The course shall give skills in design, implementation and programming of industrial computer systems, such as single board computers and PLCs, with the associated computer networks, sensors and actuators.
General Competence	The course shall give competance in industrial and embedded computer systems, PLC systems and mechatronics.

[10]This includes certain specializations of the 2- and 5-year Mechanical Engineering (MIPROD, MTPROD) study programs, but also Engineering and ICT(MTING) students who have selected the Mechanical Engineering specialization.

2.7.2 Course Work

This section describes the course work in TPK4128 Industrial Mechatronics as it was in the spring semester of 2022. Table 2.5 provides a slightly altered version of the semester plan as presented to students in Blackboard.

Table 2.5: TPK4128 Industrial Mechatronics course plan for the spring 2022 semester as presented to students in blackboard

#	Date	Topic(s)	Assignment
1	10. jan	Industry 4.0	1: Virtual machines + Linux
2	17. jan	Industry 4.0 / Computer systems	2: C - refresh
3	24. jan	Computer systems / Operating systems	3: Basic tools
4	31. jan	Operating systems / Scheduling	4: Concurrency
5	07. feb	Real-time systems / (C programming)	5: Memory, errors and time
6	14. feb	Networks in general /Linux	6: Linux on RB pi + finish 1-5
7	21. feb	Networks	7: TCP/Ip - sockets
8	28. feb	OPC UA	7: Finish tcp/ip + 8: Start OPC/UA
9	07. mar	Python programming / ROS (Lars Tingelstad, recorded + zoom)	8: continue OPC/UA
10	14. mar	Robot Operating System (ROS) (Lars Tingelstad, recorded + zoom)	9 Webcamserver with Python/OpenCV
11	21. mar	No Lecture - use tall of this week to complete all unfinished assignments	10 ROS2 + Camera (+ all unfinished)
12	28. mar	Actuators (Switched place with PLC lecture)	11: Electrical motors
13	04. apr	Somewhat more Advanced PLC programming	12: FBD + SFC or Indexed Line Assignment
14	25. apr	Dependability basics / Systems development	Indexed Line Assignment

Assignment 1: Install a Virtual Machine and Linux on your own computer

The students are tasked to install a Linux distribution on their own computers as a virtual machine through the VirtualBox software. They should also ensure that the GNU $C/C++$ programming tools are configured in the Linux OS.

Assignment 2: C refresh

This assignment is provided to students over several weeks. They are tasked to freely learn about C-programming, with links to various learning resources for this.

Assignment 3: Basic tools

The students are first tasked to familiarize themselves with the Linux environment, with references to the commands to navigate, move and create files in the terminal. They are then tasked to create a simple Hello World program in C, learn to compile it, and finally how to compile it with a Makefile.

There are then two appendices. One provides instructions on how they can program C in the eclipse Integrated Development Environment (IDE). Another provides a very brief introduction to version control systems Git and Subversion.

Assignment 4: Multiprogramming and concurrency

In this assignment, students are to practice multiprogramming using threads, processes, and semaphores in C. It consists of several sub-assignments:

A The students are asked to implement a program with a global and local variable. Furthermore, they make instances giving parent and child processes using $fork()$ and $vfork()$ commands. The students compare how the variables change depending on which command was used to call instances.
B The same as the last task, but with POSIX threads instead.
C Create a program with a semaphore representing 3 imaginary resources and 5 threads wanting to access a resource. Only one thread can access a resource at a time.
D First, create two POSIX threads iterating two global variables. They are then asked to implement this with Mutex semaphores to ensure that only one thread can access the variables at a time.
E Finally, they are to solve deadlocks in the Dining Philosophers problem using semaphores.

Assignment 5: Memory, errors and time

This is an assignment with a wide scope. Students are introduced to memory allocation, pointers, linked lists, error detection, and timing in C. It consists of several sub-assignments:

A They are to create a program allocating memory areas and writing integers to them indefinitely until a memory leak causes the program to crash.
B A skeleton linked list program is provided with a script to test it. The step is long because the students must implement a linked list program with associated functions almost from scratch.
C The program from step A) is updated to throw an error when crashing.
D The students create and time two programs, both creating two threads and then waiting 5 seconds, one using sleep() and the other using a busy-wait-delay function.

Assignment 6: Linux on Raspberry PI

The students are tasked with installing a Linux distribution on a Raspberry PI.

Assignment 7: TCP/IP Sockets

Students are to establish socket-based client and server connections between two terminals on the same virtual machine or Raspberry PI. Near-finished client and server scripts in C are in the handouts. They then select between two further parts. In one, they are to extend this to communication between two different computers. This only requires identifying the IP address and inserting it.

In the far more involved and time-consuming option, they are to extend the program such that:

a "One of the sides will now send your full name one letter at the time, one each second, the other will receive, display each received letter as it arrives, and the currently recieved "full name".
b Extend this to being able to send a text-string from one side to the other, and then the other side shall send back each letter in the string as the letter following it in the alphabet. One letter each second for example."
c "You are supposed to be able to send a new string before having received the first one. A plus if you manage to mix these strings sending a letter from each of these every second time. Just use the letters in the strings as they are for clearity then."

Performing both is also possible.

Assignment 8: OPC UA Server/Client

A GitHub repository with an open62541-based C implementation of OPC UA server-client communication is provided. The students are to establish contact between two computers using this. In practice, this merely involves changing the IP addresses as the server and client are almost entirely implemented.

Assignment 9: Building a webcam server using OpenCV and Python

A GitHub repository is provided containing a strictly Python-based webcam server/client and a skeleton of the same with OpenCV in python, along with the required dependencies to install this. The students are to finish the camera, client, and server programs in OpenCV and stream video from one computer to another.

Assignment 10: Implement a ROS2 camera node using OpenCV

The students are asked to install a ROS2 distribution on their Raspberry PIs and build a simple robot controller from a tutorial. Almost all of the required code is provided in the Github repository, meaning the students will mainly copy and paste.

Assignment 11: Three-phase electricity / brushless DC

This assignment is intended to be performed using ELVIS boards. However, it was done in Multisim this semester because of faulty equipment. In the first part, they are to analyze how a three-phase inverter is used to create a Pulse-Width-Modulated (PWM) waveform. In the second part, they are to load a brushless DC motor with a H-bridge and complete a table of the control sequence of the H-bridge signal IDs to drive the motor in clockwise and then counterclockwise directions.

Assignment 12: PLC using FB and SFC

The students are simply to watch two youtube videos implementing a Sequential Function Chart (SFC) based PLC program in Codesys, doing the same themselves while watching. The program contains function blocks (FB) as well.

Chapter 3

Development Process

This chapter covers the what, why, and how of the product development process of this thesis. It first provides an overview of the process, then details the Needfinding activities performed to gather information, insights, and potential solutions. It then describes how an Indexed Line assignment prototype was created and tested with students.

3.1 Process overview

An overview of the process with regards to the Design Thinking stages described in Section 2.1 is visualized in Figure 3.1. In many ways, this work can be viewed as two separate simultaneous processes, the design of the ILA and the work to evaluate and find solutions to improve the OCW. However, they are, in many ways, the same process. Both go towards improving the same course, and there is a very high degree of synergy between them. For example, additional ILA's can replace or expand upon assignments in the OCW. Information and insights from one process have been interchangeably used to inform the other. For clarity's sake, discussing them separately at times can still be valuable, and this is thus done in the following.

3.1.1 Indexed Line assignment

A major difference is that the ILA was already at a later stage of the Design Thinking process at the start of the semester, as it is a continuation of the work performed in the previous project thesis, Appendix B. This pre-study offers many insights from an extensive DT process and many suggestions for how this assignment could be implemented. However, there was still much remaining work to achieve a finished assignment, considering no training model was available during the entire project thesis duration.

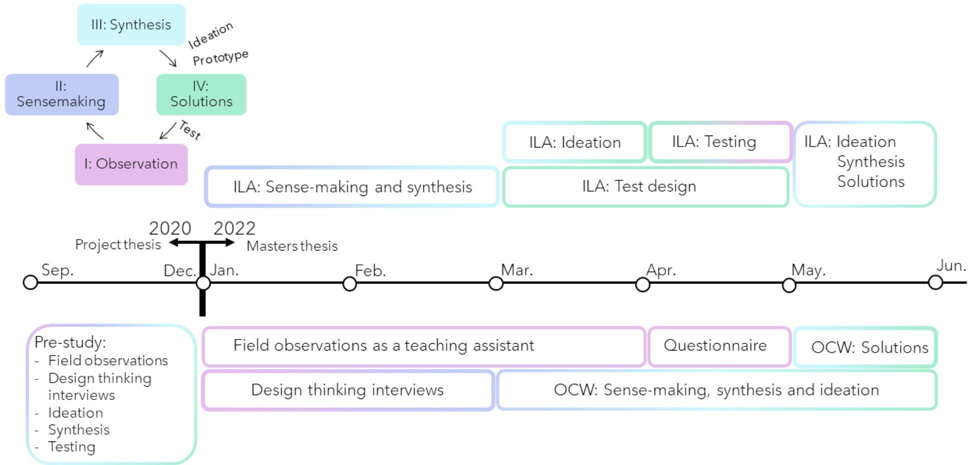


Figure 3.1: An overview of the process with regards to the Design Thinking stages described in Section 2.1. Activities colour-coded to corresponding step(s).

January/february

The training models were at hand when starting the master thesis. However, access to a PLC was delayed until early march[1], and testing was impossible without the PLC. Not having all the equipment served as a major painpoint, especially considering the minimal documentation FischerTechnik provides, which makes it difficult to see what is feasible without actually testing it. Time was then mostly spent exploring different technologies and how they could be implemented in the assignment, largely based on suggestions 14.-20., see Section 2.5.1. In particular, OPC UA was explored extensively, as it at this stage was intended to be a major part of the created assignment. The project thesis was reviewed in detail, along with its bibliography, the notes from design thinking interviews, and other previous needfinding activities performed.

Further Design Thinking interviews were done to inform both the ILA and OCW. In some ways, this means jumping back to earlier stages of the DT process. However, this is part of its recursive nature, repeating stages, see Section 2.1.7 and [11].

[1]There are two main reasons behind this. Firstly, the global chip supply chain crisis[42] has delayed many PLC orders from Siemens. Secondly, there was a human error in the department's acquisition process. This meant that a PLC had to be sourced from a different source. After some time, one was borrowed from Elektra, a student guild at NTNU.

March

After gaining access to a Programmable Logic Controller, work was able to commence with creating an assignment and testing with the Indexed Line. This is described in Section 3.5.

April

A prototype of the indexed line assignment was finished in time for early April and promptly tested. Most of the time in April was spent conducting this testing, changing the assignment, gathering feedback, and synthesizing potential new solutions and changes based on this, both for the ILA and OCW. This process was performed iteratively, changing the approach to testing and the assignment text underway based on the feedback acquired and different aspects that were selected to test. This is described in Section 3.6.

May

After finishing testing, a final version of the assignment was created based on the feedback, along with details for deployment. Extensive effort was made to synthesize the information and insights gathered from all the needfinding activities performed to create holistic ideas for how the future of the course could and should look. The students were sent a questionnaire evaluating both the ILA and OCW to acquire quantitative data to supplement all the other qualitative information.

3.1.2 Other course work

The author worked as a teaching assistant for every assignment in the course. From the start, this was intended to inform the work with the ILA, as it is highly informative towards creating an assignment in that course context. Therefore, extra effort was put into preparing and overseeing the assignments. By early February, it became clear that there was a significant potential for improvement with the course, in addition to the PLC delay causing a decreased scope for the ILA. It was also evident that the ILA should be deeply interconnected with the other assignments. The scope for the thesis was then expanded to look at the course work as a whole. Deep attention was then paid to every detail of the OCW, the issues the students encountered, what they enjoyed and how it could be improved. Taking a holistic view of the course work, all the needfinding activities performed were used to inform both the ILA and OCW.

Ideas for how the OCW could be improved were continually generated throughout the project period. However, most of this work was done in May, when the entirety of the data was made available.

3.2 Design Thinking Interviews

An essential part of the process has been the conduction of extensive user interviews. The interviews performed as part of the previous project thesis have been used to inform this thesis. However, 12 additional in-depth interviews were completed this semester. These interviews were performed early on in the project period and used to form what the prototyped assignment would look like. Exit interviews were done similarly after testing the assignment, described in Section 3.6.3.

3.2.1 Interview Subjects

The subjects have primarily been students, but also some educators. Students who have already taken this course were interviewed as they can draw on the similar experience and possess knowledge about the context the assignments take place in. Interviews were also conducted with students who are yet to have the course (but likely will according to their study path) and those who will not have the course. This is to get insights unclouded by previous experience and to explore a broad spectrum of users. Among the subjects in the project thesis were also lecturers, as they provide the perspective of the person conducting the lab and have substantial experience of the supervision of university-level lab assignments.

3.2.2 Interview structure

On *page 97* Kelley and Kelley[14] present design thinking interviewing techniques. As you aspire to get at the hidden insights and latent needs of your prospective users, questions should be phrased and asked in such a way that they do not produce yes-or-no answers, but instead, get them to "*examine and express the underlying reasons for their behavior and attitudes*"[14]. A central part of this is the **five whys**, where iterative questions starting with why are used to dig progressively deeper into the subject matter[5]. By allowing the user to set the agenda, you increase the possibility of serendipitous insights and prohibit your personal understanding from clouding the interview[10].

Before starting the interviews, the subjects were told that they are encouraged to speak freely and be relaxed in considering the relevance of their answers, not letting this inhibit them. The project thesis made it evident that two main questions were especially fruitful, providing much information from the students and ample opportunity to dig deeper. Therefore, the interviews were performed with only two predestined questions, a slightly altered version of the same questions from the project thesis.

- Can you tell me a story about a laboratory assignment or similar that you really enjoyed or found helpful, productive, educational?
- Can you tell me a story about a laboratory assignment or similar that you did not enjoy, that frustrated you or you found useless?

Bear in mind that this is an iterative process where follow-up questions should be devised mid-interview in order to go in-depth on the aspects brought up, here-under a sizeable amount of whys. The interviewer should always encourage the subject to continue speaking and be very restrictive in bringing up their own opinion, allowing the subject to reach conclusions on their own. An example of how the series of answers and follow-up questions proceeded for one such story is provide[2]:

- **Interviewer:** Can you tell me a story about a laboratory assignment or similar that you really enjoyed or found helpful, productive, educational?
- **Subject:** I really liked the assignment in TPK4190 where we controlled the robotics arm, making it move around ping-pong balls and shoot them out of the air cannon.
- **Interviewer:** Why did you enjoy this assignment?
- **Subject:** It was just really cool to see the robot arm move based on our programming, and I wanted to share video of it with my friends. The lab itself was also well arranged, everything worked and we were able to learn and master the programming in the time we were in the lab.
- **Interviewer:** Why do you think it is cool to see the robot arm move?
- **Subject:** In some way it is almost child-like enjoyment, it is cool to see robot arms move in the same way it is fun to drive an RC car. You also get to see the result of your programming, and see that the things we learn in the course are usable in the real world.
- **Interviewer:** Why do you think it is helpful to see the result?
- **Subject:** It is in some way a reward for the work. Seeing the result actuate also makes it easier to see whether you have programmed it correctly or not. I think it also helps to connect theory to practice.
- **Interviewer:** Why do you think it is helpful to connect theory to practice?
- **Subject:** It reinforces that the things we learn actually have a use and are not just theoretical, which motivates learning it. It also gives more mental "pegs" for the subject matter.
- **Interviewer:** What do you mean about mental "pegs"?
- **Subject:** I guess having performed and seen the practical work gives more mental connections on the subject matter. I'm not sure I would remember it now 3-years later had it been purely theoretical, but having the added visual component makes the assignment and what I learned stick with me. I also think I got a deeper understanding of how robotics operate that I would not get had I merely read about it. When we later visited

[2]This is both abbreviated and paraphrased. The interviews were also conducted in Norwegian.

the Toyota factory in Nagoya with class, I think the memories of this combined with this lab has kind of merged together to reinforce what I learn in later robotics courses.

- **Interviewer:** Can you give an example of this "deeper understanding" or what you mean about it?
- **Subject:** I guess I really got a feeling for how the position of joints and arms added up together to form the position of the manipulator. I also got an understanding for collision prevention, we had some accidents where the arm crashed into the table and stopped.
- **Interviewer:** What did you learn about collision prevention?
- **Subject:** Well, we learned that you must consider the path the robotics arm takes, it is not just arbitrary movement from point A to point B in space. You could also imagine the consequence such a collision would have for a larger more powerful robotics arm.
- **Interviewer:** When has this been useful and why?
- **Subject:** I got insights as to the importance of safety mechanisms in production environments and how easy it can be to do damage to people or material if this is not taken seriously. When I had a later control theory course this helped me, as I could see its application and the importance of it when the robot arm stopped when it met the table and the control system measured a large force.

- **Interviewer:** Thank you, these have been really helpful answers. I want to track back a bit, you mentioned earlier that the way the lab was arranged was also helpful. Can you expand on this?
- **Subject:** Well, we got there and the equipment was already setup and functioning. There was a teaching assistant there that was well-versed in helping us and fixing issues with the hardware that came up[3]. It was very clear what we had to do as well, and there was a programming interface that was easy to control and understand.
- **Interviewer:** Why do you think it is important that the lab was well set up?
- **Subject:** Well, the software and equipment was new to us, but we were still able to complete the task on our own, and had some freedom in choosing how the solution should look.
- **Interviewer:** What do you mean by that?
- **Subject:** While we got help from both the TA and the assignment text, especially in getting started, we still felt that the resulting program was our own.

[3]The author has, in fact, worked as a teaching assistant in this course TPK4190 as well. Note that this course also had a PhD student as a scientific assistant (SA) available, that had designed the assignment, maintained it between groups and was able to help with larger emergent issues that the TA could not fix it. This meant that the course coordinator was freed from spending time on this lab.

- **Interviewer:** Why is it good that you felt that the program was your own?
- **Subject:** Because of how it was setup, we were able to learn this technology and got progressively more independent as the lab went on. This gave a feeling of mastery, as we learned a new skill and were able to use it.
- **Interviewer:** Why is it important to be independent?
- **Subject:** If the TA had to help us all the time, it would still be cool to see the arm move I guess, but I don't think I would have learned as much or gotten that validating feeling of my capabilities. It is also more fun when you get the freedom and mastery to chose the solution yourself, it was eventually almost like playing a game.

- **Interviewer:** Can you tell me about any other assignments you found enjoyable?
- **Subject:** ...

- **Interviewer:** Can you tell me a story about a laboratory assignment or similar that you did not enjoy, that frustrated you or you found useless?
- **Subject:** ...

And so on, it would progress, typically resulting in multiple stories for each question. Different answers from the subject could be referenced against each other, particularly the difference between the good and bad ones. After progressing through the stories for both the satisfactory and unsatisfactory assignments, additional questions would be asked at the end pertaining to other interesting lines of inquiry that emerged based on the subject's earlier answers. When the interviewee was a current or earlier student in TPK4128, such questions were also asked directly to the OCW.

3.3 Field Observations as a Teaching Assistant

Kelley and Kelley [14] place emphasis on the necessity of field observations; on *pages 89-94* they write: "*Observations in the field are a powerful complement to interviews, turning up surprises and hidden opportunities. When you spot a contradiction between what you see and what you expect, it's a sign to dig deeper.*". Doing this turns up what activities they appreciate, what frustrates them, and notably, the latent needs that people are not conscious of and thus would not show up in an interview. Patnaik and Becker [10] point out that people are generally so accustomed to their problems that they work around them. As they are not conscious of them, these problems will not be discoverable in interviews, but can be through observation. Getting at this type of latent needs can provide some of the most valuable opportunities for innovation and is central to needfinding[12][13].

While working with the previous project thesis, the author was a teaching assistant in the related course TPK4125 Mechatronics doing field observations there, which will also inform this thesis. It has been further informed by acting as one of two teaching assistants in TPK4128 this semester, which has been of enormous value when reviewing the course work of this very course. This has allowed for exploring every one of the assignments in detail. Care was taken not to view solution proposals in preparation for the assignments in order to experience firsthand how it is to perform them[4]. Furthermore, being a TA meant seeing how students went about completing every assignment, observing complications that came up, and how they eventually solved them with or without help. Questions were asked of the students underway to help these observations and see how they experienced the assignments. Notes were taken after every assignment in order to log what occurred. This helped design the ILA and was even more helpful in discovering painpoints and possible improvements for the OCW.

3.4 Extracting Insights: Sense-making

Vast amounts of information were acquired throughout the Needfinding activities conducted in this work and the project thesis. However, to be truly useful, it needs to be distilled into Frameworks as defined in step **II: Sense-Making**, Section 2.1.3. Information pertaining to both the OCW and ILA was constantly mixed and categorized throughout this process to identify recurring patterns, idiosyncrasies, and contradictions from the data. Having put the information into frameworks allowed for the extraction of insights and painpoints, and uncovered a deeper understanding of the user and use context[12]. Furthermore, it unveiled new ideas and points of inquiry that informed further iterations of sense-making and the Design Thinking process. This was partly done through iterative series of concept maps, becoming clearer with each iteration as progressively more links were identified between the data points. This was done constantly throughout the project period.

3.5 Indexed Line Assignment: Ideation and Prototype Design

A fully functional prototype of the assignment was designed in March 2022. This section describes the decisions made as part of this process, *leading up to* testing in April. The decisions and subsequent changes made *during* testing,

[4]Furthermore, some of the assignments did not have solution proposals available, which is a problem that needs to be fixed before the next iteration of the course. If not, the TAs might be unable to help students if they do not know the/a solution. Even worse, this might result in TAs spending so much extra time preparing for earlier assignments that they have used up their 100 hours before the last assignments, resulting in no TAs

along with a complete description of the designed prototype, are described in Section 4.2.

3.5.1 Considerations

The problem description (Section 1.2) states that:

> The resulting assignment should provide students with the desired learning outcomes concerning teamwork and competence with automation, PLC control and industrial computer systems. It should be engaging while doing so and inspire further learning. It should also answer faults identified in the other assignments of the course.

This was central when designing the prototype, along with the insights and suggestions gathered as part of the previous project thesis, see Section 2.5.1. It was desired that it would build on and interconnect with concepts in the OCW. Additionally, it was informed by the further needfinding activities performed during the work with this master's thesis.

With reference to Table 2.4, it can be strongly argued that an assignment with a PLC and the training model would essentially answer every item in the desired learning outcomes of the course. Then it remains to make sure that they actually learn these subjects. As PLC programming would mostly be new for the students, care had to be made that they got enough help along the way while still giving them a sufficient and considerable amount of tasks to complete on their own. If you provide too much help, it becomes dull, and they do not experience mastery. If you provide too little help, it becomes frustrating, they do not complete it in time and do not get to perform the activities they are supposed to do. This is a delicate balance, but if you get it correctly, the students will experience mastery and learn while finding it engaging as to inspire further learning. Working as a teaching assistant in the course was crucial to understanding precisely this. [5].

3.5.2 Directional prototyping

First directional prototyping[17] was done to see what was feasible to do with the equipment and in the time allotted for the students, as described in Section 2.1.5. From the very start, it was clear that the core of the assignment would entail students programming the Indexed Line such that it could automatically load a workpiece, transport it through the machining stations, and on to the end. This would be done with a Siemens S7-1500 PLC and the Siemens TIA Portal software. However, major decisions remained pertaining to which

[5]Furthermore, this exact balance is a significant part of the issue with the OCW, something that will be described in more detail in latter sections.

portions of the work would be pre-made and what the students would do themselves, programming language, details of the operation, and which other concepts could be added. Three major design choices were made in this phase:

Programming Language

The previous project thesis made the assumption that ladder logic would be the programming language used. However, this semester, it was quickly discovered that this would make an incredibly convoluted and recursive program. A switch was then made to Sequential Function Diagrams (SFC) in the GRAPH environment of Siemens TIA Portal, as the stage-based programming fits well with the sequential sensors and actuators on the indexed line and gives a highly readable program[6].

Processing multiple workpieces

It was explored whether part two of the assignment could entail programming the indexed line such that it could process multiple workpieces at once, such as in Figure 3.2. However, when attempting this, it became clear that this would require a far more expansive program with many dependencies and cases based on where the pieces are relative to each other. Looking at Figure 3.2, if the milling process is finished, it cannot continue before the next workpiece at the drill is loaded onto the slider plate and so on. The GRAPH environment is poorly suited for this, and it would, at the very least, take a lot more time and skill than the students have at hand to complete. Using a language more function-based like Structured Text (ST) is more suitable, and this is done in FTSim, [32]. However, SFC was opted for in this introductory assignment because of the readability and accessibility. This meant that the simultaneous operation of multiple workpieces was removed from this assignment version. However, students were asked to make it such that work can start on another workpiece as soon as another reaches the end, as this is fixed with a simple jump-to-start recursion. Simultaneous operation of multiple workpieces with structured text is described as a possible additional ILA in Section 4.3.3.

OPC UA

Support for OPC UA is only available on newer versions of the S7-1500 firmware, and this firmware version was not supported on the PLC used because of its age. This meant that testing with OPC UA had to be omitted from the prototype created as part of the master thesis. As will be described in 4.3.3, this idea of having an OPC UA part at the end of the first assignment was later dropped, instead opting for a separate assignment doing this.

[6]The transitions of the SFC are still in ladder logic, meaning that this is introduced to the students as well. ***14. Look to other modes of logic control (Section 2.5.1)***

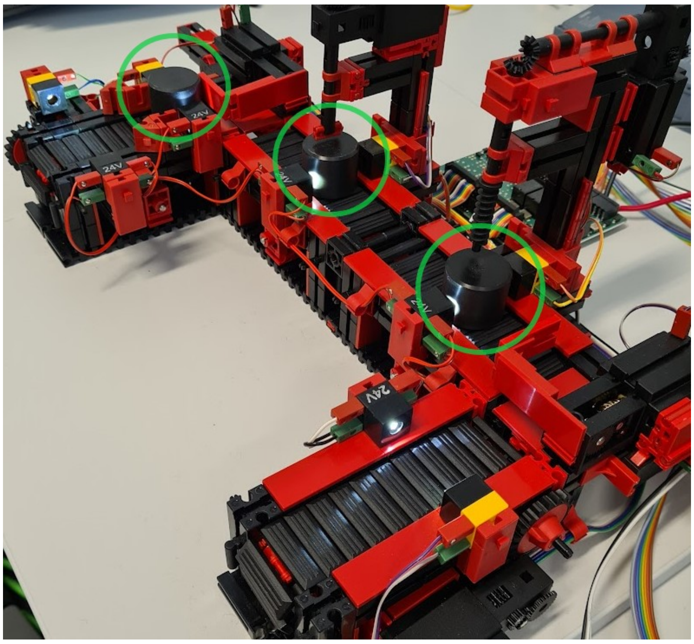


Figure 3.2: An example of simultanous operation of multiple workpieces on the Indexed Line with Two Machining Stations[1]

3.5.3 Incremental prototyping

Based on the directional choices made, a primary structure was decided. Work was then commenced to create the assignment text and decide in detail precisely what tasks were to be performed and what information and materials should be provided for this. This was an incremental process, with many minor choices and revisions underway to make the assignment streamlined and understandable. The incremental prototyping largely carried over into the testing phase, with the assignment text and the way the tests were conducted being iteratively changed. The details of those choices are provided in Section 4.2.

3.6 Indexed Line Assignment: Testing

Based on the results of the previous processes, a prototype of the assignment was designed for testing. This assignment text can be found in Appendix A and will be discussed in detail in Section 4.2. There was only one PLC at hand, so it had to be tested with one group at a time. The students were asked to sign up for 3-hour slots in groups of one to three. Testing was conducted as a normal assignment over three weeks in the start and beginning of April 2022. In total, 14 groups and 26 students completed the assignment.

Had multiple PLCs been available, it would be possible to test simultaneously, which is more analogous to how the assignment typically would occur. However, distributing the testing over time allowed for multiple benefits. It made it possible to iteratively change the assignment structure, contents, and text over time, quickly identifying faults and seeing the results of attempted fixes. It also made it such that significant attention could be paid to observing and analyzing each individual run-through. .

3.6.1 What to test and why

When designing a prototype and testing, it is essential to identify what one wants to test. However, this can easily be forgotten. Again, "*Prototypes are designed to answer questions*"[15]. The test, and more importantly, the questions asked both during and afterward, were designed to answer the following points:

- Are there any errors that occur that should be either fixed permanently or written down?
- Are there any major painpoints that occur?
- Are the students able to understand what they are to do?
- Are the students provided sufficient information and tools to accomplish this?
- Are the students able to solve it independently[7] in the time allotted?
- What degree of setup should be preconfigured?
- To which degree should the students be asked to prepare?
- Is there enough time and do the students have the capacity for further advanced activities?
- Do the students find it engaging?
- Do the students perceive relevance from their activities to the course learning outcomes and actual factory situations?
- What potential issues and strengths do the students find with the OCW?
- Does this assignment solve those issues and continue the strengths?
- Is the assignment suitable for working in groups, alone or both?
- Would the students be interested in further assignments like this, if so, what?
- Do the students have any ideas, feedback, observations or comments beyond this?

3.6.2 Test setup

While the contents of the assignment changed over time, the base setup remained the same throughout.

1. The test was performed in its own room, containing a PLC, the training model, and a computer with TIA Portal loaded on it.

[7] Independently, in the sense that they are able to solve it with a moderate amount of teaching assistant help, or even without.

2. The students were shown into the room. The test leader would give a brief introduction to the equipment and tasks, or leave them with the assignment text. This choice was made deliberately on each run in order to test whether the assignment text was sufficient on its own.
3. The assignment text provided students with a background of the equipment, the tasks they were to perform, an explanation of the programming environments, and common errors that might occur. A partially implemented program was provided to give the students a basis and example to start.
4. The test leader leaves the room when the introduction has been given, with instructions on how to contact for teaching assistant help. The test leader was placed just a few rooms down, functioning as the teaching assistant.
5. A deliberate choice was made each run of how often the test leader would check in. On most occasions, the test leader would only come in when there was a request for help from the students, simulating the context of a normal assignment with teaching assistants and testing whether students could complete the assignment independently. On other occasions, the test leader would check in every half hour to observe the students at different stages.
6. Upon leaving the room, the test leader would take detailed notes of how far the students had progressed, what they said, painpoints, and any other details they might have observed.
7. When the students reported having finished the assignments, the test leader would reenter the room and check whether the program functioned as tasked, potentially relaying details that had to be improved.
8. Whenever time allowed, exit interviews were completed with the students, see Section 3.6.3.
9. When the students had left, the test leader would comb through the students' implementation in detail. This would sometimes reveal efficiencies and ways to complete the tasks that had not been thought of beforehand.
10. Finally, more notes were taken on everything said, read, and observed. The test leader would then immediately start to ideate and workshop ideas and insights from the test.

3.6.3 Exit interviews

After the students finished the assignment, exit interviews were performed whenever time allowed. This was possible for 11 out of 14 groups, with varying duration and levels of detail. Questions were asked to identify what they thought of the assignment, how they proceeded with it, places they stopped up, the reading order of the learning materials, and how they solved the tasks. Exit interviews were performed similarly to the DT interviews described above, with an open structure, allowing the flow of the interviews to be guided by the statements students made.

3.6.4 Questionnaire

The qualitative feedback and results yielded by the needfinding activities are the most conducive to a design thinking process and, in some ways, contradictory to a more rigorous approach. However, quantitative data is helpful in terms of evaluating the success of an implementation. The Design Thinking interviews and testing herein put the subject face to face with the creator of the assignment, which can make them reluctant to give negative feedback. It is then useful to get anonymous feedback as well. For these reasons, an anonymous questionnaire was sent out to the students in the wake of testing. It contained 14 questions:

1. **What week did you perform the assignment?**
2. **How would you rate the assignment? (1 is lowest, 5 is highest)**
3. **How would you rate the other assignments in TPK4128 as a whole? (1 is lowest, 5 is highest)**
4. **How would you rate this exercise in comparison with the rest of the exercises in the course?**
   Answering options: Far worse(1), Worse(2), The same(3), Better(4), Far better(5)
5. **How would you rate this exercise in comparison with other practical exercises you have had at NTNU?)**
   Answering options: *Far worse(1), Worse(2), The same(3), Better(4), Far better(5)*
6. **How fun did you find the assignment?**
   Answering options: *Very boring(1), Boring(2), Middling(3), Fun(4), Very fun(5)*
7. **How helpful did you find the assignment text and hyperlinked videos within?**
   Answering options: *Very unhelpful(1), Somewhat unhelpful(2), Neither helpful nor unhelpful(3), Somewhat helpful(4), Very helpful(5)*
8. **How relevant did you find the assignment to the desired learning outcomes of the course?**
   Answering options: *Not relevant at all(1), Low relevancy(2), Somewhat relevant(3), Relevant(4), Highly relevant(5)*
9. **How relevant do you find the assignment to actual production environments?**
   Answering options: *Not relevant at all(1), Low relevancy(2), Somewhat relevant(3), Relevant(4), Highly relevant(5)*
10. **Did you find that the equipment used (training model, PLC, TIA Portal) was helpful to learning about the subjects?**
    Answering options: *It was a hindrance to learning(1), Not very helpful(2), Either or(3), Helpful(4), Very helpful(5)*

11. **Did you find that the equipment used (training model, PLC, TIA Portal) functioned well?**
    Answering options: *Very not well(1), Somewhat not well(2), Neutral(3), Somewhat well(4), Very well(5)*
12. **Do you wish there were more assignments similar to this one in the course?**
    Answering options: *Yes, No, Maybe*
13. **Do you have any further feedback about the factory model assignment? This can include things you particularly liked, points of improvement, activities that were unnecessary, or anything at all.**
    Optional to answer. Free text.
14. **Do you have any feedback about the rest of the exercises in TPK4128? What did you like or dislike? What assignments in particular should be improved? Did you find them relevant to the lectures and learning outcomes? How did you find the difficulty level, etc?**
    Optional to answer. Free text.

Chapter 4

Implementation and Results

The outcomes of the product development process completed as part of this master thesis and the previous project thesis are presented in this chapter. First, the information, feedback, insights, and general findings gathered from the Needfinding process are presented. In the next section of the chapter, the designed Indexed Line Assignment is described, along with the findings from testing and instruction on how it should be deployed in the future. Finally, a set of suggestions for how the course work as a whole can be improved is presented by discussing the constituent assignments, both individually and in relation to each other.

4.1 General Findings, Feedback and Insights

From all the information gathered, two main findings are apparent, which will be demonstrated in the following chapter:

- The students are primarily positive towards the Indexed Line assignment.
- The students are primarily negative towards the remaining assignments in the course.

This raises the question: why is this the case, what needs improvement, and how can this be achieved? The results that gave this conclusion will be presented here. A discussion of the underlying factors determining the success of an assignment, based on the discovered strengths and weaknesses of the ILA and OCW respectively, then follows.

4.1.1 Questionnaire

The questionnaire yielded positive results for the Indexed Line Assignment and negative results for the course as a whole, see Table 4.1.

Of 28 students having performed the assignment, 19 answered, yielding a decent response rate of 68%. The sample size is large enough to give decent pointers to the student experience, especially combined with the other activities performed. The results of each question will not be discussed in detail, only the ones of particular interest.

Table 4.1: Answers to questions 2 and 3 in the questionnaire.

Question	*2. What would you rate the assignment?*	*3. How would you rate the other assignments in TPK4128 as a whole?*
Rating	1 2 3 4 5	1 2 3 4 5
Amount	0 0 0 10 9	7 7 4 1 0
Average	4.47/5	1.95/5

Comparing the Indexed Line Assignment to other assignments

Questions 3 and 4 are presented in Table 4.2. It is clear from question 3 that the students find the ILA far superior to the OCW, which indicates that it serves as a useful reference for how to design assignments in the course. Furthermore, 84% of respondees rate the assignment as being better than other practical exercises they have had at the university, suggesting that the ILA is a good assignment in its own right, not just relative to the rest of TPK4128.

Table 4.2: Answers to questions 3 and 4 in the questionnaire

Question	**Number average**	**Text average**	**Distribution**
How would you rate this exercise in comparison with the rest of the exercises in the course?	4.84	Much better	16xMuch better 3xBetter
How would you rate this exercise in comparison with other practical exercises you have had at NTNU?)	3.95	Better	2xMuch better 14xBetter 3xThe same

In-depth questions about Indexed Line Assignment

Questions 6 through 11 aim at getting further information on the success of the constituent factors in the ILA and are provided in Table 4.3

Question 7 over time: Large changes were made to the assignment text between 8. and 18. of april[1]. Question 1 was included to attempt to identify changes over time like this one. Nine respondees completed the assignment before these changes averaging a score of 4.22. Ten respondees completed the assignment after these changes averaging a score of 4.40. This can indicate an improvement over time, but the sample size is too small to make any conclusion from the difference in these two numbers alone[2]. However, the results

[1]Version 3 was made in this period, differing substantially from versions 1 and 2, see Section 4.2

[2]For example, if a before-respondee who answered **3** had answered **5** instead, this would put the before-results above after, showing the volatility of making this comparison with such a small sample size

from testing and exit interviews suggest that there was indeed an improvement after this change.

Question 11 has the largest spread of these questions. It has the highest amount of top scores **(10)**, but is also the only question where a student gave a rating of *2, somewhat not well*. This can likely be explained by the fact that some groups encountered technical issues with the equipment. The technical issues were mostly minor and could be swiftly remedied by looking at the common hardware errors in the assignment text (Appendix A). However, one group did get a relay error with their training model that made the sliders unable to move. This group performed the assignment between 4.-8. April and the 2-rating comes from a respondee from the same period, but it is not possible to conclude whther this was the same group.

Table 4.3: Answers to questions 6 through 11 in the questionnaire

Question	Number average	Text average	Distribution
6. How fun did you find the assignment?	4.37	Fun	7xVery fun 12xFun
7. How helpful did you find the assignment text and hyperlinked videos within?	4.32	Somewhat helpful	9xVery helpful 7xSomewhat helpful 3xNeither helpful nor unhelpful
8. How relevant did you find the assignment to the desired learning outcomes of the course?	4.26	Relevant	6xHighly relevant 12xRelevant 1xSomewhat relevant
9. How relevant do you find the assignment to actual production environments?	4.21	Relevant	7xHighly relevant 9xRelevant 3xSomewhat relevant
10. Did you find that the equipment used (training model, PLC, TIA Portal) was helpful to learning about the subjects?	4.47	Helpful	9xVery helpful 10xHelpful
11. Did you find that the equipment used (training model, PLC, TIA Portal) functioned well?	4.37	Somewhat well	10xVery well 7xsSomewhat well 1xNeutral 1xSomewhat not well

12. Further Indexed Line assignments

In question 12, the students are asked if they would like further ILAs. **Seventeen** students answered ***yes***, **two *maybe***, and **none** answered ***no***. This firmly signals that this is a template for conducting assignments that should be used going forward and that having multiple assignments with the ILW2MS is desired.

13. Further feedback on the Indexed Line assignment

As this question was optional, *10 out of 19* respondees answered it. The answers below are unchanged except for some fixed spelling errors and some translated from Norwegian. The answers correspond well to the oral feedback given in the exit interviews. For questions 13 and 14, every number in the list denotes a discrete respondee.

1. "*Enjoyed the process of using steps and transitions and then physically study the result for the factory training model. This way it was very clear what went wrong when you observed a failure in the factory model instead of just an error on the pc. In the start it was somewhat unclear what the purpose of the Steps and Transitions where, but that was due to a lack of preparation. When we then watched the hyperlinked videos and got some tips it was very clear and fun to work with.*" [3]
2. Translated from norwegian: "*Large program to familiarize oneself with it. Would not have been able to navigate correctly without help. Otherwise fun with practical and work-oriented.*"
3. "*The exercise text was a bit long and cloudy, would appreciate a more concise and easily readable exercise text, with explanations and links to tutorials in an appendix (or shortened). This was not a big issue at all though, just a small annoyance when first starting with the task.*"[4]
4. "*A video showing a short introduction to the PLC-ladder-diagram software and how to program a few steps would be helpful in the start of the assignment. Took a while to get to know the system.*
5. *Very fun to have a hands on exercise, where all the equipment worked! We only had a minor issue with one of the conveyor belts, however did this not affect the whole experience.*"
6. Translated from Norwegian:"*Fun to do something practical and see physical results.*"
7. "*Very fun and learned a lot! Also good text and good length on the assignment.*"
8. "*I would like to work a bit more on the practical setup of the PLC and perhaps some more complex workflows. Perhaps this would be best as a seperate Lab though*"
9. "*part 2 with a more advanced task.*"
10. "*We were a little confused at first as to what we should do (looked like the* "*template*" *ran correct on the model, could be explained a little bit clearer that there was a functioning version already installed that we should* ""*mimic*""*). Was really fun when we understood the assignment*"

14) Further feedback on the Other Course Work

As this question was optional, *15 out of 19 respondees* answered it. The answers below are unchanged except for some fixed spelling errors and some translated

[3]This answer is interesting in that it succinctly describes that ***3) Make causality apparent (Section 2.5.1)*** has been successfully followed.

[4]This feedback somewhat contradicts with point 7 in this list. Both sides of this issue came up in the exit interviews as well. Two main takeaways can be gathered. Firstly, the language in the assignment text can likely be more concise. Secondly, different students have different needs. Some students benefit from a longer exercise text, while others might view parts of it as unnecessary distractions. However, it seems that it is better to have this minor annoyance for the second group of students than to provide too little information for the first.

from Norwegian. Individual answers to questions 13 and 14 should be taken with a grain of salt and not viewed as fact or as the view of the entire student body. Some answers contradict each other, and some statements are arguably inaccurate. Insights can mainly be extracted when the broad range of user feedback is viewed in context.

1. "*Found it hard to see a context between the lectures and exercises. There are listed three points under Learning Outcome on the course page(the student provided a link to the course website[7]). I feel that this course is heavily weighted towards the two first points and a lack of exercises and lectures towards the last point. (Specification and use of interfaces and protocols. Sensors, actuators, power supplies and motor drives.)*[5] *The difficulty level was varying, some exercises took under 2 hrs while others took multiple Labs due to things not working (ex. Raspberry pi's) or confusing exercise texts where we needed to use a lot of youtube-videos and other websites to complete it.*"
2. Translated from norwegian: "*Very variable. I rarely understood what I was supposed to do, and was completely dependent on help. I like the curriculum, and think the course is very exciting, however demotivating and poorly explained assignments ruined it a bit. I have not watched the lectures.*"
3. "*I liked having to go to lab to do exercise with actual components. Having student assistants to answer questions and help was nice. It's harder to get in the "flow" when doing an exercise from home.*"
4. Translated from Norwegian:"*This is the worst course work I have had. The theory and exercises are not connected. I think this last assignment was very good!*"
5. "*I think the general exercises of TPK4128 are quite bad. For the exercises on installing a virtual-machine, installing Linux on RB Pi etc. are good. I found it valuable figuring these things out on your own, through googling issues as you go, but I believe this format is not ideal for a lot of the other exercises. Most of my issues stem from most of the time going to figuring out stuff that was not really relevant. This meant that what I spent the most time on was not really relevant to the learning goals for the specific exercise, and I think it would benefit from exercises being more "plug and play" like this one. For exercise 9, as an example, finding a working camera module for the RB Pi was a big issue. After spending 3 hours searching and trying different cameras I was nowhere, but as soon as I got home, I plugged in my normal USB desktop-camera and the assignment itself was done in less than an hour.*"
6. "*Total mismatch between the lectures and the exercise program. Unclear ex-*

[5]This refers to the third point in the "Knowledge" section of the desired learning outcomes, Table 2.4. It can be argued that the student partially misunderstands the first part of this point, as there currently is strong representation of interfaces and protocols. The student is more correct as to the second part (Sensors, actuators...) only being present in assignment 11 of the current OCW, fortunately the ILA does expand on these concepts.

ercise texts with very little room to actually learn something. Lack of presence for both student assistants and lecturer (especially) to answer questions and clarify the aim of the exercises."

7. "*All former assignments have been critically bad.*
   a. *The assignments get frustrating and often take >10 hours each*
   b. *They provide too little information to be able to solve them independently. "Learning to use google and the internet" is not a good tip.*
   c. *They contain a somewhat "open" and broad structure to them, yet they force you to use handout code. Using time to get to know the handout code and trying to follow the logic is more challenging than just starting from the bottom yourself. If we are to use handout code, there should be a larger "tutorial"-aspect to the assignment text that lets you solve it independently.*
   d. *Each exercise could have references to relevant literature or educational videos, to make them easier to solve.*"
8. "*I found the rest of the exercises to not be up to the expected standard. Many of them were not up to date, untidy and difficult to understand what the main point of the exercise was. Some exercises were blatantly to copy and paste code from GitHub and make it run, did not learn much from these.*"
9. Translated from norwegian:"*I struggle to relate the course work to the lectures. Additionally, it is difficult to do assignments in C when I have never programmed in C before. A more thorough introduction to C is necessary, and I think it is lackluster of the course coordinater to leave this 100% to the students. I have talked to students of other study programs who have similar concepts in C, and they have had many previous courses that build up under the concepts we get in these assignments. There is limited learning benefit from reading of results in the console, when I don't know what to look for, or how the programs should behave.*"
10. "*all assigments should be improved. This is a course with topics which should be fun, but you just end up with googling and copy what you find.*"
11. "*Lackluster, learned very little. Also the online lectures have been not so good...*"
12. Translated from Norwegian:"*Difficult to understand what you are supposed to do from the assingment texts, didn't learn much from the assignments.*"
13. "*I have wasted a lot of time getting Makefiles and all that to work. I feel the help/guide regarding the setup of the C/C++ environment needs work. Youtube has been my only friend there so far. Note, I have not physically attended many labs and have been working mostly from home with only the Assignment text as help.*"
14. "*More work on PLS.*"
15. "*Most of the exercises ended up being problem solving, rather than understanding the subject of the exercise. it is a useful tool to have (understanding the error messages), but it isn't an efficient way to understand the subjects*

(easy to give up/ getting trapped in an weird error you cant figure out)"

4.1.2 Insights

The insights extracted from the field observations, Design Thinking interviews, testing, exit interviews, and other activities are presented here. This gets at the underlying reasons for why course work fails or succeeds. The following is primarily centered on the OCW[6] as the many of the insights underlying the ILA were acquired in work with the project thesis and can be viewed in short form in Section 2.5.1 or in detail in Appendix B. Furthermore, these results in many ways confirm and elaborate on the results acquired in the project thesis, showing how not following those suggestions leads to unsatisfactory course work.

The Students are Intrinsically Motivated, the Course has High Potential

There is much that suggests the students are intrinsically motivated[9] for the subjects of the course, meaning they have a high interest for the learning outcomes in their own right, not just for the sake of satisfying the evaluation requirements. Firstly, TPK4128 is optional, and students will have deliberately selected it over other alternatives, likely in pursuit of the "Robotics and Automation" or "Advanced Product Development" specializations[43]. Secondly, many students have stated that they are highly interested in the subjects. However, they find the course work disappointing, and it thus fails to capitalize on this interest. This was especially clear in one particular exit interview, where the student stated that the course curriculum was almost perfectly aligned with their areas of interest but that it was then doubly frustrating when the course work did not live up to their expectations. This led many students to become progressively more extrinsically motivated and thus take on a surface approach as the course work progressed, only wanting to complete the requisite number of assignments to be eligible for the exam.

This interest speaks to the course having a high level of potential, and in that respect, it is a good problem to have. It suggests that if the course work is sufficiently improved and structured correctly, the students are intrinsically motivated and will seek to acquire a deep understanding of the subjects, making it a very valuable course.

The Course is not adjusted to the Students' Preliminary Skill Level

The course is generally not adjusted to the students' previous knowledge and skill level, especially in programming. The majority of students will mostly have some basic knowledge of Python from an introductory course in information

[6]However, the results from the needfinding activities performed this semester did absolutely inform the work with the ILA to a large degree

technology[43], but not much else[7][8]. There is a long way from this to lines such as

```
newsockfd = accept(sockfd, (struct sockaddr *) &cli_addr, &clilen);
```

TPK4128 does not succinctly bridge this gap and is not a programming course.

The students' feedback is near unequivocally that the C programming assignments become frustrating and damaging as a result. This must be remedied, as it is damaging for the students' experience, and they end up with limited learning outcomes. For C programming, they end up needing to copy-paste code or get a large amount of TA help. They do not adequately learn the underlying concepts they are to understand from these assignments, as this is clouded by the time spent troubleshooting C, frustration, and the students not understanding what they are doing. This provokes two surface learning characteristics in Table 2.1[8]. **1: A heavy workload** and **4: A lack of opportunity to pursue subjects in depth** in that students spend large amounts of time figuring out minute details of syntax, which does not allow time to build their understanding. The following should be done to remedy this:

1. The learning curve needs to be flattened. As it stands, it goes from very basic to involved from one week to the next.
2. Better learning resources should be developed for the C programming.
3. Better and more extensive explanations should be made as to what they are to do, what the results should look like, why they are doing it, the application, and the relation to theory.
4. The programming difficulty should be lowered, allowing them to do more tasks and see more results instead of spending time understanding intricate C details.

In Section 4.3 questions are asked about whether C programming is necessary to the course or if the extent should be significantly reduced. TPK4128 is a course with a lot of different concepts, the students have a finite amount of time and capacity, and the course work should then be moderated to best provide the width of the learning outcomes necessary for this particular group of students.

Students can complete Challenging New Tasks if the Structure is Focused

However, students are, in fact, able to complete challenging tasks, often in entirely new subjects, if the course work is provided correctly. This is by no means easy to accomplish. They have to get enough help that they are able to com-

[7] Limited amounts of programming is sporadically implemented throughout other courses, and some might have courses in object-oriented programming (Java or C++) in the same semester as TPK4128

[8] Assignment 2 in the OCW has also been implemented in the preliminary course TPK4125 Mechatronics, which most TPK4128 students will have had. However, this does not sufficiently remedy the problem of the learning curve in TPK4128 because of the timespan between and the same reasons Assignment 2 is criticized in Section 4.3

plete the assignment in the allotted time and not get stuck before they get to the "good parts" where the learning lies. Meanwhile, they still need to be challenged and thus experience mastery. The assignment needs to be tailored so that students can complete a meaningful amount of work independently[9]. However, specific measures can be taken to achieve this balance by structuring and focusing the assignments. Rebolledo-Mendez *et al.* [20] found success with motivational modeling of three main traits: effort, independence, and confidence.

An example brought up by multiple students is the course TTK4115 Linear System Theory[44], which serves as a valuable case study. They state that it was very challenging[10] and entailed a large amount of work, but that they found much value from it. The course work entails progressively creating a control system for a miniature helicopter throughout the semester. From the success of this course in having students accomplish a challenging series of tasks, many lessons can be transferred to the course work in TPK4128.

1. The work is compartmentalized into a series of subtasks. The students complete successive components of the work, building upon each other[11]. This allows them to experience mastery throughout the work, motivating them for the next task.
2. It is "plug-and-play," allowing students to start interacting with the helicopter quickly.
3. It is very clear what the students are to do in a given assignment and what the result should be. This is in part done by a clear and structured assignment text, ***11) Provide required actions in a step-by-step structure (Section 2.5.1)***.
4. The equipment is quality assured and maintained. The amount of unproductive problem-solving is limited by progressively improving the assignment over time and having a competent scientific assistant (SA) maintaining and helping with the assignment.
5. The assignments are focused, taking care to limit the amount of concepts and work in the individual assignment. ***7) Don't introduce too many concepts at once (Section 2.5.1)***
6. It has a "cool" practical result. Students find it engaging and rewarding when they see their work result in the physical behavior of the miniature helicopter. ***3) Make causality apparent (Section 2.5.1)***. Furthermore, they see how it relates to the course theory and, more importantly, to the

[9]If they are not handheld enough, they will be dependent on external help. If they are handheld too much, they will not experience independence either.

[10]Especially considering this is a course for cybernetics students, meaning that the course is adjusted to a higher skill level for these subjects than the students spoken to (MTPROD) would have had.

[11]Students also referenced the programming courses (Information Technology, *TDT4110* and Object-Oriented Programming, *TDT4100/TDT4102*) as being good in this regard

real-world applications of linear systems theory. ***2) Make it analogous to actual factory situations (Section 2.5.1)***

To create a great course work program, TPK4128 should take inspiration from TTK4115, and the characteristics described above.

Troubleshooting is valuable in moderation

Learning to troubleshoot is an integral part of being an engineer, citing Murphy's law "*Anything that can go wrong, will go wrong.*" Practical course work is central to learning this; it teaches students both to find errors and do problemsolving[45]. There is much to suggest that problem-based learning is conducive to a deep learning approach. However, this is very dependent on the nature of the problem[46]. This is discussed in the final subsection of the discussion chapter in the project thesis (Appendix B), titled "**The Delicate Balance of Learning Through Troubleshooting**", stating:

> "If it is prohibitive of their process, this can frustrate and prevent them from completing the tasks in the allotted time. Hindering them from attaining the learning objectives and preventing an experience of mastery. There is thus a trade-off between time spent troubleshooting and time spent progressing with the subtasks of the assignment. Many of the suggestions given for the implementation seek to address this. Particularly when introducing students to many new concepts, it can be too much to absorb at once to have to do extensive problem-solving as well. One should consider if some of the troubleshooting lessons are better taught through other parts of the course. A common problem with practical electronics assignments is that errors are due to invisible or hard to find faults, or equipment malfunctioning. The fact that students learn by working through errors, should not be an excuse for having a less refined assignment setup. While a certain amount of learning through troubleshooting is definitely valuable, one should strive to make sure that the implementation is of such integrity that emergent problems are visible and due to personal errors on the part of the students[12]."

A core takeaway is that learning through troubleshooting can not be used as an excuse for the assignments being poorly explained or the equipment malfunctioning and being ill-maintained. Errorseeking needs to be balanced with the other learning outcomes of an assignment and can to some degree be refined

[12]This is further explained in suggestion ***4) Errors should be personal errors (Section 2.5.1)***

and focused if done correctly[13][14].These suggestions were reinforced and amplified from the observations done in this thesis. Throughout the OCW many reoccurring problems cause large frustration and prevent the students from completing the assignment, which would be entirely preventable if the assignment provider had done maintenance in advance. Although much work can be done by simply improving the structure, contents, and provided information in the assignments, it is also necessary to have adequate personnel resources to maintain and develop the assignments. This is made difficult by external factors in the higher education sector, which will be discussed in Chapter 5.

Information seeking is valuable in moderation

Similar to what is discussed for troubleshooting in the previous section, there is tremendous value in students learning to seek information. One would struggle to find a software engineer without ten open Stack Overflow tabs at any given moment. This is a central part of troubleshooting, but also to learning. However, it needs to be moderated and balanced with providing the students with the requisite learning materials and information in the assignment. Quoting answer 7b: "*They provide too little information to be able to solve them independently. "Learning to use google and the internet" is not a good tip*". Again, more information needs to be provided in the assignment texts. The students can not be left entirely reliant on Google, especially if they do not know what to look for.

Looking beyond the assignment texts, the accompanying learning resources are generally inconsistent in the cases where they are present. This brings to mind the need for a well-structured knowledge base as identified by Biggs [22], see Table 2.2. Take the C-programming assignments as an example. There are many different links to C programming resources for them. However, the students find it difficult to find what they need to know and are required to comb through many different resources cluttered with pieces of information they do not need to learn. Some are too basic, and some are too advanced. If the knowledge base had been better structured, they could get the same learning outcomes in less time.

The Level of Difficulty is far too varied

There are large spikes in the difficulty level throughout the OCW. This needs to be smoothed out. Many of the assignments will take the students multiple

[13]The difference can be: *1) The students have a slight issue installing a requisite package, but figure it out in 10 minutes and can continue with the tasks of the assignment, while also having gathered understanding about dependencies.* or *2) The students have large issues in getting the software to work, having to spend multiple hours doing arduous work manually checking every dependency, never getting started with the tasks of the assignment.*

[14]Also, ***13) Provide a list of common errors***, which can be continually developed by ***12) Include a feedback option (Section 2.5.1)***

assignment sessions to complete. For example, several groups were still on assignments 5-7 when it was time to do assignment 10. These exercises are often time-consuming and difficult in unnecessary ways, and not in terms of challenging the students to push for mastery, either because of excessive troubleshooting or the assignment overshooting the students' skill level. Other assignments will be almost trivial in their ease and completion time, often being entirely copy-paste from existing code. Few, if any, manage to hit the delicate balance of independent mastery discussed above.

Interconnectivity and Consistency

Paraphrasing the words of one student from a Design Thinking interview "*it sometimes seems like a bunch of assignments taken from ten different courses and randomly mixed together*". On the positive side, this can be understood to speak to the variety of the course. However, it is more about the students finding the OCW disconnected (from each other and the lectures) and the large variations in how they are delivered. This can also repeatedly be read from the answers to question 14. In order to instill a deep learning approach in students, it is central that they can view the concepts in an integrated manner[8].

The course could benefit significantly from the individual assignments being more connected and *streamlined*. While seeming idiosyncratic at first, the concepts carry over to each other. As it stands, this is not capitalized on. Carrying concepts from one assignment to another reinforces the learning from both the previous and current assignments. It allows for deeper learning as the students understand better how the different technologies function together in a production environment. In this way, students can also engage in more advanced applications as they continue to build upon previous work, gaining confidence in their capabilities and understanding as they go, similar to the helicopter lab discussed above. Furthermore, it should not be understated that many students find little relation between the lectures and the course work. It is essential to bridge this gap for the course to succeed.

In terms of consistency, it has been stated that there are too large variations from one week to the next, not just in the subject matter. This includes the large difficulty spikes as discussed above, but also the way the assignment text and tasks are structured. This serves as a source of confusion. Changes should be made to consistently give the students more precise and more detailed step-by-step assignment texts, for which multiple examples are given throughout this assignment. This is not to say that the form of the assignment texts should be entirely standardized, as individual assignments necessitate different structures. However, it could benefit from being more consistent than it is today.

Visible Results are the Key to Motivation and Deep Learning

Almost every example offered by students of practical assignments they value highly is when something exciting happens at the end. This serves as a reward for having done the tasks correctly, providing intrinsic motivation to push through[15], fulfilling psychological needs as described by Vansteenkiste *et al.* [21]. Much of the positive feedback the ILA has received is because of precisely this, and much of the negative feedback concerning the OCW is for the lack of this. Again, this spells out a clear area of improvement for the course[16].

It is not just important in terms of providing a reward. Engaging visible results can promote intrinsic motivation and deeper understanding in other ways. Having clear results allows students to elucidate how the technologies can be applied in practice and actualize the connections between theory and practice. It makes it much easier to see if their work functions as intended, helping troubleshooting and problem solving ***3) Make causality apparent (Section 2.5.1)***. There is much reason to believe that this is the primary factor behind the high rating the ILA has received in terms of overall satisfaction, entertainment (fun), and relevance.

It should be noted that this does not necessitate *physical* equipment. Digital results can also be engaging as long as they are observable, transferable to practice, and have causal links to the students' work. To put it plainly, the students want to see something interesting or "cool."

4.2 Implementation of Indexed Line Assignment

This section provides the details of the Indexed Line assignment created. It describes the assignment text the students were given and, more importantly, why it is structured as it is. An account is given of the changes made to the assignment during and after testing to arrive at the final version. Then, how the groups fared while performing the assignment is recounted. Finally, instructions are given as to how the assignment can be deployed in the course in the future.

See also the prototype development process described in Section 3.5 and the test structure in Section 3.6.

[15] It should be noted that this only holds when it is a result of a meaningful amount of work they have done. Interviewed students made negative remarks about the laboratory work in their Fluid Mechanics (TEP4110) and Thermodynamics (TEP4120) courses[43], as it mostly involved pushing the on-button and writing down what happened

[16] The workload for implementing this is varied. Physical components, including the ILA, require some work to implement and maintain. However, in other cases, fairly easy-to-implement changes can significantly affect how engaging the assignment is perceived.

Assignment Versions

The assignment was changed iteratively based on the results of the testing. Four versions of the assignment text are included in Appendix A. Reference will be given to these throughout this section. *It is highly recommended that the reader views the final version (A.1)*, as this is in many ways the main product of this work. The other versions are only of interest if the reader wishes to view changes over time. However, these changes will be relayed in the following text.

- ***Final Version (A.1):*** was made after testing finished to include changes based on all the feedback and insights. It serves as a basis for the assignment in future years.
- **Version 3 (A.2):** was provided to nine groups of students (seventeen persons) between April 19th and 29th of 2022. This is the version with the most comprehensive changes with regards to its precursor.
- **Version 2 (A.3):** was provided to three groups of students (five persons) on April 6th and 7th of 2022.
- **Version 1 (A.4):** was provided to two groups of students (four persons) on April 5th and 6th of 2022.

4.2.1 Assignment Structure and Learning Materials

In the following the assignment text in Appendix A is described, with basis in the final version (Appendix A.1). An account is given of why specific elements are included, as well as changes made underway.

A: Introduction

First, a brief introduction is given. It contains some text to prime the participants for the fact that they are interacting with a prototype so that they will be open to giving feedback, ***12) Include a feedback option (Section 2.5.1)***. The wording of this is changed from the test versions and the final because of the different contexts.

B: Background

Preparation The students are not asked to prepare much for the assignment but are told that it can be useful to familiarize themselves with the related content in the lectures[17] and read through the assignment text. The project thesis provides the suggestion ***10) Ask the students to prepare, but in moderation (Section 2.5.1)***:

[17] However, it was stated that students did not find the related lectures all that relevant, which is an area of improvement previously discussed.

> "Doing preparations before the assignment is positive for learning and making sure the students finish on time. However, it is not certain that students actually do it. Some will first start reading up on the assignment when the lab hours begin. The students observed recognize that doing preparation is valuable, however they forget to do it or don't prioritize time for it in their busy workdays. When this is said, a lot of students do preparatory work, and more would do it if one is deliberate in stating it is needed for the course. However, the provider of the assignment should have a realistic view of this and not rely too much on students preparations."

For other assignments, it is appropriate to ask for more preparation than has been done here. However, the degree to which students can familiarize themselves with the ILA without the equipment at hand is limited. As expected, most students did little preparation. However, those who had prepared were in fact able to get started with the assignment faster.

This limited preparation was also observed in the OCW. This is perhaps symptomatic of a culture at NTNU where students rarely prepare, which is discussed in Section 5.1.6.

Why? It is explained how the activities they perform are related to the desired learning outcomes of the course. This can be a helpful addition to the OCW as well, to show the students the motivation for the work and how it relates to the bigger picture.

Indexed Line, PLC and TIA portal theory An overview of the equipment used and some background theory is provided, similar to how it is described in Section 2.4. This is done in order to help the students better understand the equipment they are using, provide them with some theory they can connect the practical examples to, and to ***9) Introduce the relevant concepts and background theory beforehand.***. For version 3, this was extended to give a further explanation of exactly how the actuators and sensors on the indexed line function.

An area of confusion occurred in which a figure (made by FischerTechnik) in the assignment text gave reference to the actuators and sensors with *Q1, Q2, Q3...* and *I1, I2, I3...*. The problem is that the tag table[18] in TIA portal also uses *Q*, and *I* followed by numbers to address the ports on the input and output modules of the PLC. If the cables were wired to produce a tag table with identical variable names to that figure, the wiring would be a "rats-nest". Therefore, the tag table variable numbers differ from the figure, but some confused students had programmed based on the latter, which is incorrect.

[18]A tag table relates ports on the PLC input and output modules to named variables in the program.

To avoid confusion, this has been changed to use A and S in the final version. The complete tag table used in the assignment can be seen in Figure 4.1.

		Name	Data type	Address ▲	Comment
1		sl1_front_limit	Bool	%I0.0	Front limit switch for slider 1
2		sl1_rear_limit	Bool	%I0.1	Rear limit switch for slider 1
3		sl2_front_limit	Bool	%I0.2	Front limit switch for slider 2
4		sl2_rear_limit	Bool	%I0.3	Rear limit switch for slider 2
5		phototr_toslider1	Bool	%I0.4	Phototransistor before slider1
6		phototr_milling	Bool	%I0.5	Phototranistor at mill
7		phototr_start	Bool	%I0.6	Phototransistor at start
8		phototr_drilling	Bool	%I0.7	Phototransistor at drill
9		phototr_end	Bool	%I1.0	Phototransistor at end
10		slider1_fwd	Bool	%Q0.0	Move slider 1 forward
11		slider1_bck	Bool	%Q0.1	Move slider 1 backward
12		slider2_fwd	Bool	%Q0.2	Move slider 2 forward
13		slider2_bck	Bool	%Q0.3	Move slider 2 backward
14		cb_start	Bool	%Q0.4	Move first conveyor belt
15		cb_mill	Bool	%Q0.5	Move second conveyor belt
16		milling	Bool	%Q0.6	Milling station on
17		cb_drill	Bool	%Q0.7	Move third conveyor belt
18		drilling	Bool	%Q1.0	Drilling station on
19		cb_end	Bool	%Q1.1	Move final conveyor belt

Figure 4.1: Tag table in Siemens TIA Portal used for operation of training model[29].

C: Setup

The students' first actions involve connecting to the PLC in TIA Portal. Much of this will be set up beforehand or explained in easy steps. This can be an intimidating program upon the first encounter, so it is important to guide them through the initial steps. Care is taken to instill confidence that this is completely doable for them. The required steps are provided in clear steps, which were further clarified for readability between versions, ***11) Provide required actions in a step-by-step structure (Section 2.5.1)***. The students are provided with a preconfigured project with some of the initial steps leading up to slider 1 implemented, see Figure 4.2. This gives them a reference to work from, as starting from scratch might be too much. Furthermore, the students can upload it to the training model and see it work early on in the assignment as to ***1) Introduce with a simple "Hello World" (Section 2.5.1)***.

In the first version, the tag table was only partially implemented, and students were asked to complete it. The idea behind this inclusion was that students would better understand the program and the connection between the PLC and the training model. However, it was removed in later versions. The most important reason behind this is that it delayed the point where students could actually start programming. Furthermore, it was viewed as somewhat

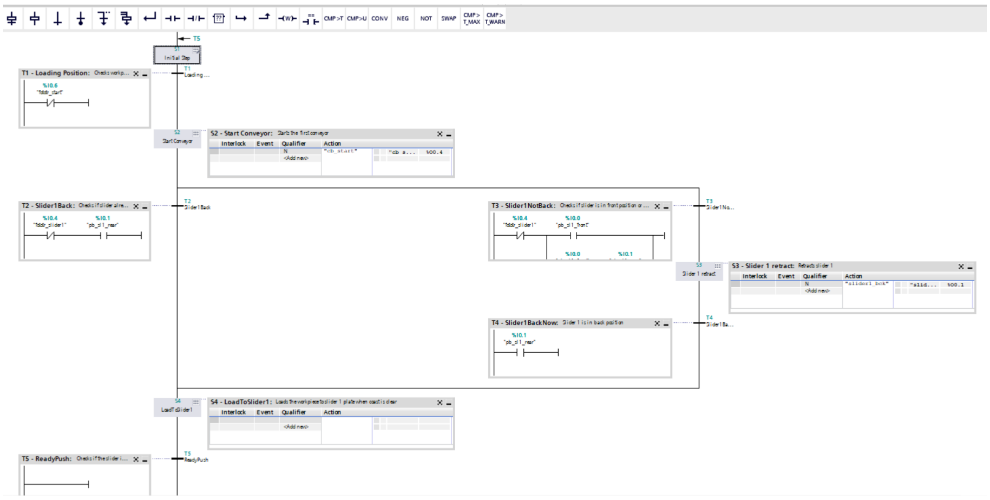


Figure 4.2: The preconfigured TIA Portal project provided to the students

overwhelming to do at this setup stage, and it did not contribute much additional learning. The choice was made to focus the students' attention on programming the SFC, viewing this as the core activity and what they derived the most understanding out of, taking care to **7) Don't introduce too many concepts at once (Section 2.5.1)**.

D: Making the program

Having seen the "Hello World" in Figure 4.2 play out on the training model, the students are to start making and completing the program themselves. They are then provided with learning materials on how to program in TIA Portal. At first, they were only provided with a youtube video by YouTuber Hegamurl providing an introduction to sequential programming in TIA Portal[47]. The students generally responded positively to this, saying it was a great help in learning to interact with the program. However, some stated that they would also like some written learning materials for this. Therefore, a chapter explaining Sequential Function Charts and how to program them was included for version 3. This made for a noticeable change in that students needed much less help getting started with their program after this addition. The video and this written chapter should also be provided in the final version of the assignment as they supplement each other and address that individual students learn differently.

E: Common errors

The project thesis provides the suggestion ***13) Provide a list of common errors (Section 2.5.1)***:

> "Interviewees made it clear that this was desired. Assignment of this

> kind often have common errors, or easy pitfalls. Listing up these errors can avoid too much time being spent on these, and free up the teaching assistants for other questions. This can also help in making the assignment foolproof. These errors are probably not readily apparent before the first implementation of the assignment, and should be garnered from the feedback and teaching assistant experience."

This is included as the final part of the assignment text, and is absolutely something that needs to be used in the OCW as well. This does not mean that the students should not do any problem solving on their own. On the contrary, it means providing solutions for errors that are difficult for students to identify by themselves, thus preventing these errors from derailing the entire assignment, allowing them to focus on and complete the core activities.

In versions 1 and 2 this was included in a list of tips in the final section of the assignment. This list was expanded, and the errors were extracted to their own chapter for version 3. In particular, the subsection about software issues was expanded during testing as new issues were discovered as the students performed the assignment. The debugging functionality in the TIA Portal GRAPH environment is lackluster, generally only stating that an error has made the program uncompilable, not stating at which transition or step the issues occurred. Early on, many students got issues stemming from the **No Ending Instruction** and **Unclosed Branch in Transition** errors, which can be challenging to find if you do not know what to look for. This was in large part remedied when this was included in the list of the common errors in the assignment text.

There is also a list of hardware issues that might occur. The training model is made up of moving parts, and these will periodically go out of position due to vibrations and such. In the future, the training model must be maintained between assignments to prevent this and, more importantly, prevent damage to the equipment ***5. Make it foolproof (Section 2.5.1)***.

Of particular interest is the one named "**Slider of the track?**". When working on the program, students often make wrongful transitions pertaining to the limit switches of the sliders. This can cause them to go off the rails on which they are mounted, and fixing it in their main TIA Portal project is cumbersome as it involves creating additional steps and transitions which will later need to be removed. Thus, an extra TIA portal project is provided to the students, allowing them to easily move the sliders back into the correct position by placing their hands over the phototransistor to move it backward or forwards.

4.2.2 Example of Functioning Program

Figure 4.3 shows a full operation of the training model with a SFC programmed in the sequence graph environment of Siemens TIA portal, with short descriptions given for the steps and transitions. Further descriptions of the program variables and which sensors and actuators they correspond to can be seen in the tag table in Figure 4.1. The qualifier "N" used in every step sets the action to high while the step is active. Figure 4.4 shows images from such a operation.

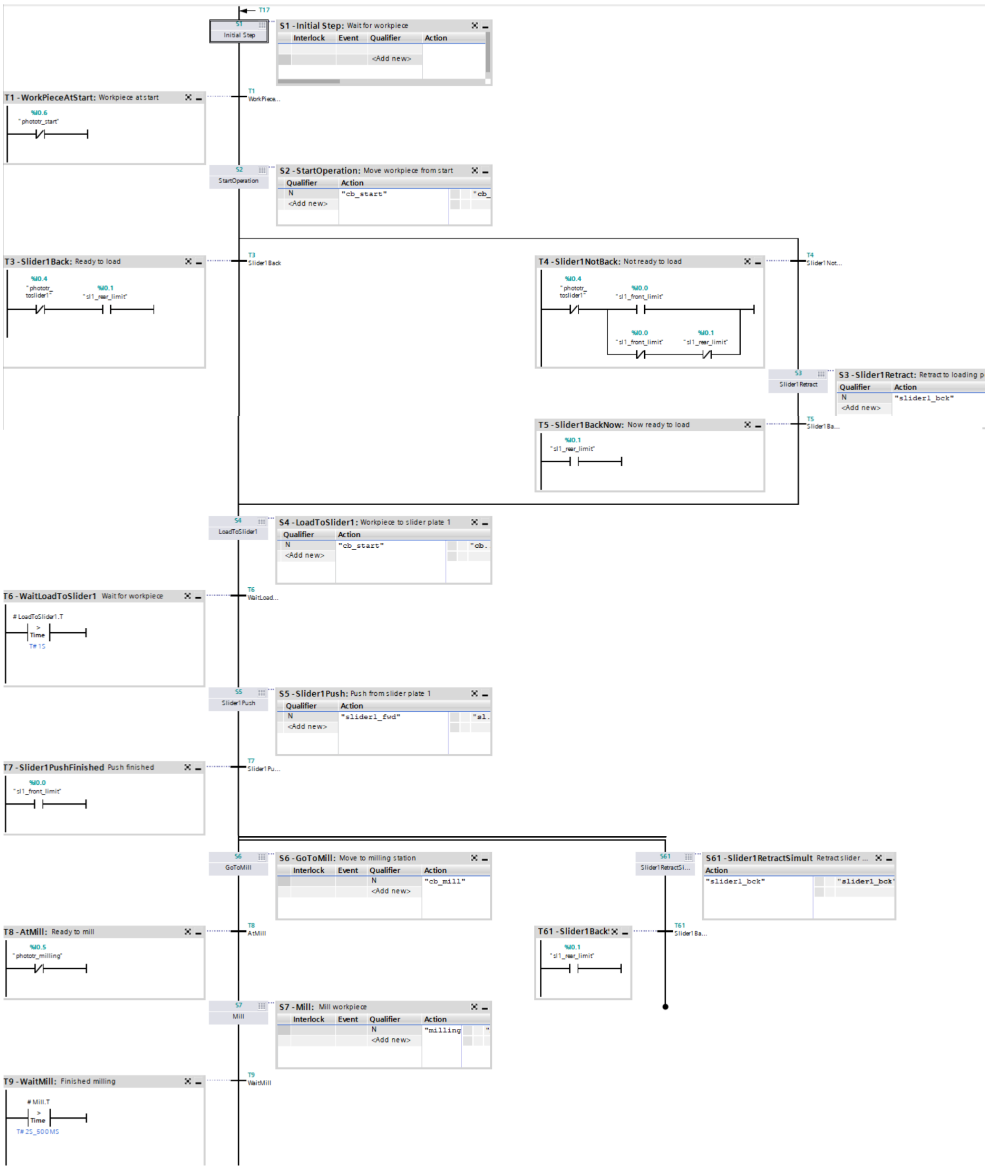


Figure 4.3: Siemens TIA Portal Sequential Function Chart (SFC) for full operation of training model.

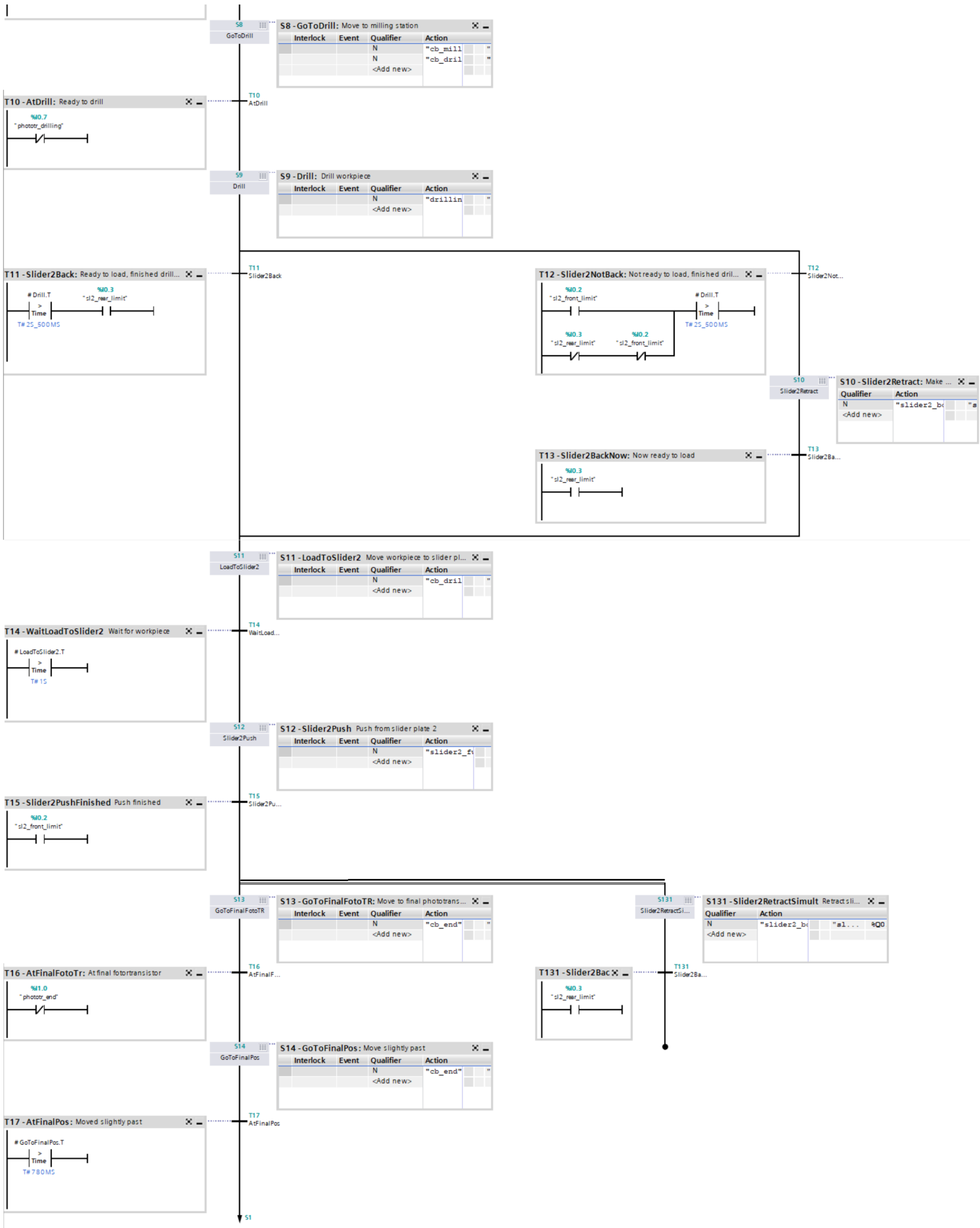
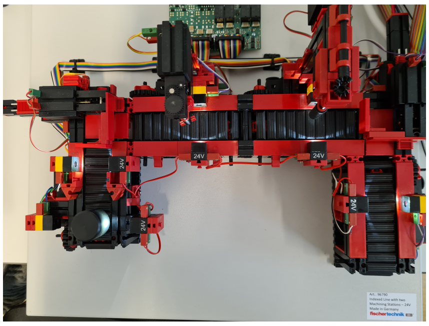
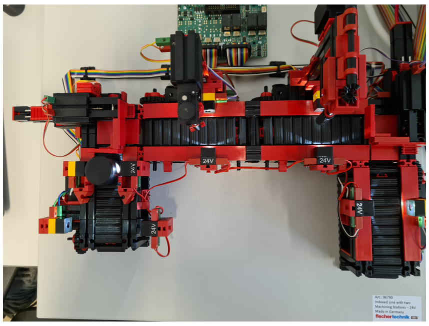


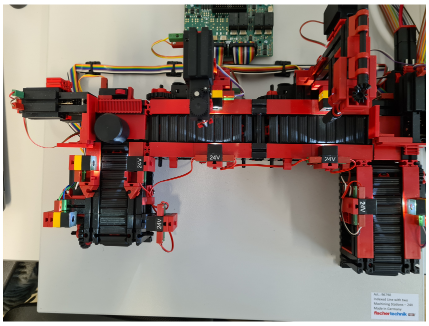
Figure 4.3: Siemens TIA Portal Sequential Function Chart (SFC) for full operation of training model. (cont.)



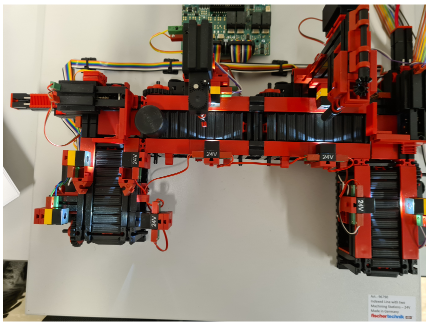
(a) S1 $\xrightarrow{\text{T1}}$ S2



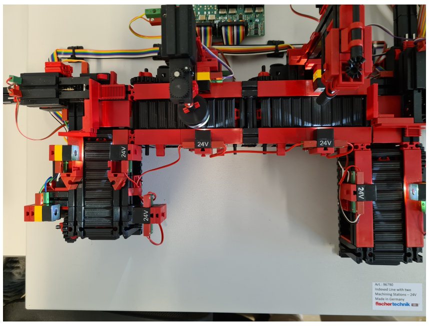
(b) S2 $\xrightarrow{\text{T4}}$ S3 $\xrightarrow{\text{T5}}$ S4



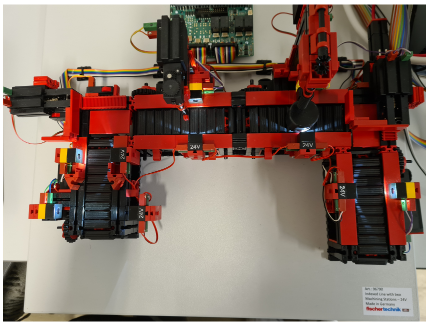
(c) S4 $\xrightarrow{\text{T6}}$ S5



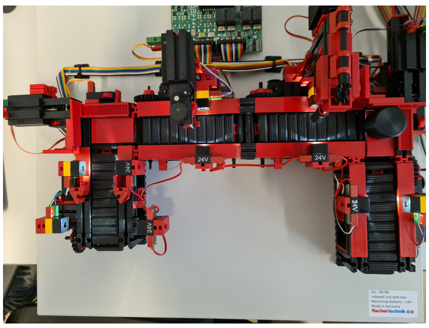
(d) S5 $\xrightarrow{\text{T7}}$ (S6 **and** S61 $\xrightarrow{\text{T61}}$ end)



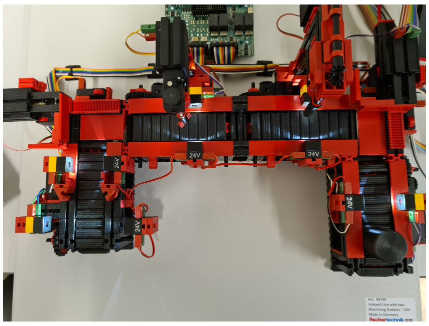
(e) S6 $\xrightarrow{\text{T8}}$ S7



(f) S7 $\xrightarrow{\text{T9}}$ S8 $\xrightarrow{\text{T10}}$ S9



(g) S9 $\xrightarrow{\text{T12}}$ S10 $\xrightarrow{\text{T13}}$ S11



(h) S11 $\xrightarrow{\text{T14}}$ (S12 **and** S131 $\xrightarrow{\text{T131}}$ end) $\xrightarrow{\text{T16}}$ S14 $\xrightarrow{\text{T17}}$ S1

Figure 4.4: Main steps of a full operation of the Indexed Line training model[1] with references to steps/transitions in Figure 4.3

4.2.3 How did the students fare?

Every single group of students was able to complete the assignment in the allotted time or less, with an average time of 2 hours and 21 minutes [19]. Most of the groups followed a similar pattern. With reference to the test structure described in Section 3.6:

1. Students were allowed into the room. A short introduction was given to the equipment for the first six or so groups. However, when testing without giving this introduction, it became evident that students did not require it as the assignment text adequately served this function. This was then omitted for the latter half of the testing groups to better simulate an actual assignment context.
2. After an average of one hour and ten minutes, the students would ask for help for the first time[20]. Most of the time up to this point was spent reading the assignment text. The students would generally be at the stage where they are preparing to offload the workpiece from the first slider. A common issue was their struggling to understand precisely how transitions function and the flow of the program. Some other groups had misunderstood how to use timers or wrongfully implemented the limit switches.
3. Students would generally spend half their programming time getting onto the first slider and off of it. However, when they finally overcame this first obstacle, they would intuitively understand the program. The rest of the programming was then accomplished relatively quickly.
4. Some students asked again for help after this. Some were struggling with the branch for loading to slider 2, others encountering a software compilation error due to **No Ending Instruction** or **Unclosed Branch after Transition**, as described in the common errors section of the assignment texts, see Appendix A. However, they were mostly able to work through these errors by themselves.
5. As they started to finish their program, some students would attempt to operate the training model with multiple simultaneous workpieces,

[19] Assuming four hours are allotted for the future implementation of the assignment, this might mean space for additional activities. However, it should be taken into consideration that more practical issues might occur in the future. The TA might be busy helping other groups and will not be as experienced with the equipment as the test leader was during the prototyping. Furthermore, one should not add additional activities just for the sake of it. If students can learn the required concepts in a shorter time, that is good. If additional activities are added, they should expand on the program the students are to implement, not have them spend more time in setup.

[20] One group completed the entire assignment in just 1.5 hours without help except for the assignment text. Upon further inquiry, it became clear that two of three group members had experience with Lego Mindstorms[48], and the third had completed the PLC assignment (number 12 in the OCW), which might explain their skill. Three other groups were also able to complete the assignment without help but in more time. A fifth group would likely have been able to do so but was subject to check-ins.

which is not doable for reasons discussed in Section 3.5.2. The final version has clarified this to prevent the students from exploring this dead-end.

6. As there was an average of 39 minutes left after the students had completed the assignment, there was time for an exit interview in most cases.

Among many other things, the testing has reinforced that students can learn and apply fairly complicated new activities if they are provided this task in a structured manner and given enough help to get started. This is one of the most important insights gathered as part of this work and should serve as an example for the OCW. It can be argued that the Indexed Line Assignment has accomplished this by adhering to the same characteristics as the Linear Systems case study in Section 4.1.2.

4.2.4 New Solutions from Students

Independence and creativity are central criteria for and results of a Deep Learning approach. Many of the groups also implemented solutions that had not been thought of beforehand:

Simultaneous branches

Four groups used a function called a simultaneous branch. This is especially interesting because the function is not described in the learning materials, and they are not told that this is something they should do. A simultaneous branch functions such that it can complete activities in parallel with the main branch of the program. The students used this to retract the sliders again after the subsequent step to slider pushing had been completed.

This is not necessary for the program to function, but it makes for a faster process[21]. Inspired by this, simultaneous branches are used in the implementation shown in Figure 4.3.

Loading to slider without a branch

One of the groups discovered that a branch for loading to the sliders, such as in Figure 4.2 is unnecessary. If the step performing **Slider 1 backward** is simply followed by a transition with **Back limit switch 1 HIGH**, like in Figure 4.5, this will perform the same function as the branch:

- **Back limit switch 1 HIGH:** The program will go through the step in 0 seconds as the transition is instantly activated, keeping the slider in the

[21] One group of students stated that they implemented this because a faster process means higher productivity, meaning that they can relate the assignment work to a real context, ***2) Make it analogous to actual factory situations (Section 2.5.1)***. They similarly stated that having multiple workpieces processed simultaneously would improve effectivity.

correct position for loading. This serves the same function as the left side of the branch in Figure 4.2.

- **Front limit switch 1 HIGH or both limit switch 1 LOW:** The program will retract the slider until it is in the correct position for loading. This serves the same function as the right side of the branch in Figure 4.2

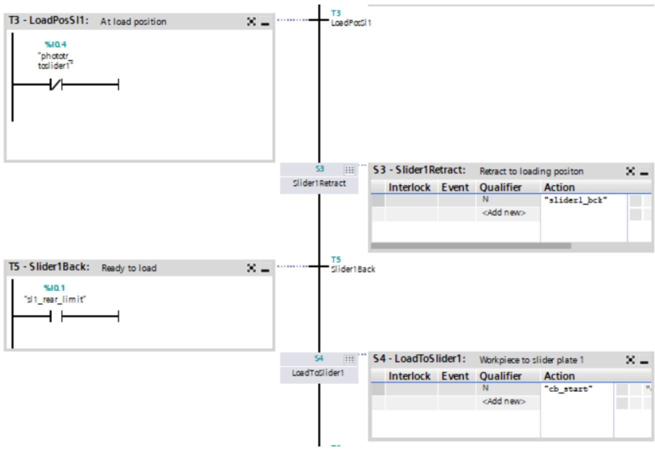


Figure 4.5: Implementation of the loading to slider 1 without using branches, contrary to the corresponding steps in Figure 4.3.

This change makes no practical difference in how the program operates but makes for faster programming. It can be argued that the version *with* the branch has higher readability, and the branch is thus retained in Section 4.2.2.

4.2.5 Deployment

This subsection provides instructions on how the Indexed Line assignment should be deployed as a normal part of the course in the future[22]. This is based on the following assumptions: 1) Students work in groups of one to three. 2) The students have up to four hours. 3) One or two student teaching assistants are available in these hours. 4) A sufficient amount of S7-1500 PLCs with TIA Portal has been procured. 5) The equipment currently available for the course is still available.

- The assignment text and structure herein described can, in large part, be used.
- Ideally, the equipment should be kept ready in its own room for the week(s) the assignment is performed. However, this is perhaps unreal-

[22]A drive with useful materials such as the TIA Portal projects, notes, and more will be sent to the supervisor upon completion of this thesis. These materials do not necessarily fit into the thesis but are of help to whoever will continue this work.

istic with the limited spatial situation at the university. The issue still remains that the equipment is cumbersome to move, so in any case, a TA or similar should set up the equipment in the room prior to the assignment being performed and help clearing it afterwards.
- The proprietary laptops owned by the course should be the students' programming unit, with TIA Portal preinstalled on them with the template project available. Having the students install the software on their personal computers is unnecessary and time-consuming and likely to be difficult with the way TIA Portal licenses are distributed.
- Each group should be provided with a computer mouse as testing showed the software is cumbersome to navigate with a laptop mousepad.
- Every group requires a ethernet cable to connect the laptops to the PLCs.
- Ribbon cables should be made for each PLC-training model pair. Cables should have 26-pin IDC connectors at one end to snap into the indexed line circuit board easily. Separated cables at the other end to be put into the PLC input and output ports. The cables should be pre-wired at the PLC side beforehand to avoid conflict with the existing tag table in the template program.
- This gives an equipment setup for every group consisting of 1) A laptop with TIA Portal, 2) Indexed line training model, 3) S7-1500 PLC, 4) Computer mouse, 5) Ethernet cable, 6) Ribbon cable.
- The TAs should have an available space to work with and familiarize themselves with the equipment and assignment in advance of the exercise hours.

4.3 Suggested changes to TPK4128 course work

In this section, suggestions are given for improving the course work in TPK4128 as a whole. It does not provide a concrete description of exactly how a new course work program should be. However, it offers many suggestions as to what can be added, what should be removed, how existing assignments can be changed, and how they can be made more interconnected.

Some suggestions are made more assertively than others. It is also highly likely that some suggestions will be contradictory. However, this should offer many ideas for improving the course work significantly based on all the feedback and information gathering performed as part of this work.

4.3.1 Other Course Work[23]

Assignment 1: Install a Virtual Machine and Linux on your own computer

While this assignment mostly worked as it should be, students reported that installing something and then doing nothing with it felt meaningless. Furthermore, the assignment text is very short and should be structured as a tutorial for how this is done. There should be some more curriculum-relevant concepts involved. Two alternative avenues for improvement are suggested:

Alternative 1, you merge assignments 1 through 3 together, streamlining them and pulling some parts of those assignments into this one. There is no good reason that the students are asked to familiarize themselves properly with navigating the Linux environment first in assignment 3. Furthermore, they should learn the basics of C here. Provide them with good learning resources for C basics, and then ask them to complete a set of basic tasks provided in a clear assignment text. ***1) Introduce with a simple "Hello world", 11) Provide required actions in a step-by-step structure (Section 2.5.1)***

Alternative 2, you make this first assignment into a software preparation session. Not just having them install Linux and C, but also the other software packages needed for future assignments and configuring the Raspberry PI. More experienced help can be brought in for this session to help with issues, as some will inevitably occur. This is better than having these issues spring up at random throughout the course, sometimes never being entirely remedied.

A combination of this is also possible. However, alternative one is the most feasible. If alternative two is opted for, the following assignments giving an introduction to C should still follow the suggestions from alternative one. Alternative one is assumed in the description of the following assignments.

Assignment 2: C refresh

First and foremost, it is not fitting that the assignment is named C *refresh* when the students will only have limited or no previous experience. Students also reported that it is simply too open. They will need a degree of handholding when experiencing a new programming language. This assignment should not exist on its own as is. It should either be replaced with a set of basic tasks provided clearly and step-by-step or be melded with the surrounding assignments.

[23] Throughout this section, it can be generally assumed that all the recommendations and suggestions from Section 4.1.2 and Section 2.5.1 are relevant unless otherwise stated. They will sometimes be mentioned to highlight them but will not be repeated for every assignment.

Some might argue that this assignment is conducive to a Deep Learning approach due to its freedom of choice. However, such an argument evades the absence of the necessary structures supporting that freedom[23].

Assignment 3: Basic tools

This assignment is one of the better ones in that it provides the steps and actions throughout, with corresponding explanations, in a well-structured manner. It would fit in better as a part of assignment 1 as it provides an introduction to navigating Linux and C-programming, quite literally ***1) Introduce with a simple "Hello World" Section 2.5.1***. Strangely, it is placed after assignment 2, even though that assignment requires the Linux skills from assignment 3.

Overall suggestion for assignments 1-3 The following provides a suggestion of how assignments 1-3 can be streamlined and interconnected to provide a better introduction to C programming in Linux. The suggestions for later assignments are highly related to these as they too involve C and will exist on the same learning curve.

Assignment 1 will guide how to install and configure Linux with C on a Virtual machine. It will then introduce navigating the Linux environment and guide the students through creating and compiling a Hello World program in C, similar to the existing assignment 3. In the following assignment(s)[24] the students should get a slightly more advanced task in C, introducing them to relevant concepts and programming skills that will be used in further assignments. With reference to Section 4.1.2, all of this should be presented in a well-structured assignment text, giving students clear information about what they are to do and why. Effort should also be made to create tasks with engaging results.

Assignment 4: Multiprogramming and concurrency

This is a significant difficulty spike in the course work. Having previously performed a limited amount of basic tasks in C, they are now asked to perform a long set of tasks involving syntax that will be non-intuitive to a beginner. This assignment gives the students a practical example of what they learn about processing in the lectures, which is valuable. However, it is essential to give the students more help. The assignment text should be longer and give them more clues, more of the code should be pre-completed, and more detailed explanations should be provided as to what happens. There is considerable potential for this assignment to give students valuable insights about processes, but in

[24]Whether the described assignment 1 is followed by one or multiple new assignments highly depends on what is done with the other C-assignments. As assignments 4, 5, and 7 also use C, they too can be significantly changed and shuffled. What is important is that the C assignments are streamlined, and the learning curve is smoothened.

the current form, they spend more time being frustrated at C. Almost none of the students completed this assignment without substantial help from the TAs.

Furthermore, questions should be asked about the importance of Mechanical Engineering students spending this much time doing assignments on the details of low-level computer functionality, e.g., this and assignment 5[25]. While it can certainly be of use, it also competes with various other concepts in the course that perhaps do not feature as much in the course work as they should. It is inferred that assignments 4 and 5 could be limited in scope, instead allowing the lectures to primarily teach these basic concepts. This would then leave space for assignments with more engaging results that could teach skills more relevant to Mechanical Engineering students. As it stands, the degree to which 4 and 5 could be made more engaging and thus promote deep understanding is limited unless significant changes are made to them.

Assignment 5: Memory, errors and time

This assignment is too long, with most students widely overshooting the allotted time. Furthermore, there are a lot of different new concepts involved, and not made clear enough how they relate to eachother.***7. Don't introduce too many concepts at once (Section 2.5.1)***

Having the students create a linked list program from the bottom is too involved to be a subtask in a longer assignment. Linked lists are a valuable tool for understanding pointers, but considering the extensive subject matter of the course, it does not have the luxury to provide this much real estate to linked lists. Knowledge of pointers could be provided through more straightforward means. At the very least, the students need to receive more help in creating this linked list program than they currently do.

Assignment 6: Linux on Raspberry PI

Some students completed this assignment in as little as 15 minutes. Installing Raspberry PI OS is very easy with the new Raspberry PI Imager[37]. This being its own assignment is likely a remnant from previous years when this process was more involved, as is evident by the assignment text referring to the Raspian distribution (later replaced by RPi OS). As it stands, this assignment should be extended with the students doing some tasks on the Raspberry PI, perhaps installing the software distributions needed for the remaining assignments, doing some programming, or even using some of the RPi sensor modules at hand.

It is problematic that there are not enough Raspberry PI V4 sets that the groups

[25] If the course were intended for Computer Science students instead, this would be entirely different.

can have their own for the duration of the course and take it home. They can take home a Raspberry PI V4 without the corresponding cables, but this creates a problem with them likely being required to buy micro-HDMI cables as these are not widespread. When the students have to put back the RPi V4 sets they have used, they might have to reinstall the software and maybe even the OS between assignments as they will not necessarily have the same one as last, notwithstanding their files.

There are also many RPi V2 they can bring home, which interface with HDMI. However, these are slow and, most importantly, do not have an integrated networking card. At the very least, each group should have its own RPi V4 set for the course duration. It is also paramount that the room the assignments are in has screens to which they can connect their RPis.

Assignment 7: TCP/IP Sockets

If just one assignment is substantially changed, it should be this one. The seemingly basic tasks the students are to complete take a tremendous amount of time, and very few students complete them. The TAs also struggled to create a functioning solution in advance of the exercise hours because of the lack of a suggested solution being provided to them.

The core of this assignment is that the students learn about basic server/client communication, which is valuable. However, it buries an arguably unexciting result and limited learning outcomes under a mountain of programming syntax. With the little reward, a heavy workload, and no real choice over solution or opportunity to pursue the subjects in-depth, this assignment is almost entirely conducive to a surface learning approach.

There is a large potential to improve this assignment by abstracting it. If the students were to interact with software that provides basic server/client functionalities, this could allow them to do more activities and produce more varied and interesting results. This would better demonstrate the core concepts and use cases of TCP/IP instead of focusing on the minute details of implementing it.

Assignment 8: OPC UA Server/Client

In contrast with the previous assignment, this one is almost entirely completed beforehand. The students will install a few packages, download a repository, and change the IP addresses — trivial work. The only thing the OPC UA client does is act as a counter, which does not aptly illustrate the capabilities of OPC UA and why to use it. At the very least, students should be provided with more tasks to perform. To accomplish this, it is suggested that this C-based OPC UA implementation in open62541 is replaced, as expanding it in C will be more time-consuming for the students: should the focus be on learning more C or learning about OPC UA?

Freely available software like UAExpert[49] is easy to use. Using this, students can add more variables and have multiple servers and clients interact.[26] This would serve as a better learning example for OPC UA, what it is, what it can do, and why to use it. ***2. Make it analogous to actual factory situtations (Section 2.5.1)***. Furthermore, the learning about OPC UA here can be connected to a later assignment using OPC UA with a PLC and the training model, introducing it here and reinforcing it later, see Section 4.3.3.

Assignment 9: Building a webcamserver using OpenCV and Python

A large practical difficulty in this assignment stemmed from dependencies. The package from the Github repository installs the required dependencies for performing the assignment. However, it relies on antiquated versions of some of the packages, which either conflict or are unsupported in newer versions of both OpenCV and Numpy. This was observed when preparing to TA a month in advance, and over three hours were spent troubleshooting and then installing and uninstalling legacy versions of Numpy and OpenCV to get it to work. It was reported to the guest-lecturer in charge of the assignment, but the person did not fix this in time for the assignment. Luckily the TAs could provide the students with knowledge of how to fix it when they performed the assignment, but it was still time-consuming and unnecessary. This must be fixed before future iterations of this assignment. It would be far worse had it not been that one of the TAs had much more time than usual to prepare and could find out how to solve it.

This speaks to the general need for maintenance and for a person to control every assignment in between iterations of the course to ensure they continue to work as intended.

Excepting this, the assignment is one of the stronger ones in the OCW. It speaks to several of the stated desires of the students. It is built up with sufficient handholding that the students get started, but with enough left undone that they write a good amount of code themselves and get better at both OpenCV and Python in general. Furthermore, it provides an observable result for the work performed with the video feed.

It also has much potential to be extended. The course work does not sufficiently show the use cases of OpenCV. You do not require OpenCV to create a webcam server; thus, creating one does not tell the students enough about what OpenCV is and why it is important. If a part were implemented where the students performed simple image recognition or similar, this would aptly demonstrate the capabilities of OpenCV.

[26] Keeping the connectivity with C in other assignments, the C open62541 client can easily subscribe to the server in UAExpert, in combination with other clients. While keeping it as a component of a larger assignment, it can give an example of how OPC UA can relate to C without spending too much time configuring it.

Assignment 10: Implement a ROS2 camera node using OpenCV

This assignment also provided practical issues, with the ROS2 distribution requiring an Ubuntu OS. Many students had Ubuntu on their virtual machines, but the Raspberry PI is a better place to work with this assignment than VM. However, the students generally had Raspberry PI OS installed, as Ubuntu runs very slow on an RPi. Therefore, they were generally unable to install ROS2 on their RPis, a problem that needs to be fixed.

Furthermore, this assignment is almost purely a tutorial, with the students copying and pasting code from a repository. Again, there should always be some code or actions that the students do independently. Few students completed this assignment partly because of the issues described above and partly because students were tired of the course and busy finishing other assignments. Some of those who completed it said it was interesting to see ROS, but wished they could do more with it. The question should also be asked whether such an assignment fits better in the robotics courses TPK4170 and TPK4171[27]. Students state that they wish for more practical work in these other courses, as it is almost non-existent currently. TPK4128 cannot stand for all the practical work in the department's robotics specialization. This time could perhaps be better spent going more in-depth with other capabilities of OpenCV, instead of ROS.

It should also be stated that when the students get to this part in the course, work is a painpoint how many different languages, technologies, software, packages, and interfaces they have to install. In turn, they only get a surface-level understanding of them. Furthermore, it seems arbitrary which few concepts they get to explore in more depth.

Assignment 11: Three-phase electricity / Brushless DC

Without the ELVIS boards, this assignment has gotten negative feedback. The boards will be available in the future. However, even with the Elvis boards available, this assignment is very different from all the other course work. Students have suggested that it be moved back to the precursor course TPK4125. Three-phase electricity and brushless DCs are part of the curriculum, Table 2.4, so one could argue that these and related concepts should be reflected in the course work. However, work should then be done to make it more engaging. It should also be more intertwined with concepts and activities in the other assignments.

The recommendation is to remove this exercise to make space for more as-

[27]TPK4170 - Robotics[50] and TPK4171 - Advanced Industrial Robotics[51] are courses provided by the same department, MTP. Furthermore, many of the students in TPK4128 will take a *Robotics and Automation* specialization in their degree. Robotics and computer vision are integral parts of both courses.

signments with the indexed line. The students will have received a practical demonstration of similar technologies in previous courses.

Assignment 12: PLC using FB and SFC

As it is, this assignment should be scrapped in its entirety. Students are simply following along with a video without doing any problem-solving themselves. This is not engaging. Teaching PLC programming should instead be left to the ILA

4.3.2 Project work

An intriguing opportunity is to replace multiple assignments with a larger group project. Gibbs [46] and others find that such works are highly conducive to deep learning. Such a project should, to an extent, allow students to select a problem, or at least allow freedom in choosing their solution, while still having a base framework as part of the project description. By allowing students to engage in independent problem-based learning, they will experience ownership. Their product can be more extensive than a base assignment (greater mastery), and they will generally be intrinsically motivated to learn the things necessary to solve emergent problems. Project work should come towards the end of the course when students have built up their skills. This is a radical change to the course work structure, but one that would likely produce positive results if correctly implemented.

4.3.3 Further Indexed Line assignments

From the questionnaire results and the feedback in exit interviews, there is a resounding yes for more assignments with the training model. The project thesis (see Appendix B) states that:

> "Implementing this[28] alone with simple ladder logic control is a substantial and worthwhile task for the students. However, there are many different opportunities for expanding on this concept, including different methods of logic control, batchwise operation with collision prevention and using communication protocols like OPC-UA for remote control or cooperation between training models. It should be strongly considered to implement this as not one, but several consequent assignments, be that in both TPK4125 and TPK4128 or with several in TPK4128 alone."

It also provides multiple suggestions for what this can include, ***Suggestions 14.-20. (Section 2.5.1)***. These ideas have further matured throughout the work

[28]Note: This references programming a full operation of the workpiece through the training model, as the students have done in the ILA

with the master's thesis. The training model can be used to better teach some of the concepts in the OCW or elaborate on them by providing an example of their application, thus creating a deeper understanding. It is also desirable that such expensive equipment should be capitalized on beyond one single assignment[29].

The assignments suggested can not all be implemented but provide some ideas for how it could be done. Further work might uncover better ways of implementing them or new ideas. However, this thesis strongly suggests that some form of further ILAs should be deployed. This subsection will, for simplicity, be based on the assumption that these assignments are implemented in TPK4128; however, they could also prove valuable in other related courses[30]. The suggestions provided below provide ample opportunity for lines of inquiry in further project and master theses on improving TPK4128, as will be reiterated when future work is proposed in Chapter 6.

ILA with OPC UA

Perhaps the most intriguing possibility is to have the students ***17. Control the training model remotely (Section 2.5.1)*** in a continued ILA. Originally, the intention was to design this as a part of this master's thesis. However, this was not possible because of PLC acquisition issues as previously covered. Such an assignment allows the possibility to reinforce concepts from several earlier assignments and cause a greater interconnectedness throughout the course work. A demonstration of how the general structure of this could look is provided in Figure 4.6. It would not necessarily replace earlier assignments but rather show the practical use of the technologies. The contents could include:

- The students will control the training model from a different location, with a setup similar to Figure 4.6
- They visually monitor the training model by reusing the RPi webcam server from assignment 9, streamed to their remote computer[31]
- Using the proprietary in-room laptop, students first set up an OPC UA server on their PLC in Tia Portal. Newer S7-1500 PLCs and TIA portal has extended functionalities for this.
- They access this from the remote laptop acting as an OPC UA client. They should do some work in configuring the OPC client and server, but this should be partly done for them beforehand in order to ensure the assignment is not too involved, particularly considering that the programming

[29] One should vary of a sunk-cost fallacy[52]. Having purchased something expensive should not inherently mean that it needs to be used further. Luckily, other factors point to the fact that further ILAs are in fact of use.

[30] If more advanced PLC control is desired in TPK4128, the ILA can be moved down to the precursor TPK4125 Mechatronics which almost all the students will have anyways.

[31] This can be extended to further use the capabilities of OpenCV. For example, by performing computer vision on the training model identifying the position of the workpiece.

will likely have to be in .NET C# which they will not be familiar with[32]. Siemens also provides a downloadable OPC UA .NET client that can be used as a basis for this purpose[53].

- A simple user interface can either be made for the students or as a part of the assignment to create a dashboard for monitoring and operating the training model.
- Students will not program the PLC GRAPH chart from their remote computer, as this is not doable over OPC UA and needs to be done on the proprietary in-room computer connected to the PLC. Furthermore, they will have already done the work with making the PLC program in the earlier ILA. Instead, they will monitor the data and positions from the PLC. Mechanisms for remote control of the PLC can also be implemented, a simple version of which is using the "tap" functionality in the GRAPH environment where students toggle a button for the PLC program to begin or progress steps.
- The value of such an assignment is partly to show the ability of OPC UA to create seamless communication between different types of systems. If more devices than described above are involved, this assignment would be even better for promoting this understanding in students. The webcam server can perhaps be made to connect to OPC UA. If multiple pieces of equipment like different training models, robotic arms, or AGVs, as discussed in the other Indexed Line Assignment possibilities, they could also serve as OPC UA servers and clients. ***20. Extend the monitoring data (Section 2.5.1)***, is a possibility and could be done with simple additional sensors.

Training models interacting with each other

When suggesting ***15) Have two training models interact***, the project thesis states:

> "In order to promote teamwork, and the exchange of understanding between groups, it should be considered implementing a part where two factories interact. This can teach the students about a broader factory context. For example, two groups can put their Training Models together, and have them interact through OPC-UA or similar. An additional mechanism needs to be created to transport the workpieces between the two factory lines, this offers new opportunities for extended learning. The easiest implementation of this is the student "acting" as a robotic arm or factory operator, and physically moving it themselves, but more advanced and creative solutions are also possible. One can implement some sort of

[32] As discussed above, the current OPC UA assignment 8 could and should be extended, and could be tailored to prepare them for this part.

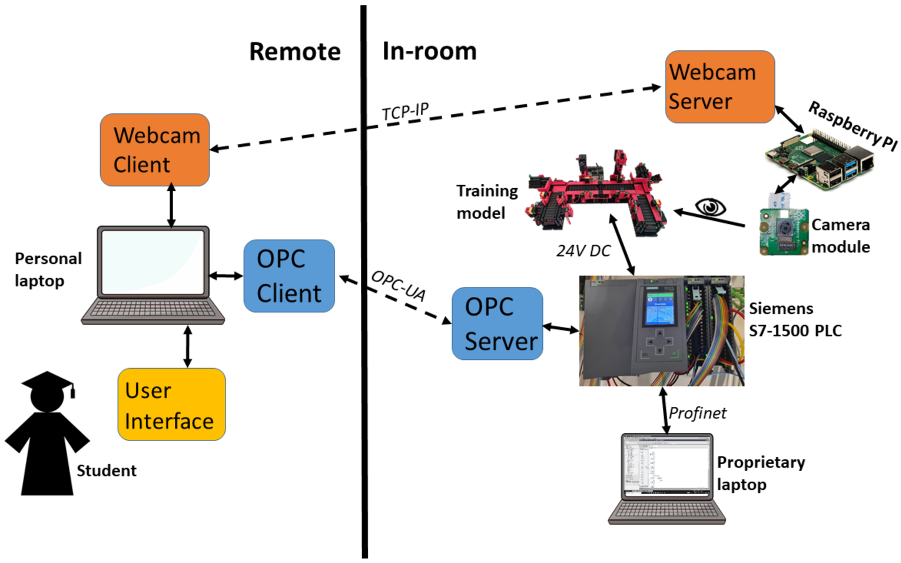


Figure 4.6: Demonstration of how an assignment with remote operation of the training model through OPC UA could look like.

> miniature arm or loading platform moving the pieces between the models. Or, one can extend the factory "metaphor" further, making a miniature Automated Guided Vehicle (AGV) for moving the piece between them. This can be done autonomously or through remote control. Whichever way it's implemented, it offers opportunities to learn students about new subjects from the course learning objectives."

Hereunder also lies the opportunity for using different types of FischerTechnik training models, as there is a large variety[54]. Depending on the extent of such activities, this can be integrated directly into the base ILA or in further assignments. Particularly the possibility of designing an AGV or robotic arm (which can also be purchased from FischerTechnik) is an interesting opportunity for further work. If this additional equipment is not purchased but instead built by a master's student or similar, the challenge is then to make it such that it is possible to scale up the quantity of this new equipment such that the whole class can use it.

Virtual lab/digital twin

Another possibility briefly discussed in the project thesis is to ***16. Create a virtual lab/digital twin*** for the course, with reference to Ilc and Lotrič [32] and Gil *et al.* [30] for how this can be implemented. This can provide valuable examples to Industry 4.0 and Internet of Things where digital twins are an integral part. This could be integrated with the further ILA suggestions made above and is particularly intriguing concerning OPC UA.

Simultaneous operation of multiple workpieces

As previously discussed, it is difficult to have the simultaneous operation of multiple workpieces, such as in Figure 3.2 using the Sequential Function Charts in the ILA. However, this is a possibility for a further assignment, using Structured Text (ST) or a similar function-based logic control instead, ***14. Look to other modes of logic control (Section 2.5.1***. However, as there is limited time in the course, care must be taken to ensure that such an assignment is sufficiently different from the other ILA. It is likely that doing such an assignment right after controlling the training model in the ILA, is viewed as repetitive and not teaching anything new[33]. The operation of multiple workpieces should then be integrated with other new concepts or in a situation where the original ILA is moved to TPK4125.

[33]Beyond learning a new type of PLC programming. However, the goal of the course is not to become a master at logic control; it is the whole range of the desired learning outcomes, Table 2.4

Chapter 5

Discussion and Conclusion

This chapter features a discussion on the work conducted, before a conclusion summarizes the thesis.

5.1 Discussion

This section discusses important aspects of the work performed. It features an assessment of the success of results and equipment involved, what remains to realize them, and an analysis of external factors that can serve as roadblocks. There is also a discussion on the students' responsibilities and action patterns and how these can be influenced. Lastly, it features a general discussion of the success and applicability of user-centered methods like Design Thinking in designing educational content.

5.1.1 Assessment of Results

This master's thesis has more or less addressed all the points in the problem description (Section 1.2). What now remains is to evaluate whether the resulting assignments, findings, and suggestions are conducive to improving the course work of TPK4128 and what remains for this to be actualized in practice.

Indexed Line assignment

From the quantitative and qualitative data collected, it can be concluded that the assignment made with the training model is a success. The students have found it to be engaging, educational, relevant, and well-functioning, while answering to the desired learning outcomes of the course. Furthermore, it seems that it remedies many of the errors with the OCW, and can thus function as a helpful guideline when working to improve the other assignments in the course. The ILA is realizable in a full class setting, while requiring some technical work to ensure that the equipment is scaled up and ready for deployment. The core assignment itself can be used with only minor changes. It is paramount that this work is done in good time before the next iteration of the course and that it is done properly. If not, then the assignment will not be successful in practice.

Some emergent issues will likely be encountered in a scaled-up version that have not been identified in this work. These should be noted and iteratively fixed. The assignment is moderately resource-heavy on the side of maintenance, and one of the chief concerns at this stage is that it will progressively deteriorate in the future if the requisite personnel is not in place to maintain it, as there are many potential error sources with the equipment. Moreover, it requires the teaching assistants to be more familiar with the equipment than an average assignment. However, it should be possible for a teaching assistant to guide a full class considering the frequency of help requests in testing and the amount of information and help provided in the assignment texts, barring large-scale unpredicted technical errors.

Other Course Work

Similarly, it can be concluded with reasonable certainty that there are many issues with the current course work that should be fixed for the course to reach the desired quality. With reference to longer descriptions of both problems and potential solutions in Chapter 4, common issues stem from the assignments being:

- ill-maintained,producing frustrating practical issues
- too difficult or too shepherded for the students to experience independent mastery
- too poorly explained for the students to understand what they are to do and why
- not engaging or of low relevance

However, it is also likely that the course has a high level of potential considering the width of concepts and technologies it can draw on and the students' general level of interest in the subject matter. TPK4128 can likely be a successful course if the problems are remedied.

Significantly changing the entire course work is no easy task and a time-consuming endeavor and will likely need to be progressively done over the mid-to-long term. Conditions are also continually changing, meaning one is never truly done improving a course. However, some of the suggested changes can be realized already in the coming semester. In particular, changes to how assignment texts are structured, what information they provide, what degree of assistance the students get, and streamlining of the assignments are achievable in the short term. Chapter 4 gives many suggestions and guidelines for how to do so, but does not give a detailed explanation of how every assignment should be changed. This means that it lies upon whoever will continue the work to discover exactly how that should look based on those suggestions and the described methods for getting helpful feedback from students.

For the course work to reach the optimal level, some larger changes are also required. The course work could likely benefit from certain assignments being entirely scrapped and replaced with new assignments that better realize the concepts of those assignments. This can be time-consuming, particularly as the most engaging practical assignments benefit from equipment and technologies that are resource-heavy to implement, maintain and supervise. This highlights a larger issue. While it is easy to make suggestions for many activities that the course could stand to benefit significantly from, this is all still entirely dependent on the conditions placed upon the course. It seems highly likely that many of the issues that plague TPK4128 and similar courses at the department are symptomatic of the course coordinator simply not having enough time to adequately maintain, design, and control the quality of the assignments. These external conditions need to be improved for it to be possible to realize the potential of the course fully, and this will be further discussed in the following.

5.1.2 Lack of Necessary Educational Personnel

The need for continuous quality control and maintenance of the lab exercise program can not be stressed enough. Besides the clear benefits of incremental development towards achieving an outstanding program, this is also necessary to avoid emergent errors with time. The software used is constantly subject to updates and changes. An updated version of the involved software can suddenly lead to the assignment not functioning, which means significant amounts of unnecessary wasted time for students and teaching assistants or them not being able to do the lab exercise at all. Thus, before every semester, involved teaching personnel should improve exercises based on feedback, and control for and fix any errors that might occur. This is not properly in place for the course as is, and many of the issues described for the course are symptomatic of this quality control not taking place[1].

What is currently available

The educational staff currently available for the course is the professor, a few guest lecturers, and two teaching assistants. Because of the low amount of educators in the mechatronics section of the department, the professor is responsible for five other courses throughout the year, along with scientific pursuits, administrative work, supervising masters and Ph.D. students, and many more tasks. This packed schedule leaves limited time to focus on improving

[1] An example is the software package dependency problems described for *assignment 9*, which would be fully fixable in advance. As they were not, this led to large, unnecessary complications with what would otherwise have been viewed as a decent assignment

the course work. The teaching assistants have 100 hours each throughout the semester, most of which is eaten up by preparing for and supervising the assignments. The degree to which they can be tasked to improve the course work is limited by both their time and their level of competency, considering they are ordinary students. The guest lecturers can be tasked with doing some work on creating assignments, something they currently do, but they too have to balance this against time spent on their own courses. Additionally, master's students can be tasked with improving it through their theses, as has been done here.

It is then evident that the amount of time and resources available for improving the course is severely limited. It follows that it is hard to see how the necessary changes to the course can be sufficiently realized without changing these underlying conditions. Moreover, information gathered from students and educators throughout this work indicates that this is not just a problem with TPK4128, but at MTP as a whole, and one that has progressively worsened over the years.

Scientific Assistants

This calls for the need for persons who can aid the educator in providing and improving the course work, beyond the TA. One such solution is using Scientific Assistants, who are Ph.D. students doing educational work alongside their thesis. These will typically have more time to spend on the course and a higher level of competence than a TA. SAs have previously been used successfully at MTP. However, in recent years the policy at the department has been not to use them[2]. Throughout this work, courses at other departments which have been held forth as positive examples, commonly use SAs. For example, the department of technical cybernetics (ITK), which provides the Linear Systems course used as a case study in Section 4.1.2, has successful laboratory course work in similar subjects to mechatronics much because of the use of SAs[3]. MTP should strongly consider changing its policy towards using SAs, as it could significantly improve its courses, freeing up time for the overworked professors to focus on their other tasks, including lectures.

Prioritizing Education

While the educational content at MTP has arguably become progressively worse in the last few years, the department has continually moved up in publication points and other measurable indicators, implying that focus has been placed

[2]Another aspect influencing this is that fewer Ph.D. students chose to enroll in this education work during their thesis period, instead focusing on finishing in a shorter time.

[3]However, ITK has also recently lowered their use of SAs, which some state has caused the laboratory course work to deteriorate there as well.

on more profitable activities at the expense of education[4]. This is unfortunate, particularly as well-implemented practical laboratory assignments provide significant benefits as described throughout this work. This is not realizable under the current conditions. Even if scientific assistants are not used, at the very least, something has to be done to ensure that the educators have more time and resources to ensure the quality of their educational activities. This is, of course, not upon the department alone but also dependent on the policies and funding of the faculty and university directed towards education. The Norwegian state is also a vital actor here, providing most of the university funding and designing the incentive-based finance structures for goal achievement in different objectives.

5.1.3 Assessment of the Required Equipment

This project has, from the beginning, been based on the information that multiple FischerTechnik Indexed Line training models and Siemens S7-1500 PLCs had already been ordered, meaning this exact equipment is a given initial condition for the work performed that could not be changed[5]. However, an assessment should still be made of whether this is the correct equipment for this work's stated purposes, given the equipment's costly nature. It is also necessary to explore what the full potential of this equipment is and if this potential is capitalized upon.

In a development project, it is typical that requisite equipment is first ordered after a preliminary exploration of the solution space and possibilities, while in this process, the equipment was a given from the start. There are indeed alternatives for the equipment and PLC that are better in some aspects.

Alternatives for training model Firstly, it is quite clear that the setup of a FischerTechnik training model and Siemens PLC used in the ILA has proven very valuable in teaching the desired learning outcomes, outperforming the OCW and improving the course. However, there exist similar pieces of equipment that might have served the same purpose. The ILW2MS is not the only training model of its kind provided by FischerTechnik. There are, in fact, many other similar training models, and these could potentially have been used instead[54][6] Many of the models are also modular in that they can be assembled into a greater factory model, but the ILW2MS is not one of these. This is perhaps a lost opportunity, which would have created significant potential for extending the assignment.

[4]It has become one of the top departments in Norway in terms of publication points per academic staff. This is especially unusual for a Department of its size.

[5]It later came to light that the PLCs had not actually been ordered as described in Section 3.1. However, this does not make any difference for the text of this chapter as it was still a given.

[6]There is also a potential for these to be purchased in an extension of the ILA at a later date.

Alternative Programmable Logic Controller (PLC) The exact PLC model that will be purchased for the ILA is not known at the time of writing, but is given to be a part of the S7-1500 series. This is Siemens' top state-of-the-art series, including many additional functionalities over the base S7-1200 series. It is costly equipment, especially when the proprietary and therefore essential TIA Portal licenses are considered. Siemens is also not the only PLC manufacturer; there are cheaper models from other companies. It is also of note that NTNU already possesses a license for Mitsubishis proprietary GX Works software[28], and not for TIA Portal. As it is, the ILA does not use the S7-1500 to its full potential, and the functionality used could be achieved with other variants. However, this leaves the opportunity for this potential to be used in more advanced assignments, not just in this course, but in many others at the department. Finally, it should not be understated that the S7-1500 with TIA Portal did serve as a well-functioning setup for controlling the training model in the ILA, and is of far greater value than not using an actual PLC as is the case for *assignment 12* in the current OCW.

While this thesis has frequently stated the many benefits of practical laboratory assignments; a downside is that they typically imply greater logistical concerns than just using a laptop. If the students were to install TIA Portal on their personal computers, this would likely cause many practical issues, particularly regarding the license. It is then very beneficial that the course has many laptops at hand, and that the software is installed with a license on these before the assignments as described in Section 4.2.5. This equipment is also cumbersome to move and store. Good solutions must be found for moving the equipment in and out of the assignment room and setting it up. Furthermore, care must be taken that the equipment is not damaged during transportation or during the assignment, as particularly the training model is somewhat fragile, ***5) Make it foolproof***. One solution for this is described in ***18) Store the equipment in a proprietary container (Section 2.5.1)***.

In conclusion, the equipment does a good job in fulfilling the intents and purposes of the ILA, and helps make the assignment engaging, relevant, and educational. However, other less-costly variants could fulfill the same function, and the equipment can thus be viewed as somewhat overkill if it is not used for further assignments than the ILA.

5.1.4 Effects of Covid-19 Pandemic on the project

Restrictions due to the Covid-19 pandemic have impacted the course this semester and the two previous years. This should be considered when evaluating this project's findings, particularly as it pertains to the students' experience of the lectures and OCW. There is much from both scientific literature and the Needfinding performed in this work that suggests the pandemic has had adverse effects on higher education, students learn less from digital lectures, they struggle to find structure, are less motivated, have reduced well-being, lab assignments are limited, and they do not get to fully interact with their lecturer or fellow students[55]. Until February 15th, restrictions were in place mandating 1-meter social distancing, 4-day quarantine requirement, and limiting the degree of physical presence allowed on campus[56]. After that, 4-day quarantine recommendations were in place until April 5th.

Restrictions on the Course

The pandemic hindered the course in multiple ways. The first three assignments could not be done physically, only having TAs available over video, which proved suboptimal. Lectures could only be conducted physically in some periods throughout the semester, first because of Covid restrictions and later because NTNU had mapped out the room scheduling with limited physical lectures in mind. This led to most of the lectures being digital and to limited attendance at the physical ones. Covid cases and associated quarantine prevented students and lecturers from attending certain activities. It should also be taken into account that earlier restrictions have negatively affected the previous education of this semester's cohort of students, giving them a lower skill level than would be expected in a typical year. Lab exercises in courses leading up to TPK4128 were also severely restricted. All these aspects served as limiting external factors on the course that are not in place in a typical year. Taking this into account should, to a certain degree, ameliorate the negative student feedback; however, many of the issues raised with the OCW hold true even without the pandemic.

Lowered Motivation

There is also much that suggests the pandemic has lowered the students' motivation[55]. It has inhibited intrinsic motivation because of lectures becoming less engaging and interactive. In terms of extrinsic motivation, it is salient that the exam is *Passed/Not-Passed*, contrary to the letter grades used in earlier years[7]. Without letter grades, it does not make any practical difference whether students get 40% or 100% on their exam, which might limit the degree to which they push themselves. Furthermore, this has effects on the course work as well. TPK4128 Students get points for each completed assignment, which can make up 30% of their grade, encouraging them to complete all the assignments satisfactorily. These points were still in place this semester. However, they are required to get at least 40% on their exam to pass the course independent of how many points they get from the assignments, meaning that in practice, this assignment scoring is meaningless without letter grades[7]. This

[7]The course should continue to employ this assignment grading, as it rewards the student for completing them, extrinsic motivation, barring the current pandemic context. However, care

removes the extrinsically motivational aspects of the course work, beyond getting enough assignments approved to take the exams; however, they can still motivate intrinsically in their own right[9].

Future effects of the Pandemic

While pandemic restrictions will likely be gone for the entirety of the following semesters, removing many of the adverse effects, one should not entirely disregard its impact on education in post-pandemic semesters. The following two cohorts of students enrolling in the course will still have their skill level limited by previous courses occurring in a pandemic context. Furthermore, the pandemic has changed students' study patterns, which can influence how they partake in educational activities in the future as well. Lastly, the pandemic has greatly improved the competency of both students and the institutions regarding digital tools. This experience can be used to improve education from how it was pre-pandemic, with supplementary digital learning materials increasing students' learning outcomes from their courses. TPK4128 has been visionary in this regard, as videos explaining and visualizing important concepts were used to supplement the lectures in the course already pre-pandemic.

5.1.5 Applicability of Design Thinking in Creating Educational Tasks

With reference to the problem description (Section 1.2), part of the aim of this thesis is to "*serve as an evaluation of whether Design Thinking is a viable framework for creating educational activities*". This was also discussed in the previous project thesis (Appendix B), hypothesizing that it indeed is useful, stating:

> "This assumption is based on the nature of university engineering education. It is a fast-changing landscape with new technology and paradigms needing to be implemented into the education in order to ensure that future engineers have the required skills. In addition to this it features a large variance between the users. Students come from all sorts of backgrounds, and thus have different needs. When viewing university education as the educator being the product developer and student being the user, one finds that there is a substantial difference between the developer and user. Difference age cohorts learn differently, students today might be more technologically adept than students 30 years ago, however attention spans are shorter and there might be more distraction in their every day. There is also a significant difference in the knowledge base between the educator and student. Firstly on the grounds that the educator

must be taken not to be too strict in the grading to allow focus on learning during the assignments, which is the primary goal, and avoid suppressing their intrinsic motivation[9][8]. This is the philosophy currently in place for assignment grading in TPK4128, and this should continue.

> has spent a whole career developing his knowledge on the subject. Furthermore, someone capable of reaching the rank of professor in a subject will have a natural inclination towards easily grasping it. This can lead to the professor being out-of-touch with what the students already know, and how easy they learn. As they have a natural level of mastery of the subjects, they underestimate the difficulty other people will have in understanding it. These factors and the large disparity they entail, require the educator to engage with the students in order to be able to understand what they know and how they learn. One framework for doing this is Design Thinking."

These assumptions have been reinforced throughout the work with the master thesis. In fact, the described knowledge gap between students and educators might explain the aforementioned miscalculation in difficulty level and previous knowledge. Furthermore, the conclusion was made that:

> "With some exceptions, the design thinking process here described was successful at gathering understanding of user needs and how to best provide an assignment. The resulting insights and ideas are of great interest to the assignment(s), and some can be applied to creating other educational activities as well (**footnote: Albeit with a grain of salt depending on how dissimilar the subject is with regards to automation**). This understanding would be hard to get at without speaking to and seeking to understand the users. At the very least, it resulted in these truths becoming evident far quicker than they would by sitting at a desk. This holds true for me as a co-student, and would hold even more true for a university educator who is further removed from the student experience.
> ...
> The Design Thinking process of this text is described in such a way that it can be continued by the person resuming this work, and it is recommended that they do so."

These conclusions have been further confirmed in this work. In fact, they have been reinforced by seeing the added value of even more extensive Design Thinking activities in this work and the benefit of undertaking this work with previous DT insights to base it on. Many of the findings and insights of Chapter 4 would not have been encountered had it not been for the field observations, testing, and following exit interviews.

User-Centered activities should find more widespread use

The project thesis emphasizes that it does not suggest that NTNU should widely adopt Design Thinking, citing Carlgren *et al.* [57] that it has been found challenging to implement Design Thinking in large organizations, and this still holds true at the time of writing. Furthermore, it does not suggest that Design Thinking should be strictly used in continued work towards improving TPK4128. It merely states that it is a valuable framework for doing so. However, there is a strong recommendation that the core activities of user-centered methodologies should be utilized far more widely. Simply attempting to engage with students' needs and predispositions through conversation, observation, and/or testing when developing new educational activities or improving existing ones is valuable and is, in many cases, likely to create a better result. A barrier to this is the educators being comfortable and having the time to do these needfinding activities, but they can be helpful even when done to a limited degree.

These theses, with the corresponding literature, might serve as a valuable framework for continued work with TPK4128, or any educator wishing to employ similar methods. However, this does not lie in the hands of the educators alone. The institutions themselves have the opportunity to encourage such activities, create meeting spaces for students and educators, good feedback and mechanisms, and most importantly, provide the educational staff with sufficient time and resources to ensure the quality of their courses.

Shortcoming: The Lack of a Innovation team

The project thesis discussed the possible shortcomings of the Design Thinking process conducted. Regarding innovation teams it states, among other things, that:

> "A significant shortcoming in the innovation process herein described is that design thinking largely entails working in teams, while I *(sic)* did this alone[4][5][6][12]. This lead to me *(sic)* losing out on the team benefits of getting other points of view on subjects, other backgrounds and the additional workforce. Design Thinking teams are preferably interdisciplinary, or at least with members possessing different capabilities. Beckman and Barry [12] suggests learning styles fitting the separate stages as seen in Figure 2.2b. These learning styles are contradictory, and thus it is likely that a single person team will be good at some stages and unfit for others.
> ...
> The process herein described would likely have benefited from teamwork, and for this reason one of the recommendations for future work is that multiple people with different backgrounds are involved, particularly when performing needfinding activities such as testing."

This shortcoming also holds true for this work, where an innovation team was not used, except for the possible interpretation of the author and the course coordinator and fellow TAs functioning as a team. While innovation teams are more important in larger projects than this one, this has likely led to the loss of some perspectives that would be encountered had the work been performed in a team. Furthermore, it is likely to have led to some degree of confirmation bias and tunnel vision. While extensive user information has been acquired in the development process, the final suggestions and this thesis have been written by one person alone. When reading this work, the reader should take this precaution and not assume that every statement is automatically valid. It is merely meant to serve as a basis to build upon, with corresponding tools, in the continual process of improving TPK4128 and mechatronics education in general.

Shortcoming: The Informality of Design Thinking

The project thesis also discusses problems arising from the informal nature of Design Thinking, stating:

> "Design Thinking is sometimes criticized as being too informal or diffuse[58]. It is more a set of tools, guidelines and practices than a strict and rigorous framework. This can make it difficult to write about scientifically, but conversely makes it more practicable. The results of the interview and overall needfinding process herein described are by no means statistically representative. Care was made to engage users with different backgrounds, and also so called extreme users. However, the sample size was 12 at most. A survey with 50+ subjects and clearly defined questions would be more scientifically rigorous, but would fail to get at the underlying needs that Design Thinking does[12]. Design Thinking is a product development methodology and not a way of conducting ethnographic science. The resulting recommendations are suggestions made by the author based on the needfinding process, but can not be viewed as universal scientific fact. When seeking innovation the right questions will not be clear in advance. By allowing the user to set the agenda and being iterative and adaptive with questions one can get a deep and intrinsic understanding of their needs and get ideas for possible innovations. This way of improvising questions, in addition to the individual interviews being more time-consuming than a classical survey, means that it is difficult to extract conclusions of the kind "7/10 students want X". This is a central dichotomy to design thinking, where the same reasons that make it valuable and effective, are the same reasons that make it hard to make objective statements."

The downsides and central dichotomy are also relevant for this master's thesis. However, it is partly remedied by supplementing the DT with the quantitative results in the questionnaire presented in Section 4.1.1. This combination of quantitative and qualitative results is symbiotic, with the different results shoring up the deficiencies in others. The questionnaire results would be hard-pressed to encounter the whys and hows of the student feedback, contrary to the needfinding activities. On the other hand, the quantitative results allow for making statements about the success of the ILA and partial failure of the OCW with more certainty, serving as protection from confirmation bias. However, it is still necessary to emphasize that the results gathered in this work are by no-means empirical facts but suggestions and findings that should be interpreted in moderation and with an account of the context.

5.1.6 Student responsibility

Throughout this thesis, much has been written about the responsibility of educators and institutions. However, the students themselves are also dynamic actors in the course whose choices and actions determine the quality of the course and the learning outcomes they acquire. They have a responsibility to provide good constructive feedback when allowed the opportunity and to engage actively in the educational activities in which they participate. For example, while the quality of the lectures and covid play a role, one could, to some extent, question the validity of the course feedback from students who also say they have barely attended lectures. Students also report engaging in little preparation in advance of assignments. A core principle of higher education is that students are responsible for their learning, and any high-quality course work is insignificant if the students do not participate in it. However, there is a responsibility and considerable potential for the provider of those educational activities to inspire students to desired attitudes and actions.

Can the student action patterns be taken as a given?

An individual course or degree will have a set of expectations and desired modes of engagement from the students. It is then pertinent to explore whether this can be influenced. To some degree, it certainly can be influenced. One can work to instill a specific culture, which is reinforced by the actions of fellow students, TAs, educators, and the institution[9]. The tenets of this culture should be clearly stated and believable, and leaders (e.g., lecturers) must act as a good example in living up to them. Gibbs [8] further states that the approach students take to learning is malleable and is influenced by the context they find themselves in.

Furthermore, there are motivational factors that can be influenced. Extrinsically, exams and assignment grading will motivate students to diligently work on learning activities as it provides a measurable reward[8]. Intrinsically, if the

[8] This is of course partially lessened this year because of no letter grades in TPK4128

learning activities are viewed as engaging and helpful, this will inspire students to complete them and sometimes go above and beyond. On the other side, if educational activities are viewed as lazily designed or ill-maintained, this will not only cause the students to be less engaged in taking part, it will work against the desired culture: "If NTNU does the bare minimum of effort in creating educational activities, why should I do more?". Exams can also inspire intrinsic motivation in students if they are designed to reward a deep approach with subtasks based on reflection and which allow creativity[9].

However, not all students' patterns can be changed. While there are, of course, significant differences between individual students, there are certain traits and study patterns that are common throughout the student body. Many of these traits are firmly in place and difficult to influence. Moreover, they are influenced by external factors beyond the institution's control and change over time[10] . While some aspects of the students' behaviors can be influenced as described above, others are difficult to change. Educators ought then not to design their educational activities based on an idealized student body that does not exist. If the goal is to provide students with the desired learning outcomes, it is better to go with the flow and adapt the education to the changing patterns of the student mass. User-centered product development is a helpful tool to achieve this. This is, of course, not to state that the educators should blindly listen to all student feedback, lower the difficulty of the degrees and remove all challenging activities. On the contrary, if the education is adapted to the students, it can make it so that they can complete more complex tasks, learn more and become better students. This thesis suggests that it is, in many cases, easier and more productive to change with the students instead of trying to change the students.

Do the students themselves know best how they learn?

From the feedback gathered as part of this work, there are many statements about a lack of relation to curriculum, unperceived relevance, activities viewed as unnecessary, etc. All such statements should be viewed with a critical lens. By default, the course coordinator will have a more in-depth knowledge of the field and connections that are difficult for students to perceive. Activities experienced as frustrating or beyond the comfort zone might, in fact, teach students valuable skills. There are nuances, external factors, and opposing points of view

[9]This is often not the case, and studies show that the positive correlation between the exam grade and a deep approach to learning is generally low[19]. However, TPK4128 should be commended because its exam questions are generally more open, allowing creativity and critical analysis.

[10]The economic situation of students will influence the time and energy they spend on their studies. Part-time work in the semester has been found to influence the time spent on studies negatively[59], and the disposable income of Norwegian students has fallen compared to housing costs and wage level since 1990[60].

that the students will not have had in mind when making the statements used to inform this work. All this is important to keep in mind when evaluating educational activities, and student feedback should, for these reasons, not be entirely taken at face value.

However, while the educator might know better than the student *what* they should learn, the students will often know better *how* they best learn. Again, this means that it is vital to strive for an understanding of what engages the students and adapt the learning activities accordingly. From the entire span of students interacted with as part of this work, there is much to suggest that a bigger problem is a lack of interest on the part of university educators on how students best learn.

5.2 Conclusion

The creation of educational activities is a complex field. Students are a diverse group with constantly changing behavior and constitute just one of a multitude of factors, external and otherwise, that influence both how courses should operate and what is feasible, making it so that there are no clear answers that are not heavily context-dependent. However, it is necessary to strive to continuously improve educational activities to educate engineers with the requisite skills to answer society's needs. These activities should also be designed so that students have long-term recall of the learned concepts and have the intrinsic motivation and knowledge foundation to acquire new skills in perpetuity after completing the course. Among the characteristics conducive to inspiring this deep learning approach is the use of practical assignments, such as those examined throughout this thesis. In order to ensure that the practical course work lives up to these objectives, educators must actively engage in how the structure of the educational activities and institutional culture influences students' actions and learning outcomes, for instance, by employing user-centered product development. One such methodology is Design Thinking, which has been used with success throughout this work.

An Indexed Line assignment has been designed, which likely produces the desired results in students. On the other hand, there is much that indicates the other course work in TPK4128 is lackluster in its current form. However, this can also be greatly improved based on recommendations given in this thesis, albeit with a significant amount of work remaining for this to be fully realized.

Educational quality is also dependent on external factors. The Covid-19 pandemic has had adverse effects throughout the entire project period. It should also be emphasized that the current situation concerning educational resources at the department functions as a major roadblock, preventing assignments from realizing their potential. In order to produce engineers with the skills and knowledge necessary to meet the considerable challenges facing society today, the Department of Mechanical Engineering (MTP) must, to a larger degree, prioritize education.

Chapter 6

Future Work

There are various avenues for future work on the subjects covered in this thesis, many of which have been discussed throughout. These avenues are discussed in this standalone chapter in order to ease the actualization of such work by making it more readily accessible.

6.1 Implementing the Indexed Line assignment

This thesis strongly suggests that the ILA designed should be implemented in the TPK4128 course. The bulk of the work in realizing this lies in scaling up the technical side so that it can be used in a full class setting, as described in Section 4.2.5. It must also be ensured that the TAs and other personnel involved in guiding the assignment have sufficient knowledge of the equipment. The order must be placed expeditiously for sufficient S7-1500 PLCs. Otherwise, the assignment activities, structure, and text can be used as described in this text, with some minimal changes depending on the technical details of the upscaled version. As this primarily involves technical and not academic work, it should not be done in a further student thesis but instead by other available personnel at the department.

6.2 Improving the existing course work

This thesis also clearly states that the current course work in TPK4128 needs to be improved. Many of the issues affecting the course are described, along with recommended solutions in Chapter 4. This process will take time. However, there are many small and large changes that the course coordinator can make before the next iteration of the course that are likely to create noticeable improvements. This includes improvements in presentation, streamlining, and results.

Exactly how the future course work should look is unclear at this stage. The process toward reaching the full potential of TPK4128 is iterative, and student feedback must be acquired on the success of changes. More extensive changes include replacing or entirely remaking certain assignments, merging them, or supplanting multiple successive assignments with project work. Changes such as these could potentially be designed as part of future student theses.

6.3 Further Indexed Line assignments

In Section 4.3.3, suggestions are given for possible further Indexed Line Assignments. It is evident from student feedback that this is desirable. There are ripe opportunities to realize this through student theses. With reference to longer explanations in Section 4.3.3, possibilities include:

1. Designing a system for controlling and monitoring the training model and/or other equipment remotely over OPC UA, with a corresponding user interface.
2. Creating a digital twin of the training model.
3. Constructing an AGV, robotic arm, or similar that can interact with the training model and extend its operation toward mimicking a larger factory operation.
4. Designing an assignment around using multiple different types of fischertechnik models.

The suggestions can be implemented individually or in combination. Moreover, there are likely other intriguing possibilities beyond those discussed. The desired learning outcomes of the course enable a tremendous range of possible technologies and equipment to be used to demonstrate and teach the concepts. It is recommended that such future work builds on the insights gathered in this work and that user testing is done to ensure student satisfaction and identify potential faults and strengths.

6.4 Deeper studies on Practical Assignments

As detailed in the problem description, an objective of this thesis is to "*serve as a general exploration of what makes practical assignments educational and motivating.*" This is also a possibility for further inquiry. It should be explored if the insights and findings apply to other contexts and courses. Work can be done to do a more scientifically rigorous and objective study into these areas, as this is beyond the capabilities of the Design Thinking methodology employed herein.

A literature study on learning has been conducted in this work. However, the author's engineering and product development background and approach limit the level of understanding. It would be interesting for a pedagogy student or similar to continue this line of inquiry with greater theoretical weight.

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Appendix A

Indexed Line Assignment Prototype

This appendix includes the assignment text for the Indexed Line exercise as prototyped with students in spring 2022. There are four versions with changes based on testing results and student feedback. These run from newest to oldest. The final version which was created after the final group of students had tested the assignment is the one of most interest. The others are included in case the reader is inclined to track the changes made throughout.

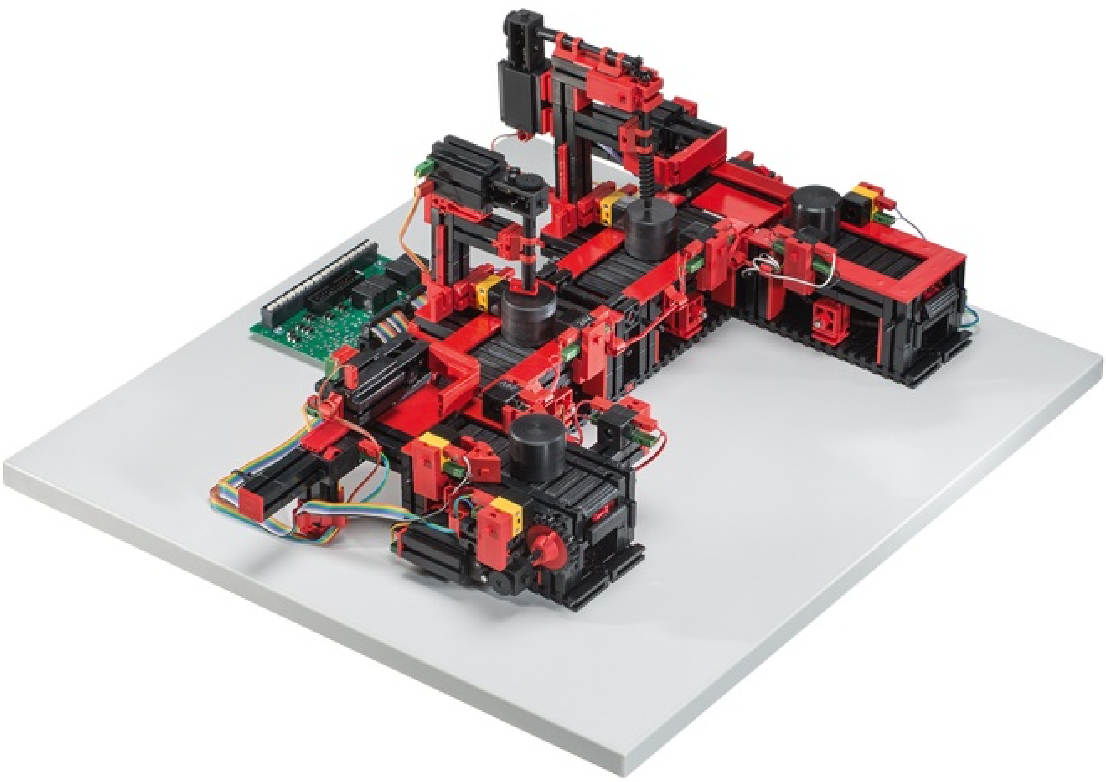
A.1 Final version

NTNU
Kunnskap for en bedre verden

Department of Mechanical Engineering

TPK4128 - Industrial Mechatronics

Factory Model exercise



1 Introduction

In this assignment you will use a Siemens S7-1500 Programmable Logic Controller (PLC) to operate a factory training model. This assignment was designed as part of a masters thesis by Andreas Knudsen Sund in spring 2022. While it was tested with 14 groups of students then, this is the first implementation with a full class. Therefore, it is likely that some technical errors will occur. Be sure to notify the teaching assistant or similar about issues you encounter such that this can be fixed for the next iteration.

Section 2: Background provides some background information on the equipment. Section 3: Assignment describes the steps you are to take to perform the assignment. Section 4: Sequential Function Charts gives a tutorial of the programming interface you will be using. Section 5: Common errors describes some common errors and issues and how you can fix them. You will likely be jumping between these chapters when going through the assignment steps in order to get the information you require to solve the task.

Good luck!

2 Background

2.1 Preparation

The degree to which you can familiarize yourself with this assignment without the equipment at hand is limited. However, it is recommended that you look through the assignment text in advance of the exercise hours, particularly the background chapter. Remember to read the assignment text thoroughly before starting to program the training model.

2.2 Why?

With reference to the desired learning outcomes of the course, this assignment should address most if not all of them. It functions as an industrial control system, using a PLC over bus communication to control sensors and actuators in a minitature factory environment.

Hopefully the assignment will tie some of the concepts from earlier exercises together, provide a practical application of concepts from the lectures and, most importantly, show how they can be useful.

2.3 Indexed Line with Two Machining Stations

The *Indexed Line With Two Machining Stations* is part of a series of miniature educational factory-line training models from *fischertechnik GmbH*, see fig. 1. It features a U-shaped factory line with conveyor belts and pushers to provide translation, push-buttons and phototransistors to measure position and a milling and drilling station to simulate processing of the workpiece.

The Indexed Line requires a 24V power supply. It has 9 digital inputs consisting of 5 NPN phototransistors and 4 pushbuttons. There are also ten 24V outputs, all DC motors, controlling a milling station, drilling station, 4 conveyor belts and the backwards and forwards operation of two sliders. The location of the inputs and outputs is given in fig. 1 with reference to table 1.

Phototranistors: There are 5 light/phototransistor pairs, at S5-S9. The phototransistors are normally-open (NO), meaning that they pass HIGH when they receive light. However, when the workpiece is at a phototranistor position it will in fact be blocking this light, meaning that you should use normally-closed (NC) contacts for them in the program.

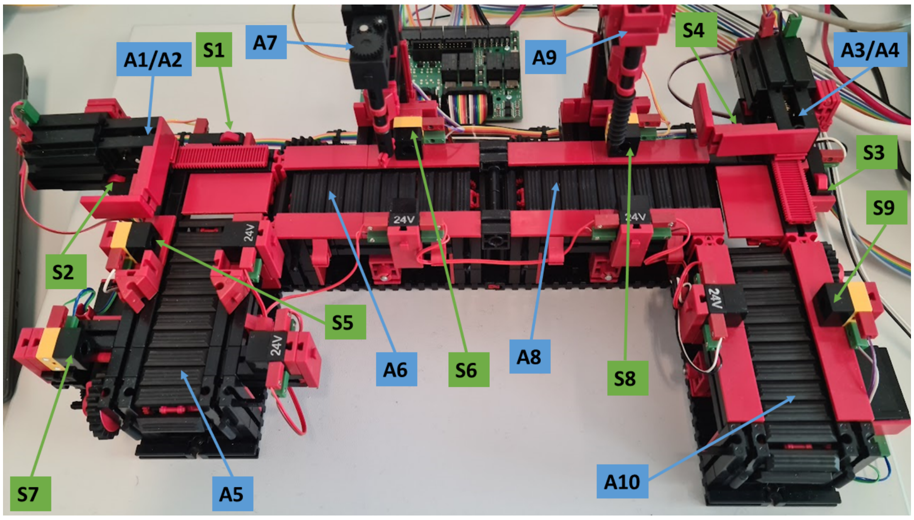


Figure 1: Outputs and inputs of the Indexed Line With Two Machining Stations from fischertechnik GmbH with reference to table 1

Terminal No.	Function	Input/Output
1	Power supply (+) actuators	24V DC
2	Power supply (+) sensors	24V DC
3	Power supply (-)	0V
4	Power supply (-)	0V
5	Push-button slider 1 front	S1
6	Push-button slider 1 rear	S2
7	Push-button slider 2 front	S3
8	Push-button slider 2 rear	S4
9	Phototransistor slider 1	S5
10	Phototransistor milling machine	S6
11	Phototransistor loading station	S7
12	Phototransistor drilling machine	S8
13	Phototransistor conveyor belt swap	S9
14		NC
15	Slider 1 forward	A1
16	Slider 1 backward	A2
17	Slider 2 forward	A3
18	Slider 2 backward	A4
19	Conveyor belt feed	A5
20	Conveyor belt milling machine	A6
21	Milling machine	A7
22	Conveyer belt drilling machine	A8
23	Drilling machine	A9
24	Conveyor belt swap	A10

Table 1: Terminals of the Indexed Line With Two Machining Stations

Conveyor-belts: There are 4 conveyor-belt, at A5, A6, A8 and A10. The conveyor-belts are only able to run in the forwards direction.

Sliders and pushbuttons: There are two sliders, at A1/A2 and A3/A4. These will move forward to push the workpiece of the loading plate in front of them, or retract to leave space for the next workpiece. In order to monitor the position of the sliders and prevent them from going to far there are pushbutton limit-switches in their front and back position. For slider 1: S1 and IS. For slider 2: S3 and S4. The pushbuttons can be operated in both normally-closed (NC) and normally-open (NO) modes, however for this assignment they will be in NO, meaning that the input is HIGH when they are pushed down.

Machining stations: There are two machining stations a mill and a drill, respectively at A7 and A9. These will not actually do anything physically to the workpiece, and will only simulate machining.

2.4 Programmable Logic Controller (PLC)

The PLC you will be using for this assignment is a Siemens S7-1500. This is the advanced line of Siemens controllers. Their high reliability in controlling industrial equipment in harsh environments has made them central to modern production facilities and to automation. With multiple PLCs working together, or along with other computerized equipment, it can be used to control a whole automation system. They are highly modular lending themselves to be adapted to different environments, for example a higher temperature range or a large amount of inputs, with advanced networking and safety capabilities as well. It is safe to say that the PLC will not be used to its full capabilities here, however it is still a good example of a use case for a PLC.

In figure fig. 2 you can see the PLC. It is mounted on a rail, with logical communications in backplane connectors at the back, and power transferred with cables at the front. To the left is the power supply module which receives mains 230V AC from wall sockets. The CPU is the brain of the PLC, performing the logical operations and communicating with the modules and external units like the PC you will be programming it from. It is also connected to a digital input module which will be receiving sensor information from the phototransistors on the training model, and a digital output module which will control its actuators. A single PLC can have up to 32 modules connected by backplane, giving other functions like advanced communications, analog outputs and inputs and much more.

2.5 Siemens TIA Portal

Siemens TIA portal is the proprietary software for programming Siemens PLCs, it has a great number of capabilities for different modes of logic control like ladder logic, structured text, functional block diagrams and so on. While there exists other software for programming PLCs like Codesys, unfortunately only TIA portal can be used to program Siemens PLCs. *TIA Portal will be preinstalled on a laptop handed out for the assignment, so you will not be required to install it on your own laptop.*

Figure 2: Siemens S7-1500. A) Power supply unit, B) CPU (1516-3 PN/DP), C) Digital Input module (DI 32x24V DC), D) Digital Output module (DQ 16x24VDC/0.5A ST)

3 Assignment

You are to implement a program such that the factory model loads a workpiece, transports it to the machining stations which machine the workpiece and on to the end.

You will be handed a base project named "TrainingModelInitialSteps", serving as a starting point. **Remember to click *save as* and pick another project name so you won't change the template.**

NB! You are `not` asked to implement it such that the factory processes multiple workpieces simultaneously, as this is beyond the scope of this assignment.

3.1 Configuring the PLC in TIA Portal

The PLC hardware will be configured for you in TIA Portal beforehand, with the exact version of the PS, CPU and modules you are using.

Configuring the outputs and inputs The wiring of the PLC to the factory line will be setup for you beforehand. Go under *PLC tags* → *Tag Table* [70] in the project tree. Here you will see how the variables in your program correspond to the different output and input gates on the PLC. The tag table denotes the variable names you will use under programming to call the different actuators (outputs) and sensors (inputs).

Connecting to the PLC Connect the PLC to the laptop with the ethernet cable. You should now establish a connection between the PLC and the computer. Select Go online and ensure that the boxes correspond to the correct network and interface, like in fig. 3. The power-switch on the

PLC power supply should be on before this step[1].

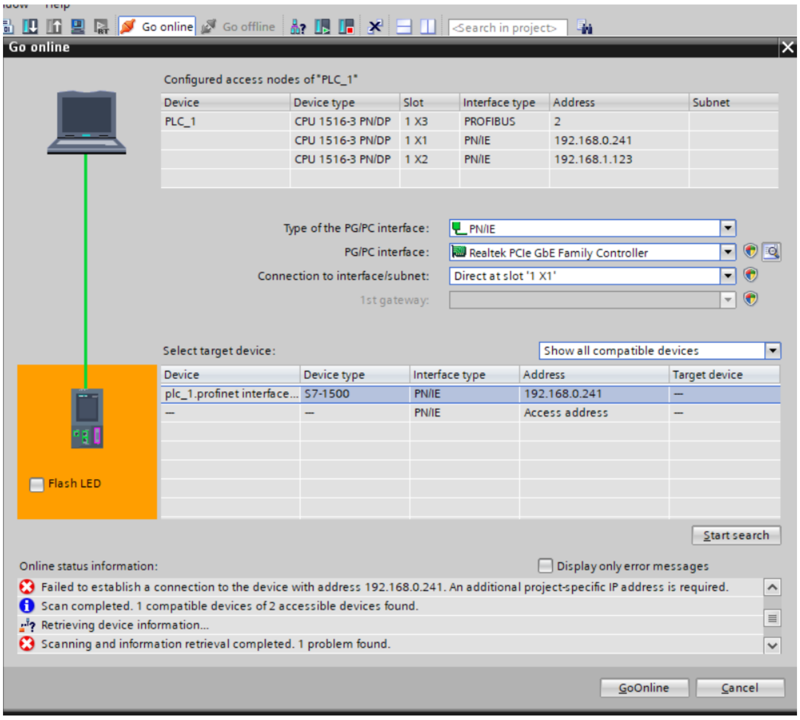


Figure 3: Going online in TIA Portal

3.2 Making your program

This section provides a rundown of how you are to proceed, however keep in mind that you will be jumping back and forth from this and section 3.3 and section 4.

1. Expand the *Program blocks* folder in the project tree. Here you will see four blocks: **Main** [**OB1**], **Sequence** [**FB1**], **Model Operation** [**DB5**] and **Sequence_DB** [**DB4**]. You can ignore the latter two[2].
2. The main block **Main** [**OB1**] is the first thing the PLC will run, constantly running through every branch of the networks and running them if the logic conditions are met. If you were to implement a simple ladder logic program this is where you would implement most of your code. However, here we will only have one network in the Main-block, which corresponds to our Sequential Function Chart (SFC).
3. Open the **Sequence** [**FB1**] block, this is where we will do most of our programming.
4. The sequential function chart will be composed of steps and transitions between them. The steps can contain actions to be performed at that step, and the transitions will contain the conditions to go from that step to the next. You will primarily use ladder logic to program the transitions.
5. A few of the initial steps and transitions are partly implemented in the base project, see fig. 4.
6. The base project should be enough to make the training model perform some actions. Try running it first, see section 3.3.

[1]This is different from the Run-switch located on the CPU which is used to activate the program

[2]These are database blocks, containing variables corresponding to the sequence block. These have a large amount of use cases in more advanced implementations, but will not be used here.

7. Check out section 4 for how a sequential function chart works and how you change the program, reference this with the steps and transitions in fig. 4.
8. You should now be well-equipped to start creating the finished program.
9. The base project has the steps and transitions required up to the point where the workpiece loads to slider 1. However **S4: Load to slider 1** and the subsequent transition is empty. Completing **S4** and **T6** is where you will start.
10. Work iteratively implementing one section of the training model operation at a time. Test your work as you go, see section 3.3.
11. Everytime you change a step in the sequence graph, you have to go back into Main block, right click the Sequence and select *Update Block call*

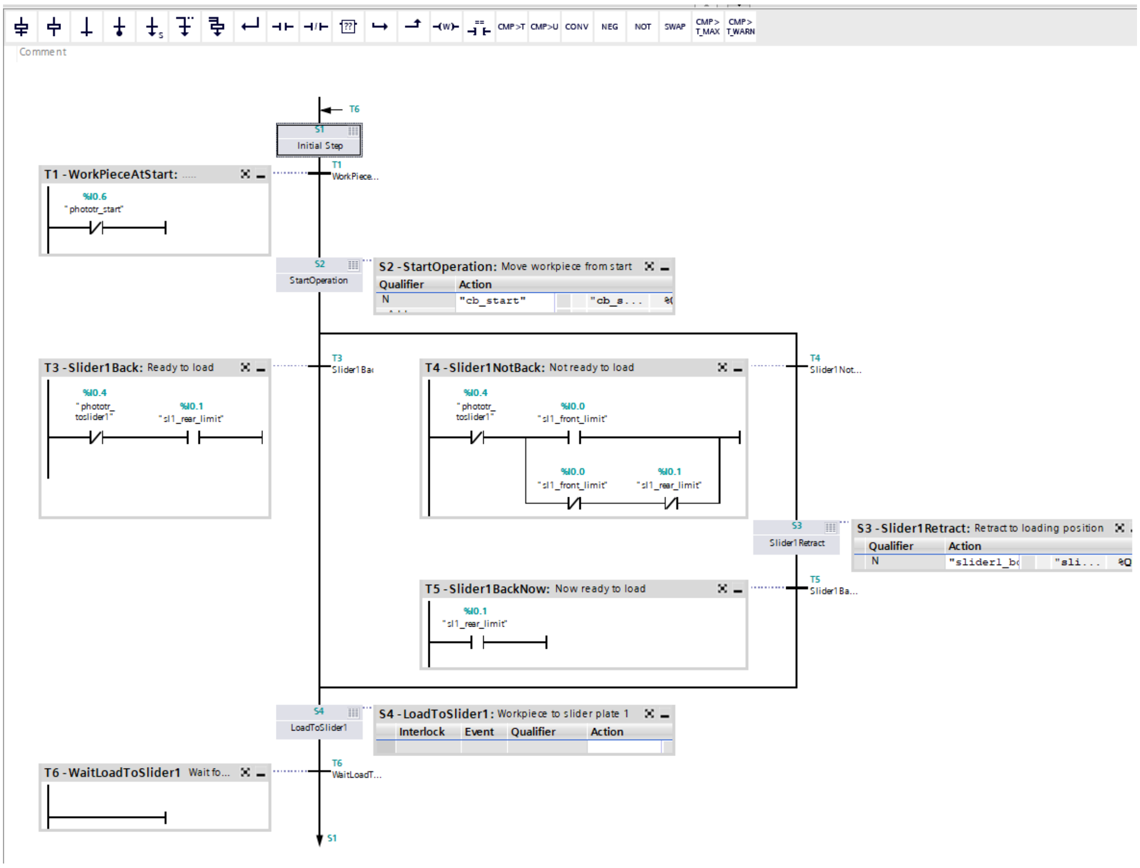


Figure 4: The steps in the preconfigured program

3.3 Running the program

The best way to progress in this assignment is through trial and error, and you should be frequently testing your code implementation on the indexed line. In order to do this:

1. Make sure Siemens TIA Portal is online with the PLC.
2. Right click your PLC in the project tree and select *Download to device → Software (All)*
3. Select yes on all the following boxes and load.
4. If everything went correctly, the code should now be on your PLC.

5. Remember to toggle the *Monitoring* option. This will light up where you are in the program in green.
6. Toggle the switch under the panel of the CPU to **RUN**. Your code will now be running on the PLC. Remember to turn this off before making new changes, or before you want to restart the program.
7. Is it working? If no, systematically check where the error is happening and whether it stems from software or hardware errors. Common errors are listed in section 5

3.4 It works!

Is the program transporting the workpiece from end to end while milling and drilling it on the way?[3] Great job! Remember to report issues you have found or things that should be improved to the teaching assistant.

[3] Does it immediately process another workpiece without toggling the run-switch ON/OFF. If not, the solution is easier than you think. Think of how the first and last step should be connected.

4 Sequential Function Charts

You will be making a Sequential Function Chart (SFC) in the GRAPH environment of TIA Portal. This section provides a brief explanation for how this works and the program elements involved. You should be able to understand the program from this section, however watching this video from youtuber Hegamurl is great help as well.

How it works is fairly straight forward. You have a series of steps and transitions. The program will sequentially run from top to bottom, going from one step to the next when the transitions in between are fulfilled. fig. 5 shows the elements of the main interface.

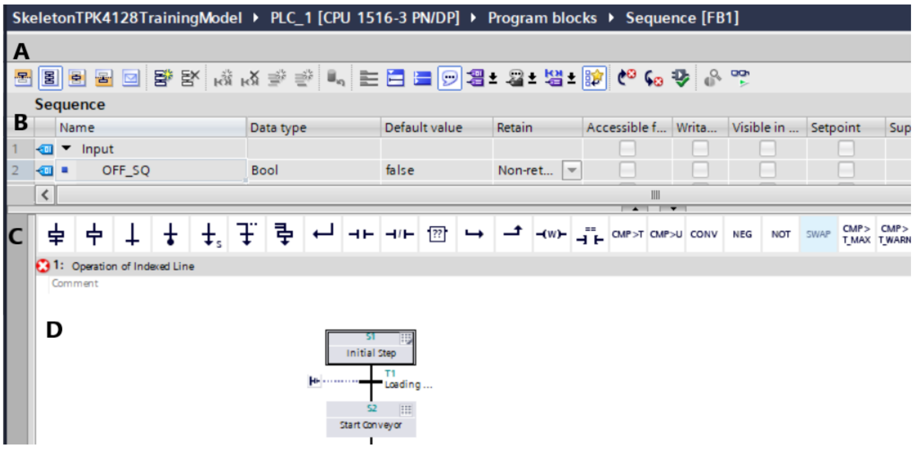


Figure 5: The basic elements of the GRAPH main interface. A) Toolbar for selecting different views or monitoring. B) Variables which you can ignore. C) Programming elements. D) The program itself.

Steps may contain actions such as powering an actuator, see **S2** in fig. 6 where the first conveyor belt is activated as long as the step is active (N). The program will stay in that step until the conditions in subsequent transition(s) is fulfilled. You can also have *branches* after steps, giving different actions depending on which transitions are fulfilled, and *simultanous branches* which will perform different actions in parallel. Toggle to insert new steps.

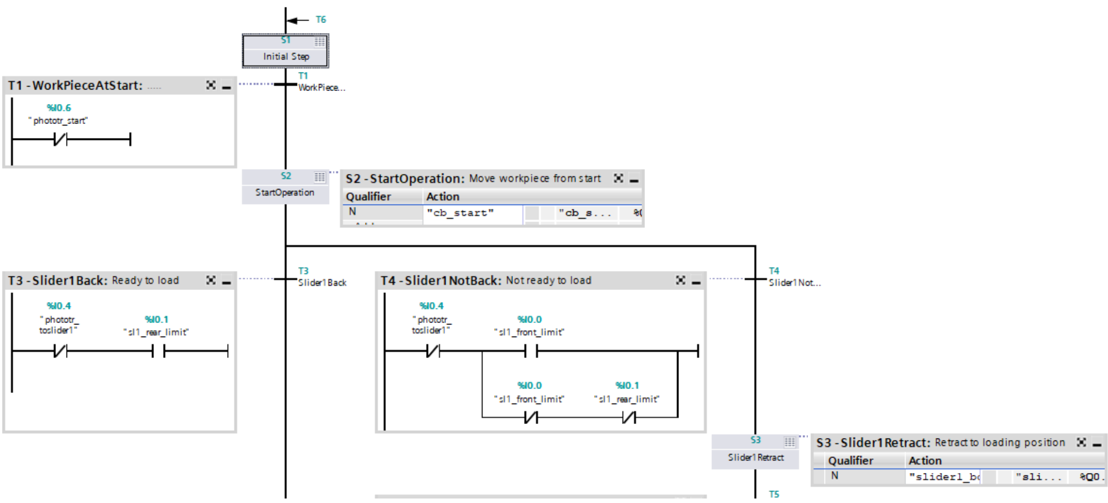


Figure 6: Some of the initial steps and transitions in the program.

Transitions contain ladder logic. Think of it as an electrical circuit with switches, when the switches are all activated current will flow through the transition and activate it such that the program goes to the next step. You will always require a transition between steps. If a transition is empty it will be instantaneously activated, and the preceeding step will run for 0 seconds. See T4 in fig. 6 This transition is on when the workpiece is in the position before the first slider (phototransistor no light, LOW) and the slider is not in correct position for loading. Here there is a branch within the transition, with the top being activated if the slider is in front position (front pushbutton HIGH) and the bottom being activated if the slider is in no-mans land between the front and back pushbuttons (front bushbutton LOW, back pushbutton LOW). Toggle ⊥ to insert a new transition.

Timing functions A lot of the logic control can be performed in terms of "when workpiece arrives at X phototransistor". However, there are stretches of the factory line where the position of the workpiece is not monitored by the phototransistors, e.g. when loading onto the slider plate. For these stretches you will have to use other means to ensure that the program does not continue before the correct previous actions are performed. One such way is through the use of timers. Use the CMP>T function from the toolbar of the sequence graph environment. You can use the time elapsed on a step or action in microseconds as a condition along with inputs like in figure fig. 7

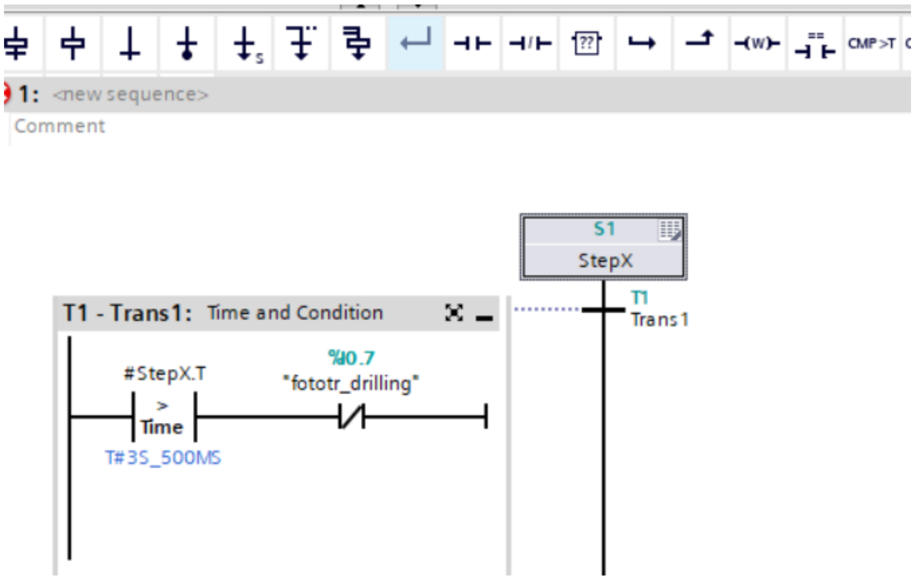


Figure 7: Use of CMP>T function

Change views Double click a step or transition to look at it close up. Toggle the one hightlighted in yellow on the top toolbar if you wish to return to the base view.

5 Common errors

This sections provides some prevalent errors that might occur, and how to solve them.

5.1 Software

The debugging functionality in the GRAPH environment is somewhat lackluster, meaning it is difficult to see exactly where errors come from.

Missing programming elements in toolbar Are some of the programming instructions you require missing from the toolbar? (fig. 5 C). On the right click: *Instructions* → *Basic instructions* for logic or timing operations. Click *Instructions* → *GRAPH sequence* for steps/transitions or sequence end/jump to step. Drag the missing instruction onto the toolbar.

No Ending Instruction After the final step the program needs to know what to do next. If you leave it open, like in fig. 8 an error will occur. A program can not end in a step, it needs a transition to know when to end. You can terminate the program in a sequence end, meaning it stops, or with a jump to step meaning it starts anew at a selected step when the sequence is finished, see .

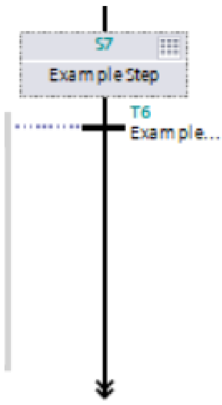


Figure 8: Program without ending instruction leading to error.

Unclosed Branch in Transition When adding elements in transition it is easy to accidentally create an extra branch in a transition. This can create a software error that is somewhat difficult to spot. See through your transitions if they look similar to fig. 9. If you intend to have a branch, make sure to close it. If not, move the elements to the top branch and delete the bottom one.

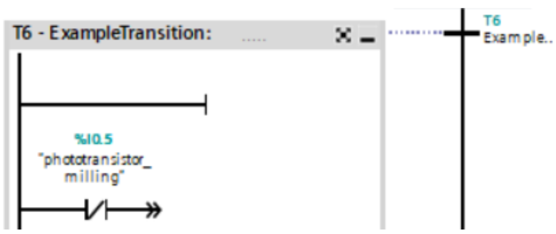


Figure 9: Unclosed branch in transition leading to error.

5.2 Hardware

Slider of the track? As you try to get the training model to operate correctly through trial and error, you are likely to run into an issue where you run the sliders too far past the limit switches in either direction. Your finished program should be such that this doesn't happen. You can load the project titled **SliderDerailed**, which with simple ladder logic will allow you to manually control the sliders by placing your fingers over the phototranistors.

Disconnected wiring: The red and green connectors on the sensors and actuators of the physical training model are not rigidly in place and might fall out. Simply put them back in place with reference to how they are in fig. 1

No contact with pushbuttons: FischerTechnik works alot like Lego, meaning that the structure is moveable. If the pushbuttons are not toggled when the sliders are in the correct positions, try to physically tweak the elements on the sliders such that contact is reestablished.

Motor is running, but belt is still: If the correct actuator is HIGH, but the belt stands still or jitters, it is likely that the gears have jumped out. Move the gears on the side of the motor such that the gears mesh.

A.2 Version 3

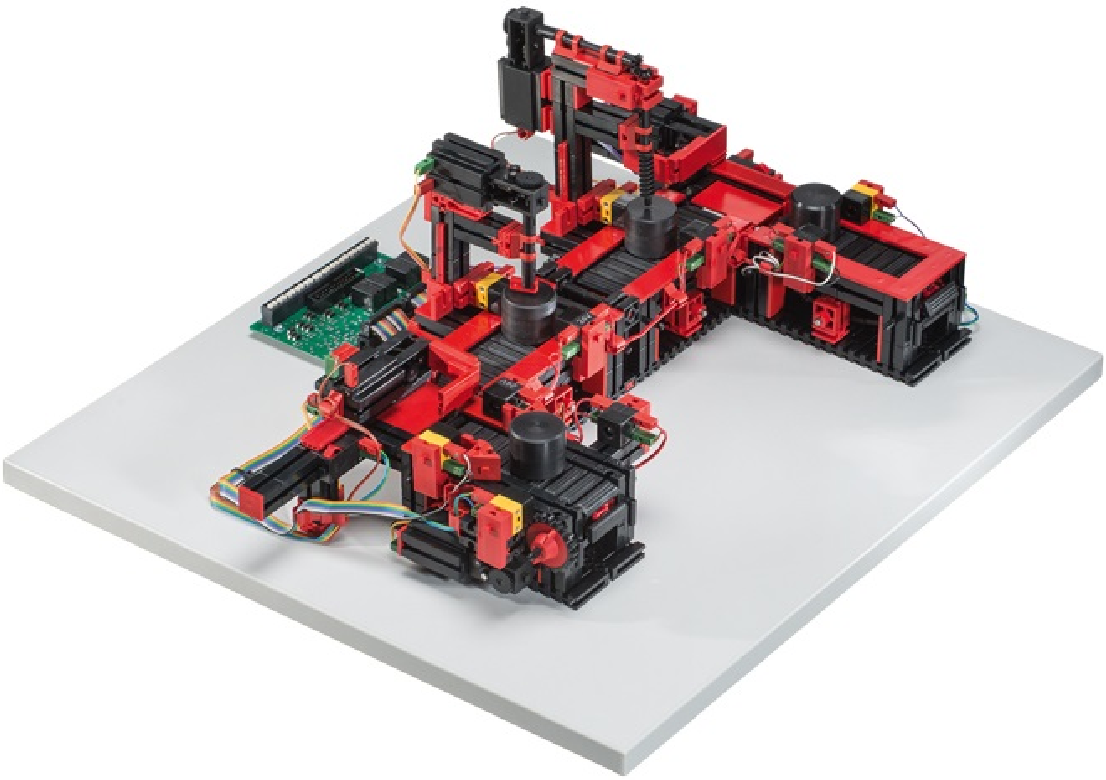
NTNU
Kunnskap for en bedre verden

Department of Mechanical Engineering

TPK4128 - Industrial Mechatronics

Factory Model exercise

Author:
Andreas Knudsen Sund



April, 2022

1 Introduction

In this assignment you will use a Siemens S7-1500 Programmable Logic Controller (PLC) to operate a factory training model. This assignment is developed as part of my master thesis, meaning that you will be performing a prototype of the assignment. Therefore, don't hesitate to give feedback on anything that comes up, ranging from errors that occur, things you think are unclear, how much you enjoy it or other things that could be improved. **You don't have to be nice.** This feedback will be essential to improving the exercise for students in following years. As the exercise is run over several weeks, I will also be iteratively improving the exercise text and contents from group to group.

NB! Keep in mind that the exercise will not be performed in the usual room. See Blackboard for the location.

2 Background

2.1 Why?

With reference to the desired learning outcomes of the course, this assignment should address most if not all of them. It functions as an industrial control system, using a PLC over bus communication to control sensors and actuators in a minitature factory environment. In the final version students will also be remotely controlling it over OPC UA, with a Raspberry PI webcam server providing a video feed. Because of older equipment[1], this unfortunately can't be implemented in the prototype version you will be running this spring.

Hopefully the assignment will tie some of the concepts from earlier exercises together, provide a practical application of concepts from the lectures and, most importantly, show how they can be useful.

2.2 Preparation

You will not be required to do much preparation for the assignment. However, it is useful if you have read-through the assignment text in advance and have familiarized yourself with PLCs and logic control as presented in the lectures. There should be ample time to finish the assignment in the exercise hour, but if you want to finish it quickly you can watch the videos linked in section 3 beforehand. You will not be required to install any software beforehand, as you will be handed a laptop for the assignment.

2.3 Indexed Line with Two Machining Stations

The *Indexed Line With Two Machining Stations* is part of a series of miniature educational factory-line training models from *fischertechnik GmbH*, see fig. 1. It features a U-shaped factory line with conveyor belts and pushers to provide translation, push-buttons and phototransistors to measure position and a milling and drilling station to simulate processing of the workpiece.

The Indexed Line requires a 24V power supply. It has 9 digital inputs consisting of 5 NPN phototransistors and 4 pushbuttons. There are also ten 24V outputs, all DC motors, controlling a milling station, drilling station, 4 conveyor belts and the backwards and forwards operation of two sliders. The location of the inputs and outputs is given in fig. 1 with reference to table 1. This corresponds to the digits on the connection terminal on the outermost side of the circuit board.

[1] The PLC used is too old to run OPC UA, however new PLCs will be available next year.

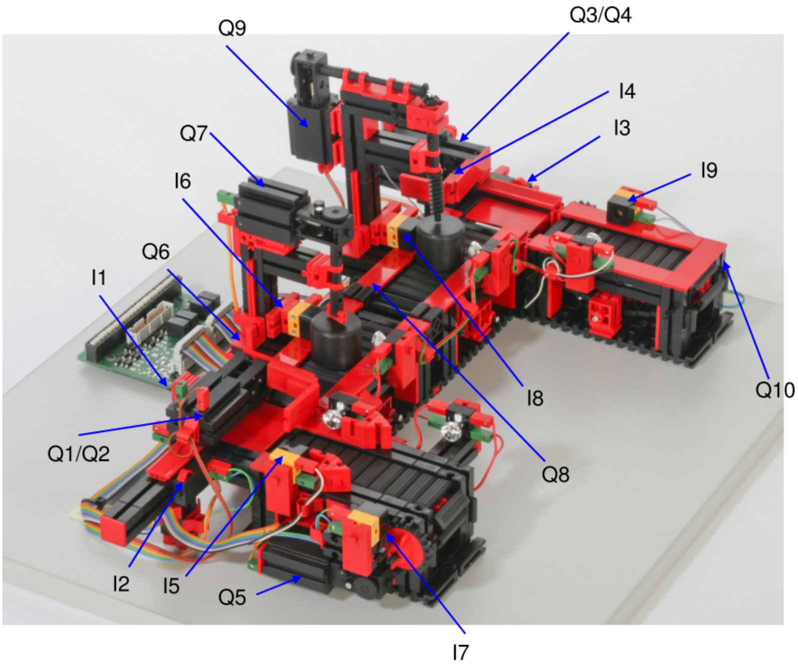


Figure 1: The Indexed Line With Two Machining Stations from fischertechnik GmbH

Terminal No.	**Function**	**Input/Output**
1	Power supply (+) actuators	24V DC
2	Power supply (+) sensors	24V DC
3	Power supply (-)	0V
4	Power supply (-)	0V
5	Push-button slider 1 front	I1
6	Push-button slider 1 rear	I2
7	Push-button slider 2 front	I3
8	Push-button slider 2 rear	I4
9	Phototransistor slider 1	I5
10	Phototransistor milling machine	I6
11	Phototransistor loading station	I7
12	Phototransistor drilling machine	I8
13	Phototransistor conveyor belt swap	I9
14		NC
15	Slider 1 forward	Q1
16	Slider 1 backward	Q2
17	Slider 2 forward	Q3
18	Slider 2 backward	Q4
19	Conveyor belt feed	Q5
20	Conveyor belt milling machine	Q6
21	Milling machine	Q7
22	Conveyer belt drilling machine	Q8
23	Drilling machine	Q9
24	Conveyor belt swap	Q10

Table 1: Terminals of the Indexed Line With Two Machining Stations

Phototransistors: There are 5 light/phototransistor pairs, at I5-I9. The phototransistors are normally-open (NO), meaning that they pass HIGH when they receive light. However, when the workpiece is at a phototranistor position it will in fact be blocking this light, meaning that you should use normally-closed (NC) contacts for them in the program.

Conveyor-belts: There are 4 conveyor-belt, at Q5, Q6, Q8 and Q10. The conveyor-belts are only able to run in the forwards direction.

Sliders and pushbuttons: There are two sliders, at Q1/Q2 and Q3/Q4. These will move forward to push the workpiece of the loading plate in front of them, or retract to leave space for the next workpiece. In order to monitor the position of the sliders and prevent them from going to far there are pushbutton limit-switches in their front and back position. For slider 1: I1 and I2. For slider 2: I3 and I4. The pushbuttons can be operated in both normally-closed (NC) and normally-open (NO) modes, however for this assignment they will be in NO, meaning that the input is HIGH when they are pushed down.

Machining stations: There are two machining stations a mill and a drill, respectively at Q7 and Q9. These will not actually do anything physically to the workpiece, and will only simulate machining.

2.4 Programmable Logic Controller (PLC)

The PLC you will be using for this assignment is a Siemens S7-1500. This is the advanced line of Siemens controllers. Their high reliability in controlling industrial equipment in harsh environments has made them central to modern production facilities and to automation. With multiple PLCs working together, or along with other computerized equipment, it can be used to control a whole automation system. They are highly modular lending themselves to be adapted to different environments, for example a higher temperature range or a large amount of inputs, with advanced networking and safety capabilities as well. It is safe to say that the PLC will not be used to its full capabilities here, however it is still a good example of a use case for a PLC.

In figure fig. 2 you can see the PLC. It is mounted on a rail, with logical communications in backplane connectors at the back, and power transferred with cables at the front. To the left is the power supply module which receives mains 230V AC from wall sockets. The CPU is the brain of the PLC, performing the logical operations and communicating with the modules and external units like the PC you will be programming it from. It is also connected to a digital input module which will be receiving sensor information from the phototransistors on the training model, and a digital output module which will control its actuators. A single PLC can have up to 32 modules connected by backplane, giving other functions like advanced communications, analog outputs and inputs and much more.

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Figure 2: Siemens S7-1500. A) Power supply unit, B) CPU (1516-3 PN/DP), C) Digital Input module (DI 32x24V DC), D) Digital Output module (DQ 16x24VDC/0.5A ST)

3 Assignment

You are to implement a program such that the factory model loads a workpiece, transports it to the machining stations which machine the workpiece and on to the end. It should be such that another workpiece can immediately be processed after one is finished.

You will be handed a skeleton project named "SkeletonTPK4128TrainingModel", serving as a starting point. **Remember to click *save as* and pick another project name so you won't change the template.**

3.1 Configuring the PLC in TIA Portal

The PLC hardware will be configured for you in TIA Portal beforehand, with the exact version of the PS, CPU and modules you are using. However, if you wish to see how this is done I recommend watching this video[2].

Configuring the outputs and inputs The wiring of the PLC to the factory line will be setup for you beforehand. Go under *PLC tags* → *Tag Table* [70] in the project tree. Here you will see how the variables in your program correspond to the different output and input gates on the PLC. Check out how the entries on the tag table correspond to the which terminal the wires are connected to, with regards to table 1. This video is a great guide for how to configure tag tables in TIA Portal.

Connecting to the PLC Connect the PLC to the laptop with the ethernet cable. You should now establish a connection between the PLC and the computer. Select Go online and ensure that

[2] Watching this german youtuber "Hegamurl" was of immense help in designing this assignment. A huge part of becoming proficient in software programming is mastering the art of google and finding the correct youtube guru.

the boxes correspond to the correct network and interface, like in fig. 3. The power-switch on the PLC power supply should be on before this step.

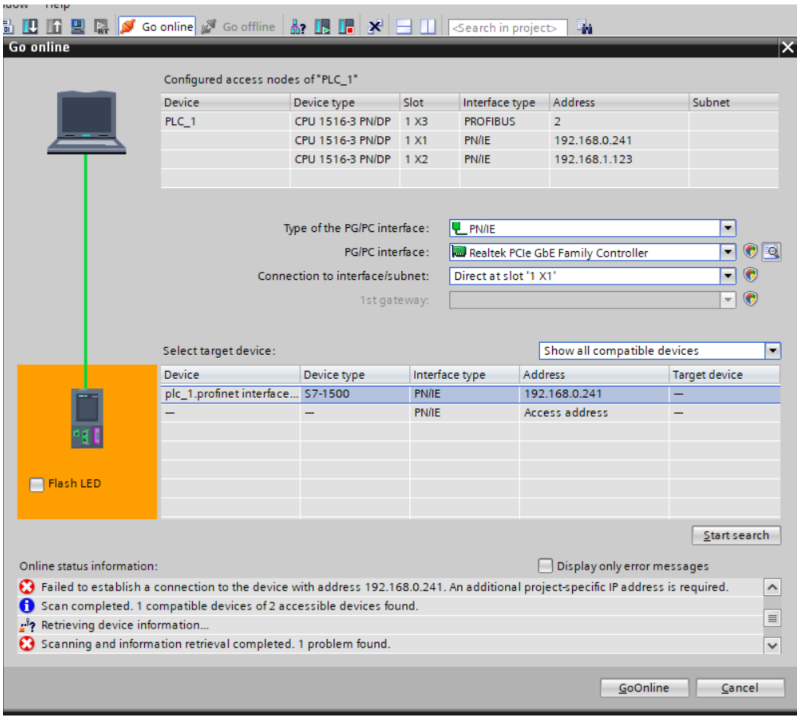

Figure 3: Going online in TIA Portal

3.2 Making your program

This section provides a rundown of how you are to proceed, however keep in mind that you will be jumping back and forth from this and section 3.3 and section 4.

1. Expand the *Program blocks* folder in the project tree. Here you will see four blocks.
2. The main block **Main** [**OB1**] is the first thing the PLC will run, constantly running through every branch of the networks and running them if the logic conditions are met. If you were to implement a simple ladder logic program this is where you would implement most of your code. However, here we will only have one network in the Main-block, which corresponds to our Sequential Function Chart (SFC).
3. Open the **Sequence** [$FB1$] block, this is where we will do most of our programming.
4. There will also be database blocks, containing variables corresponding to the sequence block. These have a large amount of use cases in more advanced implementations, but will not be used here.
5. The sequential function chart will be composed of steps and transitions between them. The steps can contain actions to be performed at that step, and the transitions will contain the conditions to go from that step to the next. You will primarily use ladder logic to program the transitions.
6. A few of the initial steps and transitions are partly implemented in the skeleton project, see fig. 4 Steps 1-3, transitions 1-4 are completed. Step 4 and transition 5 are inserted, but empty.
7. Check out section 4 for how a sequential function chart works and how you change the program.

8. You should now be well-equipped to start creating the finished program.
9. The skeleton project should be enough to make the training model perform some actions. Try running it first, see section 3.3.
10. You can double click on the different steps and transitions implemented and read a short text explaining what they do. Familiarize yourself with the actions the skeleton code performs. Keep in mind that you will have to implement many additional steps and transitions on top of this.
11. Work iteratively implementing one section of the training model operation at a time. Test your work as you go, see section 3.3.
12. Everytime you change a step in the sequence graph, you have to go back into Main block, right click the Sequence and select *Update Block call*

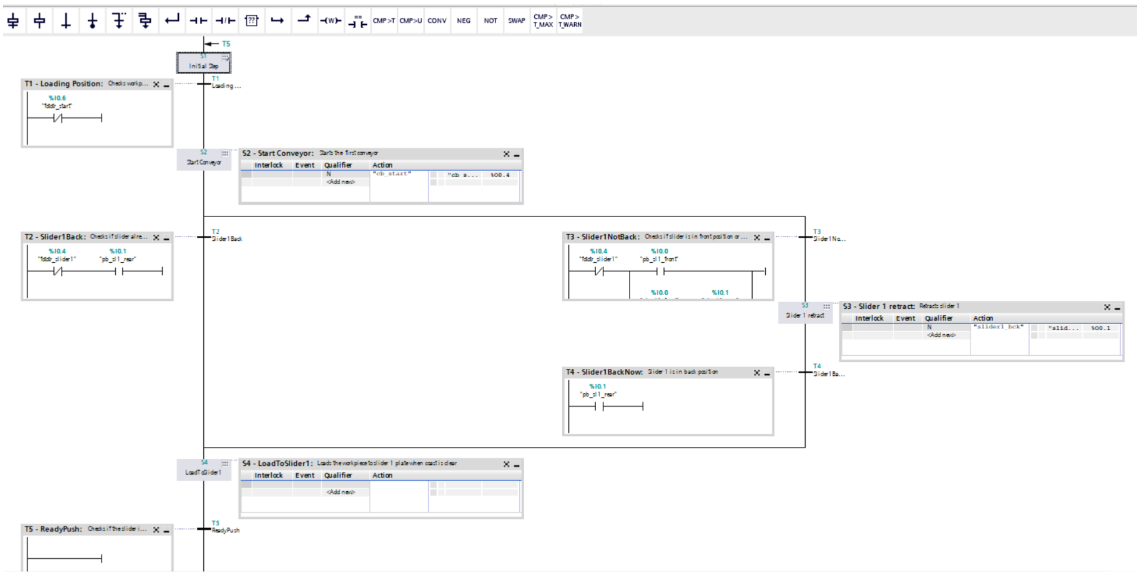

Figure 4: The steps in the preconfigured program

3.3 Running the program

The best way to progress in this assignment is through trial and error, and you should be frequently testing your code implementation on the indexed line. In order to do this:

1. Make sure Siemens TIA Portal is online with the PLC.
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3. Select yes on all the following boxes and load.
4. If everything went correctly, the code should now be on your PLC.
5. Remember to toggle the *Monitoring* option. This will light up where you are in the program.
6. Toggle the switch under the panel of the CPU to **RUN**[3]. Your code will now be running on the PLC. Remember to turn this off before making new changes, or before you want to restart the program.
7. Is it working? If no, systematically check where the error is happening and whether it stems from software or hardware errors. Common errors are listed in section 5

[3]This is different from the power-switch located on the powersupply which should be ON at all times.

3.4 It works!

Is the program transporting the workpiece from end to end while milling and drilling it on the way?[4] Great job! If you have not, that is fine too. The most important thing is that you learn. And as this is a prototype of the assignment it is normal that there are errors, remember to report the issues you have and the things you found confusing or difficult to understand to the TA. This will be great help in improving the assignment.

[4] Does it immediately process another workpiece without toggling the run-switch ON/OFF. If not, the solution is easier than you think. Think of how the first and last step should be connected. Running multiple workpieces in the line simultanously however, now that's a big challenge!

4 Sequential Function Charts

You will be making a Sequential Function Chart (SFC) in the GRAPH environment of TIA Portal. This section provides a brief explanation for how this works and the program elements involved. It is recommended you watch this video as well.

How it works is fairly straight forward. You have a series of steps and transitions. The program will sequentially run from top to bottom, going from one step to the next when the transitions in between are fulfilled. fig. 5 shows the elements of the main interface.

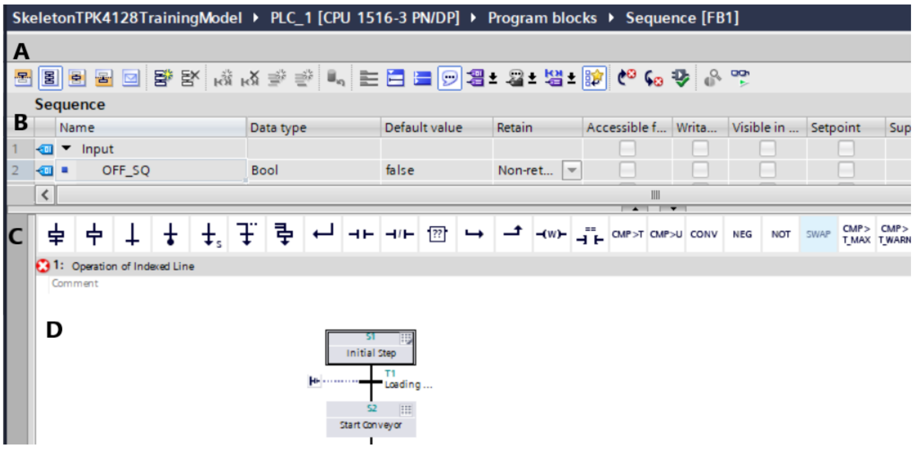


Figure 5: The basic elements of the GRAPH main interface. A) Toolbar for selecting different views or monitoring. B) Variables which you can ignore. C) Programming elements. D) The program itself.

Steps may contain actions such as powering an actuator, see S2 in fig. 6 where the first conveyor belt is activated as long as the step is active (N). The program will stay in that step until the conditions in subsequent transition(s) is fulfilled. You can also have branches after steps, giving different actions depending on which transitions are fulfilled. Toggle to insert new steps.

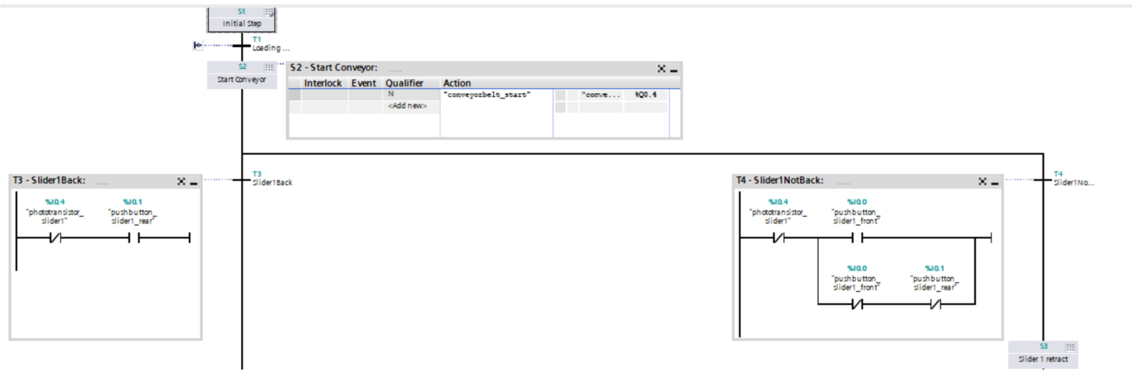


Figure 6: Some of the initial steps and transitions in the program.

Transitions contain ladder logic. Think of it as an electrical circuit with switches, when the switches are all activated current will flow through the transition and activate it such that the program goes to the next step. You will always require a transition between steps. If a transition is empty it will be instantaneously activated, and the preceeding step will run for 0 seconds. See T4 in fig. 6 This transition is on when the workpiece is in the position before the first slider (phototransistor no light, LOW) and the slider is not in correct position for loading. Here there is a branch within the transition, with the top being activated if the slider is in front position (front pushbutton HIGH) and the bottom being activated if the slider is in no-mans land between the front and back pushbuttons (front bushbutton LOW, back pushbutton LOW). Toggle to insert a new transition.

Timing functions A lot of the logic control can be performed in terms of "when workpiece arrives at X phototransistor". However, there are stretches of the factory line where the position of the workpiece is not monitored by the phototransistors, e.g. when loading onto the slider plate. For these stretches you will have to use other s to ensure that the program does not continue before the correct previous actions are performed. One such way is through the use of timers. Use the CMP>T function from the toolbar of the sequence graph environment. You can use the time elapsed on a step or action in microseconds as a condition along with inputs like in figure fig. 7

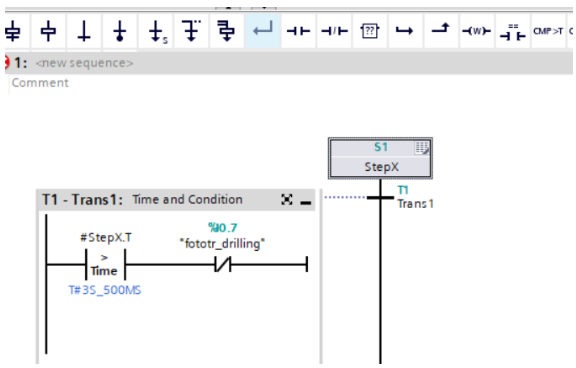


Figure 7: Use of CMP>T function

Change views Double click a step or transition to look at it close up. Toggle the one hightlighted in yellow on the top toolbar if you wish to return to the base view.

5 Common errors

This sections provides some prevalent errors that might occur, and how to solve them.

5.1 Software

The debugging functionality in the GRAPH environment is somewhat lackluster, meaning it is difficult to see exactly where errors come from.

Missing programming elements in toolbar Are some of the programming instructions you require missing from the toolbar? (fig. 5 C). On the right click: *Instructions*→ *Basic instructions* for logic or timing operations. Click *Instructions*→ *GRAPH sequence* for steps/transitions or sequence end/jump to step. Drag the missing instruction onto the toolbar.

No Ending Instruction After the final step the program needs to know what to do next. If you leave it open, like in fig. 8 an error will occur. A program can not end in a step, it needs a transition to know when to end. You can terminate the program in a sequence end, meaning it stops, or with a jump to step meaning it starts anew at a selected step when the sequence is finished, see .

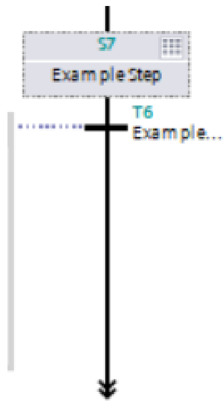


Figure 8: Program without ending instruction leading to error.

Unclosed Branch in Transition When adding elements in transition it is easy to accidentally create an extra branch in a transition. This can create a software error that is somewhat difficult to spot. See through your transitions if they look similar to fig. 9. If you intend to have a branch, make sure to close it. If not, move the elements to the top branch and delete the bottom one.

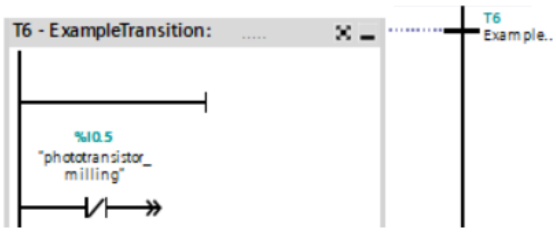


Figure 9: Unclosed branch in transition leading to error.

5.2 Hardware

Slider of the track? As you try to get the training model to operate correctly through trial and error, you are likely to run into an issue where you run the sliders too far past the limit switches in either direction. Your finished program should be such that this doesn't happen. You can load the project titled **SliderDerailed**, which with simple ladder logic will allow you to manually control the sliders by placing your fingers over the phototranistors.

Disconnected wiring: The red and green connectors on the sensors and actuators of the physical training model are not rigidly in place and might fall out.

No contact with pushbuttons: FischerTechnik works alot like lego, meaning that the structure is moveable. If the pushbuttons are not toggled when the sliders are in the correct positions, try to physically tweak the elements on the sliders such that contact is reestablished.

Motor is running, but belt is still: If the correct actuator is HIGH, but the belt stands still or jitters, it is likely that the gears have jumped out. Move the gears on the side of the motor such that the gears mesh.

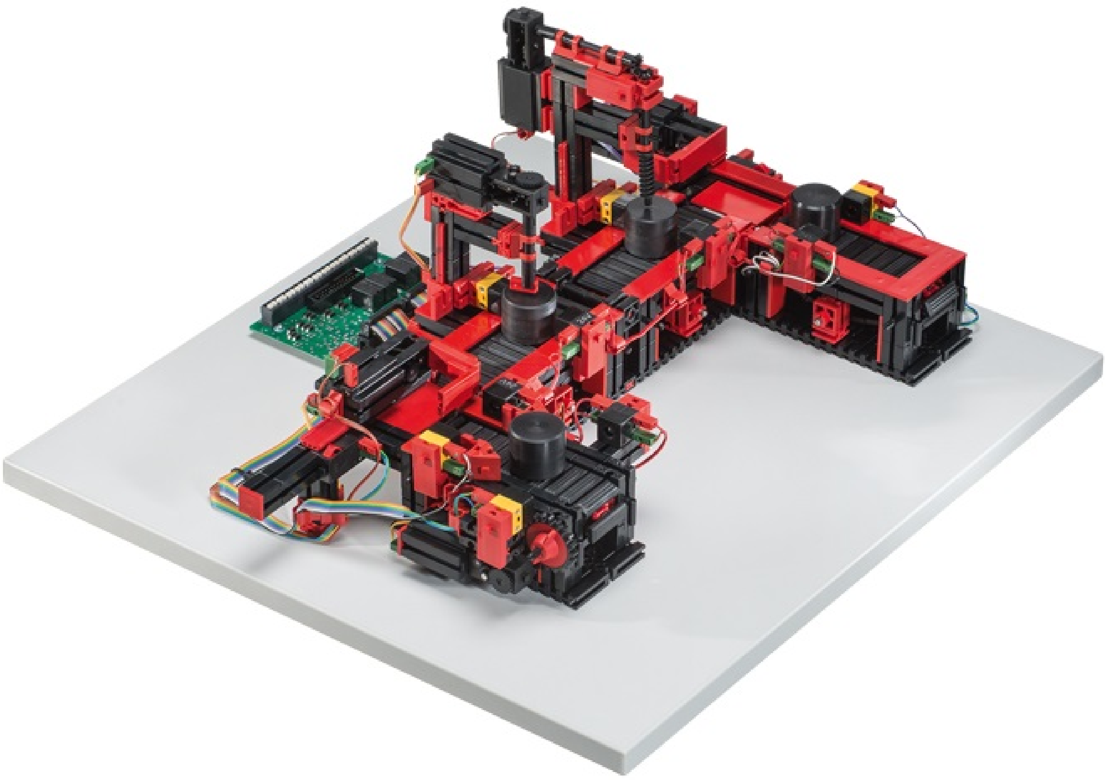
A.3 Version 2

Department of Mechanical Engineering

TPK4128 - Industrial Mechatronics

Factory Model exercise

Author:
Andreas Knudsen Sund



April, 2022

1 Introduction

In this assignment you will use a Siemens S7-1500 Programmable Logic Controller (PLC) to operate a factory training model. This assignment is developed as part of my master thesis, meaning that you will be performing a prototype of the assignment. Therefore, don't hesitate to give feedback on anything that comes up, ranging from errors that occur, things you think are unclear, how much you enjoy it or other things that could be improved. **You don't have to be nice.** This feedback will be essential to improving the exercise for students in following years. As the exercise is run over several weeks, I will also be iteratively improving the exercise text and contents from group to group.

NB! Keep in mind that the exercise will not be performed in the usual room. See Blackboard for the location.

2 Background

2.1 Why?

With reference to the desired learning outcomes of the course, this assignment should address most if not all of them. It functions as an industrial control system, using a PLC over bus communication to control sensors and actuators in a minitature factory environment. In the final version students will also be remotely controlling it over OPC UA, with a Raspberry PI webcam server providing a video feed. Because of older equipment[1], this unfortunately can't be implemented in the prototype version you will be running this spring.

Hopefully the assignment will tie some of the concepts from earlier exercises together, provide a practical application of concepts from the lectures and, most importantly, show how they can be useful.

2.2 Preparation

You will not be required to do much preparation for the assignment. However, it is useful if you have read-through the assignment text in advance and have familiarized yourself with PLCs and logic control as presented in the lectures. There should be ample time to finish the assignment in the exercise hour, but if you want to finish it quickly you can watch the videos linked in section 3 beforehand. You will not be required to install any software beforehand, as you will be handed a laptop for the assignment.

2.3 Indexed Line with Two Machining Stations

The *Indexed Line With Two Machining Stations* is part of a series of miniature educational factory-line training models from *fischertechnik GmbH*, see fig. 1. It features a U-shaped factory line with conveyor belts and pushers to provide translation, push-buttons and phototransistors to measure position and a milling and drilling station to simulate processing of the workpiece.

The Indexed Line requires a 24V power supply. It has 9 digital inputs consisting of 5 NPN phototransistors and 4 pushbuttons[2]. There are also ten 24V outputs, all DC motors, controlling a milling station, drilling station, 4 conveyor belts and the backwards and forwards operation of two sliders. The location of the inputs and outputs is given in fig. 1 with reference to table 1. This corresponds to the digits on the connection terminal on the outermost side of the circuit board.

[1] The PLC used is too old to run OPC UA, however new PLCs will be available next year.
[2] Pushbuttons can operate in both normally-closed (NC) and normally-open (NO). Phototransistors are NC

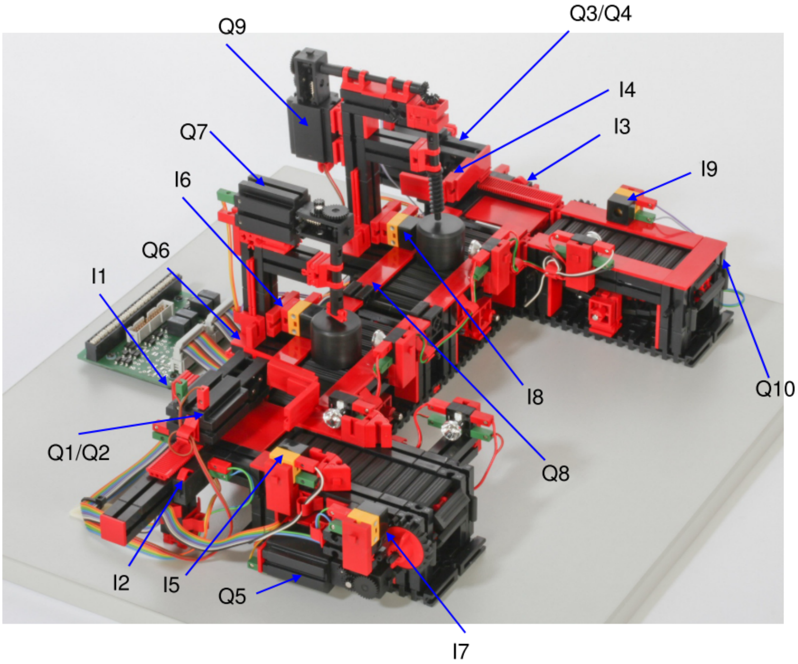


Figure 1: The Indexed Line With Two Machining Stations from fischertechnik GmbH

Terminal No.	**Function**	**Input/Output**
1	Power supply (+) actuators	24V DC
2	Power supply (+) sensors	24V DC
3	Power supply (-)	0V
4	Power supply (-)	0V
5	Push-button slider 1 front	I1
6	Push-button slider 1 rear	I2
7	Push-button slider 2 front	I3
8	Push-button slider 2 rear	I4
9	Phototransistor slider 1	I5
10	Phototransistor milling machine	I6
11	Phototransistor loading station	I7
12	Phototransistor drilling machine	I8
13	Phototransistor conveyor belt swap	I9
14		NC
15	Slider 1 forward	Q1
16	Slider 1 backward	Q2
17	Slider 2 forward	Q3
18	Slider 2 backward	Q4
19	Conveyor belt feed	Q5
20	Conveyor belt milling machine	Q6
21	Milling machine	Q7
22	Conveyer belt drilling machine	Q8
23	Drilling machine	Q9
24	Conveyor belt swap	Q10

Table 1: Terminals of the Indexed Line With Two Machining Stations

2.4 Programmable Logic Controller (PLC)

The PLC you will be using for this assignment is a Siemens S7-1500. This is the advanced line of Siemens controllers. Their high reliability in controlling industrial equipment in harsh environments has made them central to modern production facilities and to automation. With multiple PLCs working together, or along with other computerized equipment, it can be used to control a whole automation system. They are highly modular lending themselves to be adapted to different environments, for example a higher temperature range or a large amount of inputs, with advanced networking and safety capabilities as well. It is safe to say that the PLC will not be used to its full capabilities here, however it is still a good example of a use case for a PLC.

In figure fig. 2 you can see the PLC. It is mounted on a rail, with logical communications in backplane connectors at the back, and power transferred with cables at the front. To the left is the power supply module which receives mains 230V AC from wall sockets. The CPU is the brain of the PLC, performing the logical operations and communicating with the modules and external units like the PC you will be programming it from. It is also connected to a digital input module which will be receiving sensor information from the fototransistors on the training model, and a digital output module which will control its actuators. A single PLC can have up to 32 modules connected by backplane, giving other functions like advanced communications, analog outputs and inputs and much more.

Figure 2: Siemens S7-1500. A) Power supply unit, B) CPU (1516-3 PN/DP), C) Digital Input module (DI 32x24V DC), D) Digital Output module (DQ 16x24VDC/0.5A ST)

2.5 Siemens TIA Portal

Siemens TIA portal is the proprietary software for programming Siemens PLCs, it has a great number of capabilities for different modes of logic control like ladder logic, structured text, functional block diagrams and so on. While there exists other software for programming PLCs like Codesys, unfortunately only TIA portal can be used to program Siemens PLCs. *TIA Portal will be preinstalled on a laptop handed out for the assignment, so you will not be required to install it on your own laptop.*

3 Assignment

You are to implement a program such that the factory model loads a workpiece, transports it to the machining stations which machine the workpiece and on to the end. It should be such that another workpiece can immediately be processed after one is finished.

You will be handed a skeleton project named "SkeletonTPK4128TrainingModel", serving as a starting point. **Remember to click *save as* and pick another project name so you won't change the template.**

3.1 Configuring the PLC in TIA Portal

The PLC hardware will be configured for you in TIA Portal beforehand, with the exact version of the PS, CPU and modules you are using. However, if you wish to see how this is done I recommend watching this video[3].

Configuring the outputs and inputs The wiring of the PLC to the factory line will be setup for you beforehand. Go under *PLC tags* → *Tag Table* [70] in the project three. Here you will see how the variables in your program correspond to the different output and input gates on the PLC. Check out how the entries on the tag table correspond to the which terminal the wires are connected to, with regards to table 1. This video is a great guide for how to configure tag tables in TIA Portal.

Connecting to the PLC Connect the PLC to the laptop with the ethernet cable. You should now establish a connection between the PLC and the computer. Select Go online and ensure that the boxes correspond to the correct network and interface, like in fig. 3. The power-switch on the PLC power supply should be on before this step.

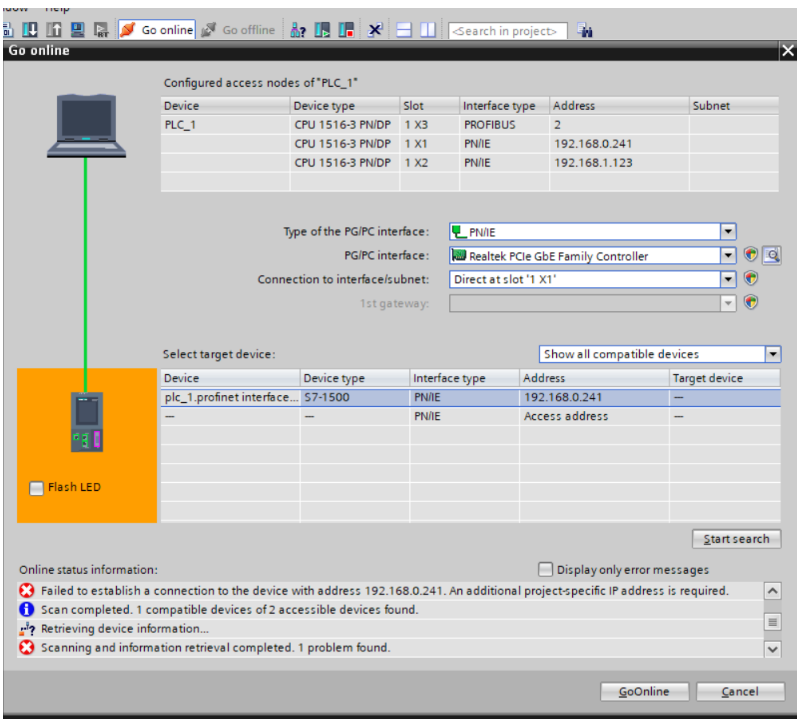


Figure 3: Going online in TIA Portal

[3]Watching this german youtuber "Hegamurl" was of immense help in designing this assignment. A huge part of becoming proficient in software programming is mastering the art of google and finding the correct youtube guru.

3.2 Making your program

1. Expand the *Program blocks* folder in the project three. Here you will see three blocks.
2. The main block **Main** [**OB1**] is the first thing the PLC will run, constantly running through every branch of the networks and running them if the logic conditions are met. If you were to implement a simple ladder logic program this is where you would implement most of your code. However, here we will only have one network in the Main-block, which corresponds to our Sequential Function Graph (SFC).
3. Open the **Sequence** [$DB5$] block, this is where we will do most of our programming.
4. There will also be database blocks, containing variables corresponding to the sequence block. These have a large amount of use cases in more advanced implementations, but will not be used here.
5. The sequential function graph will be composed of steps and transitions between them. The steps can contain actions to be performed at that step, and the transitions will contain the conditions to go from that step to the next. You will primarily use ladder logic to program the transitions.
6. A few of the initial steps and transitions are partly implemented in the skeleton project, see fig. 4 Steps 1-3, transitions 1-4 are completed. Step 4 and transition 5 are implemented, but empty.
7. This video is great for familiarizing yourself with the sequential graph environment. Watch it.
8. You should now be well-equipped to start creating the finished program.
9. The skeleton project should be enough to make the training model perform some actions. Try running it first, see section 3.3.
10. You can double click on the different steps and transitions implemented and read a short text explaining what they do. Familiarize yourself with the actions the skeleton code performs. Keep in mind that you will have to implement many additional steps and transitions on top of this.
11. Work iteratively implementing one section of the training model operation at a time. Test your work as you go, see section 3.3.
12. Everytime you change a step in the sequence graph, you have to go back into Main block, right click the Sequence and select *Update Block call*
13. If you get stuck. Look at the **Tips**-section, check the instruction documentation or ask the TA.

3.3 Running the program

The best way to progress in this assignment is through trial and error, and you should be frequently testing your code implementation on the indexed line. In order to do this:

1. Make sure Siemens TIA Portal is online with the PLC.
2. Right click your PLC in the project ree and select *Download to device* → *Software (All)*
3. Select yes on all the following boxes and load.
4. If everything went correctly, the code should now be on your PLC.
5. Remember to toggle the *Monitoring* option. This will light up where you are in the program.

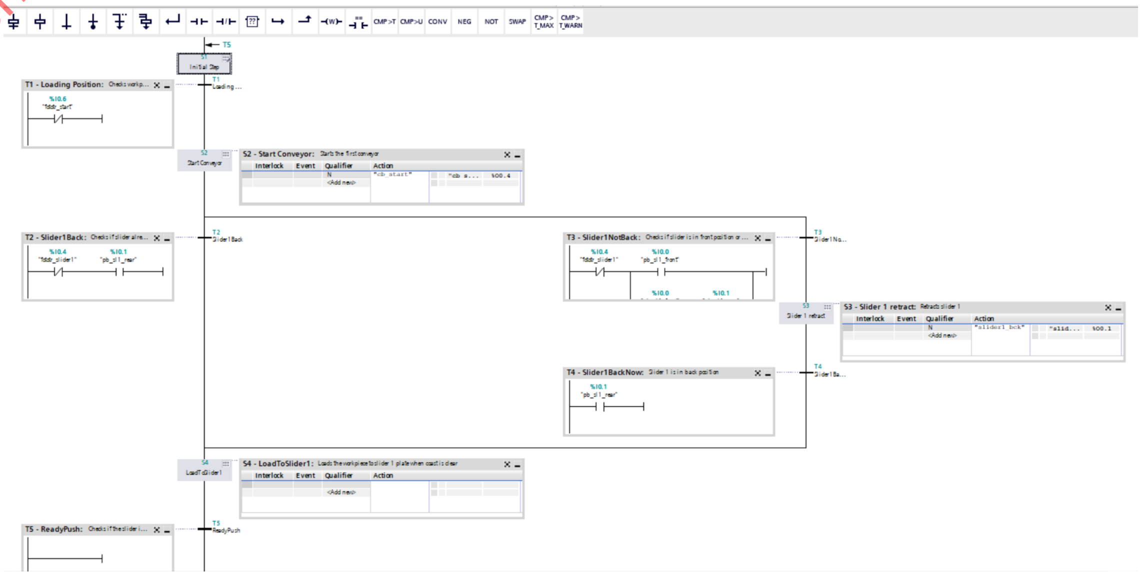


Figure 4: The steps in the preconfigured program

6. Toggle the switch under the panel of the CPU to **RUN**. Your code will now be running on the PLC. Remember to turn this off before make new changes, or before you want to restart the program.

7. Is it working? If no, systematically check where the error is happening and wheter it stems from software or hardware errors.

3.4 It works!

Is the program transporting the workpiece from end to end while milling and drilling it on the way?[4] Great job! If you have not, that is fine too. The most important thing is that you learn. And as this is a prototype of the assignment it is normal that there are errors, remember to report the issues you have and the things you found confusing or difficult to understand to the TA. This will be great help in improving the assignment.

4 Tips

Timing functions A lot of the logic control can be performed in terms of ”when workpiece arrives at X phototransistor”. However, there are stretches of the factory line where the position of the workpiece is not monitored by the phototransistors, e.g. when loading onto the slider plate. For these stretches you will have to use other s to ensure that the program does not continue before the correct previous actions are performed. One such way is through the use of timers. Use the CMP >T function from the toolbar of the sequence graph environment. You can use the time elapsed on a step or action in microseconds as a condition along with inputs like in figure fig. 5

Phototransistors are normally-closed (NC) Meaning that they are high when they receive light. However, when the workpiece is at a phototranistor position it will in fact be blocking this light. This is likely to be a common source of confusion when configuring the ladder logic elements in TIA-portal.

[4]Does it immediately process another workpiece without toggling the run-switch ON/OFF. If not, the solution is easier than you think. Think of how the first and last step should be connected. Running multiple workpieces in the line simultanously however, now that's a big challenge!

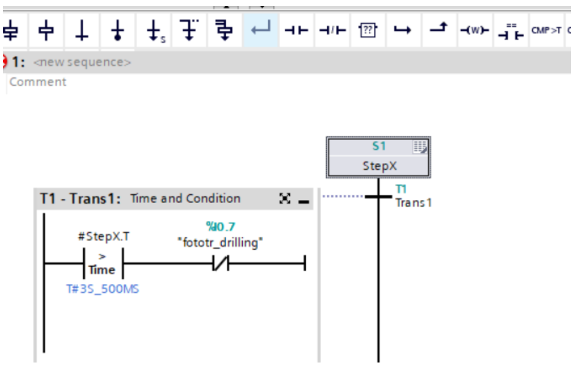


Figure 5: Use of CMP>T function

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A.4 Version 1

Version 1

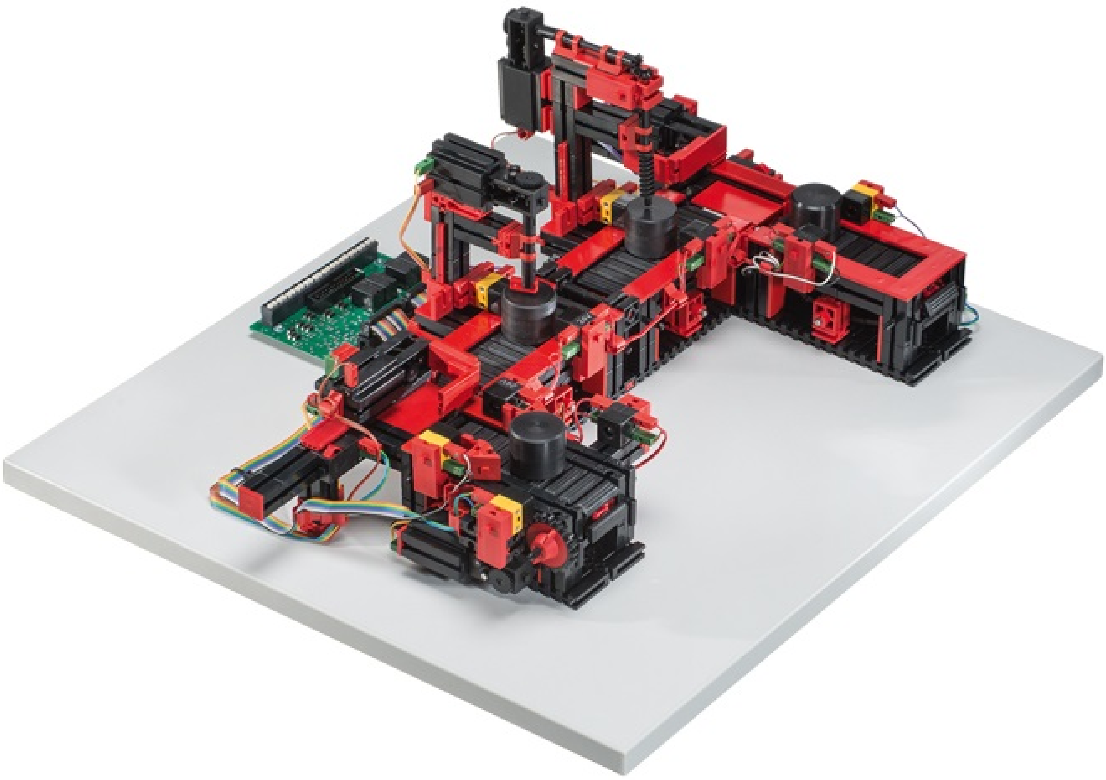
NTNU
Kunnskap for en bedre verden

Department of Mechanical Engineering

TPK4128 - Industrial Mechatronics

Factory Model exercise

Author:
Andreas Knudsen Sund



April, 2022

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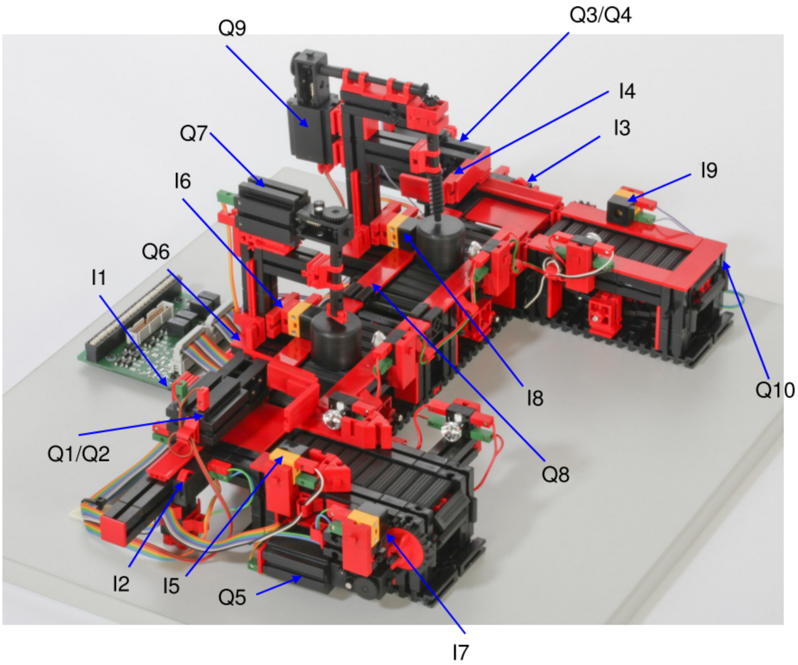

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7	Push-button slider 2 front	I3
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10	Phototransistor milling machine	I6
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12	Phototransistor drilling machine	I8
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3.1 Configuring the PLC in TIA Portal

The PLC hardware will be configured for you in TIA Portal beforehand, with the exact version of the PS, CPU and modules you are using. However, if you wish to see how this is done I recommend watching this video[2].

Configuring the outputs and inputs The wiring of the PLC to the factory line will be setup for you beforehand, with regards to table 1. However, you will need to map the outputs and inputs into a tag table in TIA portal. The tag table will be only partially implemented in the skeleton project. Be sure to employ a naming convention that is consistent and easy to read. You can choose to continue with the naming convention iniated in the skeleton project, or make your own[3] This video is a great guide for how to configure tag tables in TIA Portal.

Connecting to the PLC Connect the PLC to the laptop with the ethernet cable. You should now establish a connection between the PLC and the computer. Select Go online and ensure that the boxes correspond to the correct network and interface, like in fig. 3. The power-switch on the PLC power supply should be on before this step.

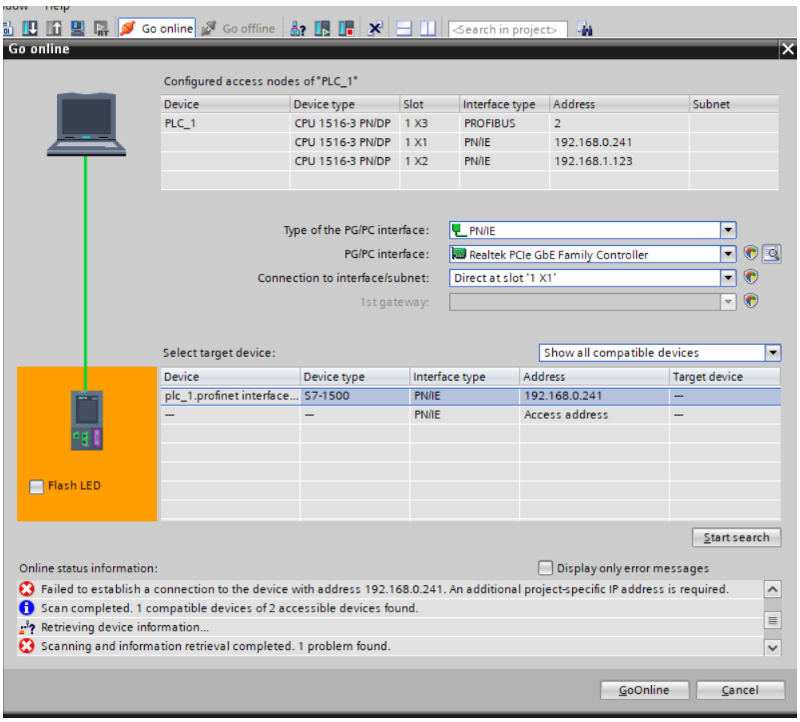

Figure 3: Going online in TIA Portal

3.2 Making your program

1. Expand the *Program blocks* folder in the project three. Here you will see three blocks.
2. The main block **Main** [**OB1**] is the first thing the PLC will run, constantly running through every branch of the networks and running them if the logic conditions are met. If you were to implement a simple ladder logic program this is where you would implement most of your code. However, here we will only have one network in the Main-block, which corresponds to our Sequential Function Graph (SFC).

[2]Watching this german youtuber "Hegamurl" was of immense help in designing this assignment. A huge part of becoming proficient in software programming in mastering the art of google and finding the correct youtube guru.

[3]If you change it, you will have to update the variables in the SFC as well.

3. Open the **Sequence** [$DB5$] block, this is where we will do most of our programming.
4. There will also be database blocks, containing variables corresponding to the sequence block. These have a large amount of use cases in more advanced implementations, but will not be used here.
5. The sequential function graph will be composed of steps and transitions between them. The steps can contain actions to be performed at that step, and the transitions will contain the conditions to go from that step to the next. You will primarily use ladder logic to program the transitions.
6. A few of the initial steps and transitions are partly implemented in the skeleton project, see fig. 4 Steps 1-3, transitions 1-4 are completed. Step 4 and transition 5 are implemented, but empty.
7. This video is great for familiarizing yourself with the sequential graph environment. Watch it.
8. You should now be well-equipped to start creating the finished program.
9. The skeleton project should be enough to make the training model perform some actions. Try running it first, see section 3.3
10. Work iteratively implementing one section of the training model operation at a time. Test your work as you go, see section 3.3.
11. Everytime you change a step in the sequence graph, you have to go back into Main block, right click the Sequence and select *Update Block call*
12. If you get stuck. Look at the **Tips**-section, check the instruction documentation or ask the TA.

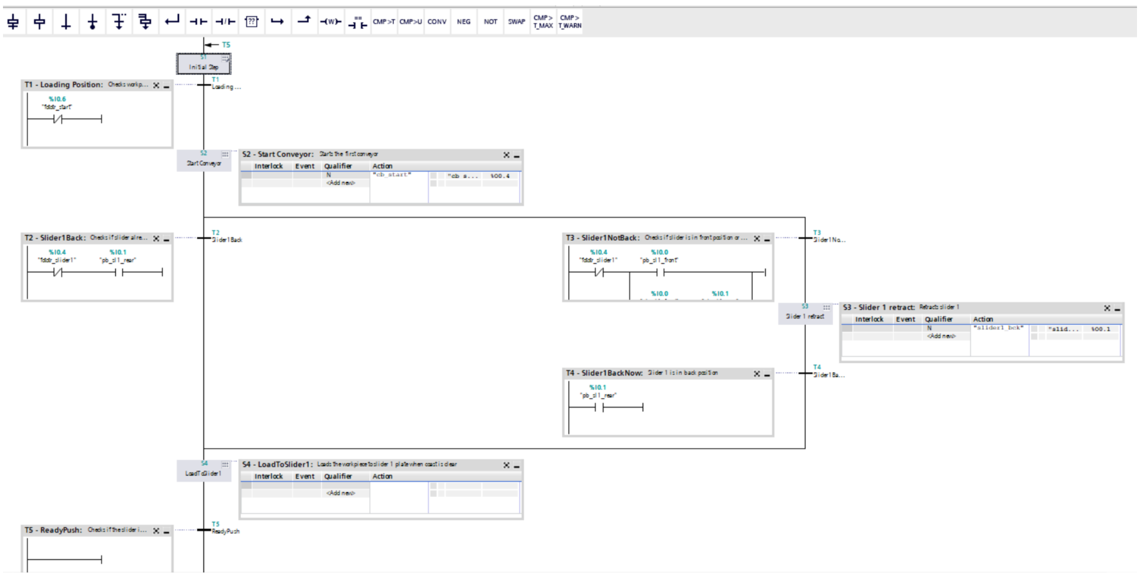

Figure 4: The steps in the preconfigured program

3.3 Running the program

The best way to progress in this assignment is through trial and error, and you should be frequently testing your code implementation on the indexed line. In order to do this:

1. Make sure Siemens TIA Portal is online with the PLC.

2. Right click your PLC in the project ree and select *Download to device→ Software (All)*
3. Select yes on all the following boxes and load.
4. If everything went correctly, the code should now be on your PLC.
5. Remember to toggle the *Monitoring* option. This will light up where you are in the program.
6. Toggle the switch under the panel of the CPU to **RUN**. Your code will now be running on the PLC. Remember to turn this off before make new changes, or before you want to restart the program.
7. Is it working? If no, systematically check where the error is happening and wheter it stems from software or hardware errors.

3.4 It works!

Is the program transporting the workpiece from end to end while milling and drilling it on the way?[4] Great job! If you have not, that is fine too. The most important thing is that you learn. And as this is a prototype of the assignment it is normal that there are errors, remember to report the issues you have and the things you found confusing or difficult to understand to the TA. This will be great help in improving the assignment.

4 Tips

Timing functions A lot of the logic control can be performed in terms of "when workpiece arrives at X phototransistor". However, there are stretches of the factory line where the position of the workpiece is not monitored by the phototransistors, e.g. when loading onto the slider plate. For these stretches you will have to use other tool to ensure that the program does not continue before the correct previous actions are performed. One such tools is through the use of timers. Use the CMP>T function from the toolbar of the sequence graph environment. You can use the time elapsed on a step or action in microseconds as a condition along with inputs like in figure fig. 5

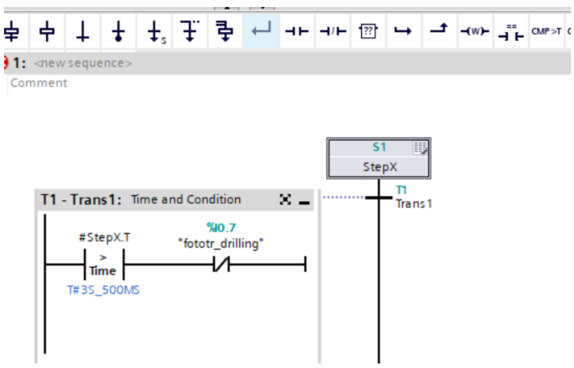

Figure 5: Use of CMP>T function

Phototransistors are normally-closed (NC) Meaning that they are high when they receive light. However, when the workpiece is at a phototranistor position it will in fact be blocking this light. This is likely to be a common source of confusion when configuring the ladder logic elements in TIA-portal.

[4] Does it immediately process another workpiece without toggling the run-switch ON/OFF. If not, the solution is easier than you think. Think of how the first and last step should be connected. Running multiple workpieces in the line simultanously however, now that's a big challenge!

Slider of the track? As you try to get the training model to operate correctly through trial and error, you are likely to run into an issue where you run the sliders too par past the limit switches in either directions. Your finished program should be such that this doesn't happen. You can load the project titled **SliderDerailed**, which with simple ladder logic will allow you to manually control the sliders by placing your fingers over the phototranistors.

Errors in physical training model There are some physical errors that might occur on the physical training model:

1. **Disconnected wiring:** The red and green connectors on the sensors and actuators of the physical training model are not rigidly in place and might fall out.
2. **No contact with pushbuttons:** FischerTechnik works alot like lego, meaning that the structure is moveable. If the pushbuttons are not toggled when the sliders are in the correct positions, try to physically tweak the elements on the sliders such that contact is reestablished.
3. **Motor is running, but belt is still:** If the correct actuator is HIGH, but the belt stands still or jitters, it is likely that the gears have jumped out. Move the gears on the side of the motor such that the gears mesh.

Appendix B

Project Thesis

This appendix includes the author's pre-master project thesis, which is frequently referenced throughout this work. It is described in Section 2.5.1

NTNU
Norwegian University of
Science and Technology

Teaching Automation with Training Models: A Pre-Study using Design Thinking Methodology

Andreas Knudsen Sund

TMA4560 - Engineering Design and Materials
Specialization Project

Supervisor:
Amund Skavhaug

Submission date:
December 21$^{\text{th}}$ 2020

Department of Mechanical Engineering

Norwegian University of Science and Technology

Preface

0.1 Personal Motivation

This constitutes my pre-master project thesis at NTNU, where I'm currently a 5th year mechanical engineering student. I have selected a hybrid of two specializations: *Advanced Product Development* and *Robotics and Automation.* This is well fitting to the nature as the subject matter is automation technology, but I also develop a lab assignment as a product and use product development methodologies for this purpose.

Throughout the last years I've particularly interested myself in the Design Thinking Methodology and its implementation. I have experience of it from courses such as *TMM4220: Innovation By Design Thinking* and *TMM4245: Fuzzy Front End*, but have adapted DT principles in other curricular and extra-curricular work as well. I thought it should be interesting and useful to use it in the development of a lab assignment. Throughout my years at NTNU I have experienced both good and bad learning activities. Understanding why some things work and some things don't, and how different students best learn is an intriguing area of inquiry, and one in which Design Thinking should be able to uncover some interesting ideas and insights.

I've also carried a large interest for mechatronics, which I've been able to pursue both in university courses and playing with micro-controllers at home. Two of those courses are *TPK4125: Mechatronics* and *TPK4128: Industrial Mechatronics*, the same courses in which the training model will be used.

0.2 Thanks and Acknowledgements

First and foremost I would like to thank my supervisor Professor Amund Skavhaug. Thank you for valuable advice, giving me the freedom to explore my own interests and intuitions and for making yourself available for meetings or swiftly answering my questions whenever I required it. Even though two thirds of the meetings went to digressions, the last third was triply effective.

Huge thanks to Nejc Ilc and Uroš Lotrič at the University of Ljubliana for being helpful, and letting me use their FTsim virtual lab, without which I would have not been able to conduct testing. I'd also like to thank Federico Lozano for helping me with the design thinking part of the project, for valuable input on my needsfinding process, and for giving me useful tips for testing. Lozano also put me in contact with Matthew Lynch and Uladzimir Kamovich who I'd like to thank for helping me navigate the uncertain terrain that is design thinking literature and finding the nuggets that are viable for citation in scientific writing. Thanks to Niklas Wik at Siemens Trondheim for lending me a PLC.

Throughout my time at NTNU I've been involved in a lot of student organizations and the student democracy at department, faculty and central level. These has truly been the activities I've enjoyed the most during my time here. Thus I would like to give my thanks to A/F Smørekoppen, Radio Revolt, Studentrådet-IV, the Student Parliament, and all the co-students I've met along the way[1]. Furthermore, I'd like to thank my mother, my father and the Norwegian social democracy for always supporting me.

To whoever will continue the work of this project: don't hesitate in contacting me if you have questions about the thesis or just want to discuss something[2].

[1]Except for some, you know who you are.

[2]Email: andreas.k.sund@gmail.com Telephone: 45297450

Summary

This is a pre-master specialization project conducted by Andreas Knudsen Sund in the 2020 autumn semester, as part of the 5th grade of the Mechanical Engineering program at NTNU. It is pre-study into the development of a laboratory assignement teaching engineering students automation through the use of a factory training model from FischerTechnik. This work is based on the product development methodology Design Thinking, and the thesis also functions as an examination on whether these methods are applicable in the creation of educational content.

The conclusion is that, with some reservations, Design Thinking is a fitting methodology due to the inherent nature of higher education. At the very least, the core methods such as viewing concepts from the users point of view and doing early testing should be adapted to a larger degree. The results of the pre-study are presented as a list of suggestions, serving as a foundation for enabling whoever resumes work on the assignment to make sure it delivers the desired learning outcomes. However, there is a lot of work that remains. The methods of the design thinking process are described in such a way that they can employed in future work with this assignment, or be re-purposed by others wishing to perform a similar process.

Sammendrag

Dette er en prosjektoppgave utført av Andreas Knudsen Sund høsten 2020, som del av 5. klasse ved sivilingeniørstudiet i Produktutvikling og Produksjon ved NTNU. Den er et forstudie på utvikle en laboratorieøving for å lære ingeniørstudenter om automasjon ved bruk av en treningsmodell fra FischerTechnik som simulerer en produksjonslinje. Dette arbeidet er basert på produktutviklingsmetodologien Design Thinking, og oppgaven fungerer også som en undersøkelse av hvorvidt disse metodene kan anvendes i utarbeiding av undervisningsopplegg.

Konklusjonen er at, med noen forbehold, så er Design Thinking en svært passende metodologi grunnet flere aspekter ved høyere utdanning. I det aller minste burde kjerneaktivitetene brukes i større grad, som å se ting fra studenten/brukerens perspektiv og teste ting før de settes til live. Resultatene fra forstudiet, gitt som en liste anbefalte forslag, fungerer som et godt grunnlag slik at hvem enn som fortsetter arbeidet kan sørge for at den resulterende laboratorieøving tilbyr det ønskede læringsutbyttet. Det er riktignok mye som fortsatt gjenstår. Metodene i design thinking prosessen er beskrevet slik at de kan fortsettes i videre arbeid med denne laboratorieøvingen, eller gjenbrukes av andre som ønsker å gjennomføre en liknende prosess.

Contents

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Chapter 1

Introduction

1.1 Background and Motivation

As the world continually moves towards increasing automation and Industry 4.0[1], it is paramount that there are enough engineers with the requisite knowledge and skills. This necessitates providing students with an understanding of the automation environment, of the equipment and processes involved, the embedded control systems, and the IT systems that allow them to communicate[2]. This involves learning the requisite theory and current state-of-the-art through lectures and learning resources. However, in order to learn the needed skills it is also necessary for the students to do practical work where they interact with the equipment they learn about. Doing practical and tangible work in laboratory environments promotes deeper understanding, and can inspire for further learning. Students often view these activities as enjoyable. It can also provide "aha-moments" developing knowledge and intuition that couldn't necessarily be attained from a book.

Engineering education and education in general can be viewed in terms of the product developer being the ones who devise and deliver the learning activities, and the user being the students attending a given course or education. Inherent to this context is a large variance among the users. Individual students learn differently and have have idiosyncratic backgrounds and knowledge bases. There is also a large gap between the providers (largely educators) and the users (students), both in terms of knowledge and experience and in terms of predispositions and preferred ways of learning. The landscape of university education is fast changing. Age cohorts have cultural differences from one another. Technological developments influence both the way students learn, and what they need to learn. This raises the need of continuously evaluating, reevaluating and evolving the content and execution of the education. Moreover, it means the educator will be unable to understand the needs and learning methods of the users without leaving his/her desk to interact with them. One framework for doing this is Design Thinking. It is a product development methodology containing a set of methods ensuring that the product fits its intended users. For the reasons outlined above Design Thinking methods have been deployed in this project.

There is a lot of published work about how to teach Design Thinking[3][4][5], but little to be found about applying it in the creation of educational content. This serves as an interesting frontier for exploration, and the hypothesis of this text is that Design Thinking is indeed valuable for this purpose. There is previous work on the use of the Fischertechnik training models in engineering education. Gil *et al.* [6] and Ile and Lotric [7] state success in using it to teach automation, and go a step further by creating virtual copies of the labs. FTsim, the digital lab created by Ile and Lotric [7], has been employed as a tool when testing the assignment with users. This thesis contributes by exploring how educational activities of this kind can fulfill the desired learning outcomes by better understanding users and the problem at hand

The primary reader for this thesis is whichever master student, teaching assistant or educator that will implement and conduct the assignment[1]. However, the resulting insights and recommendations can be applied to the development of similar technical assignments.

Chapter 2 introduces Design Thinking, the learning outcomes of the course and the technology to be used. In **Chapter 3** the methods employed and their execution is described. **Chapter 4** details the resulting insights from the DT process and gives suggestions for further work and implementation. Finally, **Chapter 5** evaluates the validity of the hypothesis that Design Thinking is a viable framework for developing educational activities of this kind. It also discusses possible shortcomings in the work of this thesis and analyzes the path forward.

1.2 Problem Description

This project serves as a foundation for how to create a laboratory assignment teaching automation in a way that fulfills the desired learning objectives and inspires further learning. Originally, the plan was to implement the assignment with associated interfaces and software to the extent of an alpha version. However, projects change along the way, and should be adapted to new developments. After a while it became apparent that the required equipment would not be available before the thesis deadline. This led to a expansion of the project scope from the technical implementation of the specific assignment, to a goal of a broader exploration of the available solution space and more conceptual study of how such an assignment should be constructed and provided.

[1]Assignment will for the rest of this text refer to the resulting laboratory assignment(s), not the project thesis you are reading.

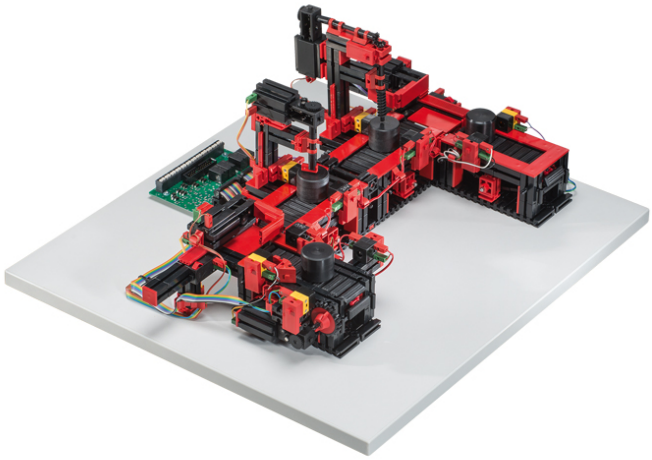


Figure 1.1: The Indexed Line With Two Machining Stations from fischertechnik GmbH[8]

The aim of this project thesis is:

- To explore how a student lab assignment(s) could be implemented for the course TPK4128 Industrial Mechatronics using the "Indexed line with two machining stations 24V" training model from fischertechnik [8](Figure 1.1) and Siemens Simatic S7-1500 PLC[9], and whether this would be useful and desirable.
- The resulting assignment should provide students with the desired learning outcomes concerning teamwork and competence with automation, PLC control and industrial computer systems.
- Use Design Thinking principles and methods in the development of the assignment. Describe the method and process in such a way that it can be employed in further work.
- Extract insights and user information from user interviews and field observations. Synthesize these insights into ideas for implementation.
- Partially implement some selected solutions using FTsim, perform user tests and evaluate the merit of said solutions[7].
- Based on this work, provide recommendations and prospective avenues for future work. Where possible, make the suggestions generalizeable to designing other similar assignments.
- Discuss possible shortcomings of the performed work and identify what remains to be done.
- Evaluate whether Design Thinking is a viable framework for creating educational activities.

Chapter 2

Theory

In this chapter the underlying principles, theory and methods of Design Thinking are described. The desired learning outcomes to be designed for are presented. As well as some background on the involved concepts and technologies.

2.1 Design Thinking

In traditional product development it is common to start at the solution stage. A majority of the time is then spent implementing the technical solution to a problem. In cases were the problem and user requirements are well-established this is acceptable. However, it is possible that the developers have preconceived notions of the users and problem that are incorrect. Furthermore, when traditional product development teams engage in user research they often employ methods like surveys and focus groups, which are suitable for selecting among preexisting solutions. However, these inflexible quantitative methods are unfit at acquiring the unspoken needs that customers are unaware of or that don't yet exist[10]. Design Thinking is a methodology of User Centered Product Development that addresses this. By spending time observing, interviewing and testing with users, and then analyzing this qualitative information, DT ensures that one reliably acquires a correct understanding of the user needs and the problem at hand. It also increases the probability that the team will come across innovations.

In a Design Thinking process there will be sequential iterations of convergent and divergent stages, as shown in Figure 2.1. The divergent processes expand on the solution space and explore, the convergent processes take into account boundaries, limitations and values and narrow down[11]. In Figure 2.2a Beckman and Barry [12] describes the innovation process as first gathering user information, making sense of it, identifying the needs to be addressed, then creating potential solutions. Figure 2.2b further expands on the activities inherent to these stages, as well as their respective suitable learning styles. The Stanford d.school process proposes 5 essential activities of design thinking, these being "Empathize, Define,

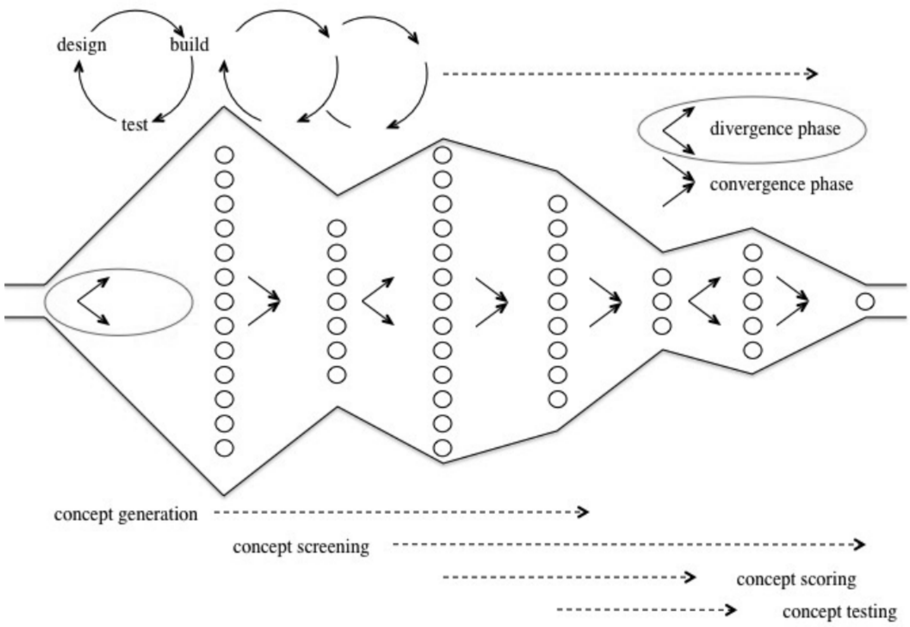


Figure 2.1: Design process as iterative cycles of divergence and convergence steps[11]

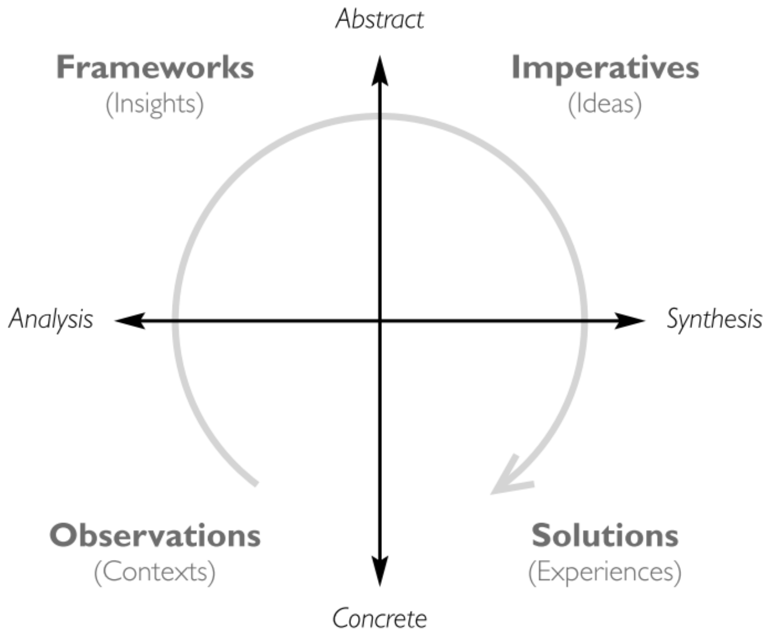
Ideate, Prototype, Test"[3][13]. Beckmans description is more rigorous compared to the Stanford d.school description of the process, which conversely is more practicable for in-field application of the methods. They both have their strengths, and will be discussed in parallel.

2.1.1 Needfinding

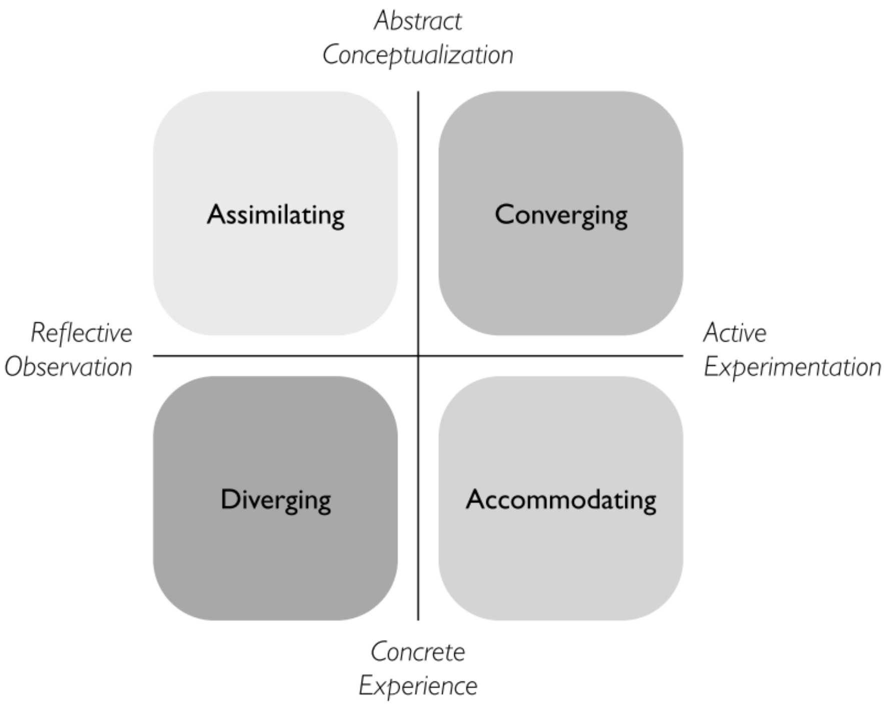
Needfinding is a central concept to Design Thinking. This is the activity of actively seeking to find and characterize the needs of potential users. The best way of solving something is clearly understanding the nature of the problem and the needs it gives rise to. While never specifically mentioning Design Thinking, *Needfinding: The Why and How of Uncovering Peoples Needs* by Patnaik and Becker, perfectly encapsulates a lot of the principles and activities central to it, while also providing the reasons for using them[10]. They list the central principles of Needfinding, some of which are:[10]

- Look for needs, not solutions
- Go to the customer's environment
- Look beyond the immediately solvable problem
- Let the customer set the agenda
- Iterate to refine the findings

These principles and the activities they warrant will be part of the basis for the work done in this thesis.



(a) Innovation process [12]



(b) Learning Styles [12]

Figure 2.2: The innovation processes of design thinking and corresponding learning styles[12]

2.1.2 I: Observation

In design thinking it is paramount to get a deep understanding of your users, how they would use your product and the context in which they engage with it. It is important to engage a wide variety of users[1]. This is a divergent process, respectively described as **Observations** and **Empathize** by Beckman and Stanford d.school. There is a plethora of different Needfinding activities that can be conducted in this phase, consisting of participant and non-participant observation, interviews and more. One should strive to get at the contradictions between what people say and do, subconscious actions they are unaware of, and information about the context of use that would appear to be illogical or non-obvious without getting into the field. This entails asking "why", of yourself when doing observations, and of the user when conducting interviews. Beckman and Barry [12] state the importance of understanding user needs at the levels of "use, usability and meaning", suggesting that meaning-based needs are the most important for radical innovation, and writing: "*Those meaning-based needs are only uncovered as the researcher continues to probe, deepening his or her understanding of the user's thinking about the innovation and its use context.*"[12]. Stanford d.school [13] and Kelley and Kelley [14] describe tools and methods for this which will be applied in Chapter 3.

2.1.3 II: Sense-Making

After collecting sufficient information about users and use context, the next step is to create **Frameworks** or **Define**. Important insights are extracted from the user information. Framing is done by identifying patterns, idiosyncrasies and interesting nuggets and putting it in system. Most importantly the innovator identifies the faults, lacks and pain points from this framework, giving rise to needs which lay out the possible areas of innovation and improvement to expand upon.

2.1.4 III: Synthesis

At this point the identified framework should be synthesized into a value preposition, or a set of **Imperatives**. This entails converging on the goals and needs that are to be met by the innovation. The stages in the d.school model don't map one-to-one with the Beckman and Barry model of Figure 2.2a. **Define** spans both **Frameworks** and **Imperatives**. **Ideate** is at the junction between **Imperatives** and **Solutions**, when the team diverges upon potential solutions.

[1] Including extreme users. Users on the outskirts of the bell-curve will have amplified needs that are easier to identify and often translatable to the average user, or provide possible niches for innovation[10][12][13][14]

2.1.5 IV: Solutions

Moving into the final quadrant, **Solutions**, various concept generation techniques should be employed to create answers to the imperatives. The concepts are narrowed down to a few avenues of exploration one finds valuable to **Test**. In order to conduct a test a **Prototype** is needed. The prototype is not required to be a near-completed implementation of the product[2], but should be tailor-made to test specific uncertainties that the team has identified[16]. In the words of IDEOs David Kelley "*Prototypes are designed to answer questions*"[15]. After testing with users, the insights can be used to further refine the solution. Elverum and Welo [17] propose the concepts of directional and incremental prototyping, the former assessing major design choices for type of solution, the latter continuously addressing sub-problems once a decision has been made based on the first.

2.1.6 Innovations Teams and Learning Styles

Design Thinking literature often states the benefit of working in teams, ideally inter-disciplinary ones[3][4][5][12]. Beckman and Barry [12] stresses the importance of different learning styles being present in the team[3]. The learning styles are provided in Figure 2.2b and relate to corresponding quadrants in Figure 2.2a. The dominant learning abilities for the individual styles are the bordering axes. For instance, abstract conceptualisation and reflective observation are the activities of the assimilating style. It is suggested that all members take part in every phase, but that the team member with the fitting learning style takes the lead[12]. They key takeaway is that having different perspectives and predispositions is valuable to a innovation team, at that one should play to the strengths of individual team members in the befitting sub-processes.

2.1.7 Additional Comments

The stages described for Design Thinking are not meant to be followed strictly in order like for example the waterfall method. Instead it is a set of processes and activities that aid product developers in identifying and meeting user needs. Different situations necessitate different measures. More time might be spent in some stages than others, the stages might be taken on in a different order and so on. However, Beckman states that teams who only go through one-or-two stages generally perform worse than those who progress through all. Furthermore, teams that go through the stages several times perform even better[12]. The process often entails iterative cycles of repeating the stages[11].

---

[2]Furthermore, Schrage [15] point out the many pitfalls of having prototypes of too high fidelity. This takes more time, prohibits some experimental activities, and can in organizations cause conflict between departments.

[3]It is possible to do design thinking alone, albeit not as effectively. It is unlikely for a team of one to possess all learning styles, meaning that a one person project might be lacking in certain phases

2.2 Desired Learning Outcomes

Industrial Mechatronics (TPK4128) is a course taught primarily to Mechanical Engineering students at the Norwegian University of Science and Technology (NTNU)[4]. The lab assignment(s) discussed in this text are intended to be used in this course, with the possibility of a slightly altered form being used in the introductory course Mechatronics (TPK4125).

The assignment is relevant to the following parts of the desired learning outcomes stated for the course on the school website[18][5]:

- Knowledge: "*The course shall give knowledge about: Design and programming of PLC, single board computers and other computer systems for use in industrial computer control systems, as well as in embedded- and mechatronics system in general.*"
- Skills: "*The course shall give skills in design, implementation and programming of industrial computer systems, such as single board computers and PLCs, with the associated computer networks, sensors and actuators.*"
- General competence: "*The course shall give competance in industrial and embedded computer systems, PLC systems and mechatronics.*"

And from the desired learning outcomes for a 5-year Mechanical Engineer[6], translated from Norwegian[19]:

- General competence: "*Can collaborate and contribute to interdisciplinary collaboration and have a general understanding of greater technical systems.*"

2.3 Programmable Logic Controllers (PLC)

Programmable Logic Controllers (PLCs) are ruggedized, single-processor, computer-based devices that are frequently used in production settings[20][21]. Their high reliability in controlling industrial equipment in harsh environments has made them central to modern production facilities and to automation. With multiple PLCs working together, or along with other computerized equipment, it can be used to control a whole automation system. They are highly modular lending themselves to be adapted to different environments, for example a higher temperature range or a large amount of inputs. They are efficient in sequential control, and have many opportunities for fault detection and diagnosis. PLCs are normally programmed with ladder control diagrams, which means it does not require ad-

[4]This includes certain specializations of the 2- and 5-year Mechanical Engineering (MIPROD, MTPROD) study programs, but also Engineering and ICT(MTING) students who have selected the Mechanical Engineering specialization.

[5]The learning outcomes are not static and such an assignment can enable teaching new concepts, opening up for extending the desired learning outcomes.

[6]Viewing the study program holistically one could take in learning outcomes related to other courses as well, given that this doesn't compromise the learning outcomes of TPK4128.

vanced programming knowledge from operators. The main architecture of a typical PLC-system is given in Figure 2.3. The central processing unit (CPU) is the most important part containing the programming instructions, interpreting input signals and executing control actions based on these and the programming. The power supply unit converts AC mains power to DC, supplying the CPU and the I/O modules. All of these are typically connected to the same rack, working as a mounting mechanism and supplying backplane power.

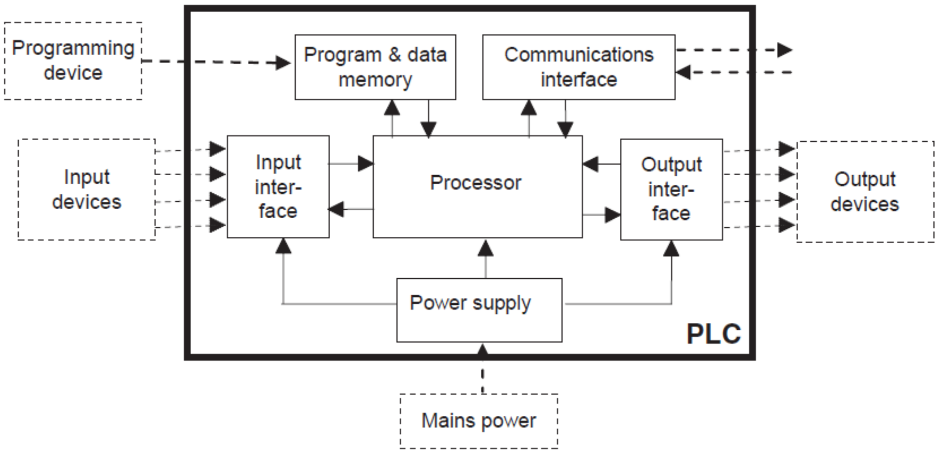


Figure 2.3: The PLC-system [21]

The PLC used for this assignment will be a Siemens Step 7 1500 series[9]. In addition to the main CPU and power supply a combined I/O module or individual output and input modules are required. These should supply 24V DC as to operate on the same voltage as the training model[8]. Programming will be done through the Siemens Totally Integrated Automation (TIA) Portal V16, uploading through a network connection from a PC or single-board computer. Newer editions of the S7-1500 contains support for the OPC Unified Architecture (OPC-UA) Protocol[7] which is a machine-to-machine communication protocol highly suited for working in client server automation system with PLCs and other computer systems[22].

2.4 Indexed Line With Two Machining Stations

The *Indexed Line With Two Machining Stations*[8] is part of a series of miniature educational factory-line training models from *fischertechnik GmbH*, see Figure 1.1 It features a U-shaped factory line with conveyor belts and pushers to provide translation, push-buttons and phototransistors to measure position and a milling and drilling station to simulate processing of the workpiece[8].

[7] Actually it is the firmware that decides whether or not it is supported, but older models can not update to the newest firmware.

[8] It will often be referred to as simply The Indexed Line or training model for simplicity

2.4.1 Technical Details

The Indexed Line requires a 24V power supply, although there exists a 9V version as well[8]. It has 9 digital inputs consisting of 5 NPN phototransistors and 4 pushbuttons[9]. There are also ten 24V outputs, all DC motors, controlling a milling station, drilling station, 4 conveyor belts and the backwards and forwards operation of two sliders. The location of the inputs and outputs is given in Figure 2.4 with reference to Table 2.1.

Terminal No.	Function	Input/Output
1	Power supply (+) actuators	24V DC
2	Power supply (+) sensors	24V DC
3	Power supply (-)	0V
4	Power supply (-)	0V
5	Push-button slider 1 front	I1
6	Push-button slider 1 rear	I2
7	Push-button slider 2 front	I3
8	Push-button slider 2 rear	I4
9	Phototransistor slider 1	I5
10	Phototransistor milling machine	I6
11	Phototransistor loading station	I7
12	Phototransistor drilling machine	I8
13	Phototransistor conveyor belt swap	I9
14		NC
15	Slider 1 forward	Q1
16	Slider 1 backward	Q2
17	Slider 2 forward	Q3
18	Slider 2 backward	Q4
19	Conveyor belt feed	Q5
20	Conveyor belt milling machine	Q6
21	Milling machine	Q7
22	Conveyer belt drilling machine	Q8
23	Drilling machine	Q9
24	Conveyor belt swap	Q10

Table 2.1: Terminals of the Indexed Line With Two Machining Stations[8]

2.4.2 Previous Work, including FTsim

There are other examples of the use of the Indexed Line, or similar equipment, in higher education. Gil *et al.* [6] describes the use of the Indexed Line to teach

[9]Pushbuttons can operate in both normally-closed (NC) and normally-open (NO). Phototransistors are NC.[8]

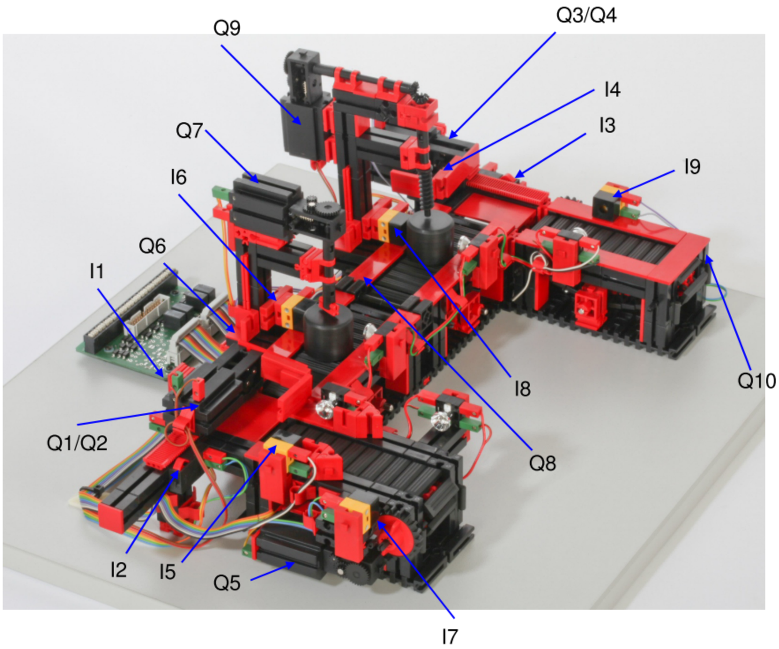


Figure 2.4: Inputs and Outputs of The Indexed Line With Two Machining Stations[8], with reference to Table 2.1

Industrial Automation students at the University of Zaragoza. Along with a physical lab where students interact with the Indexed Line, they create a virtual lab in which students interact with a digital copy. The aim is to teach students Ladder Diagram (LD) control with PLC[10]. They write "*The main conclusion is that the developed VL allows online students do the same practical training than face-to-face students.*" However, they admit that they haven't yet tested it, but they plan to do this for future work. Gensheimer *et al.* [24] use several different FischerTechnik training models in concert in order to teach object-orientation, reporting high student satisfaction and suggesting the equipment should be expanded to further use.

FTsim Ile and Lotric [7] have created the 3D simulator FTsim which mimics the behaviour of three distinct fischertechnik training models, including the Indexed Line. They use the Fischertechnik equipment in a course teaching process automation and control, and state that "*The main idea of the course is to familiarize students of computer science with concepts of automation with a focus on PLC programming and integration with the higher-computer science with concepts of automation with a focus on PLC programming and integration with the higher- level systems.*" They observe that the use of the training models additionally motivate the students,

[10] Ladder Diagrams are a easy-to-use form of schematic logic control widely used in industrial settings[23]. It is also the base programming mode of Siemens TIA Portal.

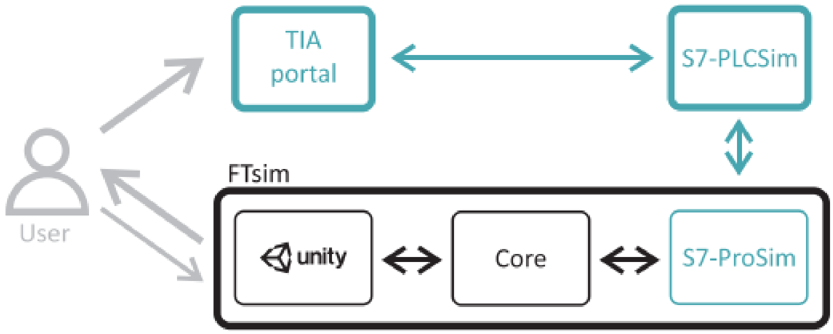


Figure 2.5: The architecture of FTsim, the virtual lab training model by Ile and Lotric [7]

all though limited time with the physical training models produces the need for the digital simulators such that students will have enough time to properly learn PLC control. The student feedback for the FTsim and the physical lab has been positive, leading them to conclude that this is a valuable learning resource. The architecture of FTsim is given in Figure 2.5. The students setup their PLC and programming blocks in TIA Portal, simulating the PLC with PLCSim (Figure 3.2), the S7-ProSim interface creates Component Object Model (COM) objects establishing communication between PLCSim and the C# scripts underlying the Unity-based[11] FTsim executable (Figure 3.1).

[11]Unity is a widely used video game engine.[25]

Chapter 3

Method

This chapter covers the product development process of this thesis. It details the needfinding activities used, how they were performed and to what success, as well as the work done to extract insights and solutions from this. It is written in such a way that a person continuing this work can employ the same methods, but also such that it can be generalized to other work in designing learning activities.

3.1 Interviews

An essential part of the process has been the conduction of extensive user interviews. The users have primarily been students, but also some educators. Students who have already taken this course were interviewed as they can draw on similar experience, and possess knowledge about the context the assignments take place in. Interviews were also conducted with students who are yet to have the course (but likely will according to their study path) and students who will not have the course at all. This is in order to get insights unclouded by previous experience and to explore a broad specter of users. Among the subjects where also lecturers, as they provide the perspective of the person conducting the lab in addition to having substantial past experience of the supervision of university-level lab assignments.

On *page 97* Kelley and Kelley[14] present design thinking interviewing techniques. As you aspire to get at the hidden insights and latent needs of your prospective users, questions should be phrased and asked in such a way that they don't produce yes-or-no answers, but instead get them to "*examine and express the underlying reasons for their behaviour and attitudes*"[14]. A central part of this is the **five whys**, meaning that you should ask the interviewee "why" a lot[4]. In the following list the main questions asked of the interviewed students are presented. Bear in mind that this is an iterative process where follow-up questions should be devised mid-interview in order to go in depth on the aspects brought up, here-under a sizeable amount of whys. By allowing the user to set the agenda you increase the possibility of serendipitous insights, and prohibit your own understanding from clouding the interview[10].

- Can you tell me a story about a lab assignment you enjoyed or found especially valuable?
- Can you tell me a story about a lab assignment that frustrated you or you found useless?
- Can you tell me about a time you struggled to understand the tasks of a lab assignment?
- What do you do when you struggle with a task?
- **At this point in the interview I show them the training model and present my preliminary idea of the assignment activites.**
    - How do you see yourself performing this assignment?
    - In what ways would/wouldn't you see this as valuable or enjoyable?
    - What should I consider when designing this?

The most fruitful questions were by far the first two. When asking the subjects about their past lab experiences they gladly told about them in detail. Asking "why" it was possible to dig deep into what they liked or disliked about particular assignments. Most had several stories for each. By asking open questions like this people readily talked about their experiences, in a way that would conversely require a substantial amount of "yes-or-no" questions to get. This interview process produced surprising insights that wouldn't have appeared without letting the user set the agenda.

3.2 Field Observations

Kelley and Kelley [14] place emphasis on the necessity of field observations, on *pages 89-94* they write: "*Observations in the field are a powerful complement to interviews, turning up surprises and hidden opportunities. When you spot a contradiction between what you see and what you expect, it's a sign to dig deeper.*". My position as teaching assistant in the related course TPK4125 Mechatronics was valuable, as I could observe students doing similar lab assignments. Doing this turns up what activities they appreciate, what frustrates them, and importantly the latent needs that people aren't conscious of and thus wouldn't show up in an interview. Patnaik and Becker [10] point out that people are generally so accustomed to their problems that they work around them. As they are not conscious of them these problems won't be discoverable in interviews, but can through observation. Getting at this type of latent needs can provide some of the most valuable opportunities for innovation, and is central to needfinding[12][13].

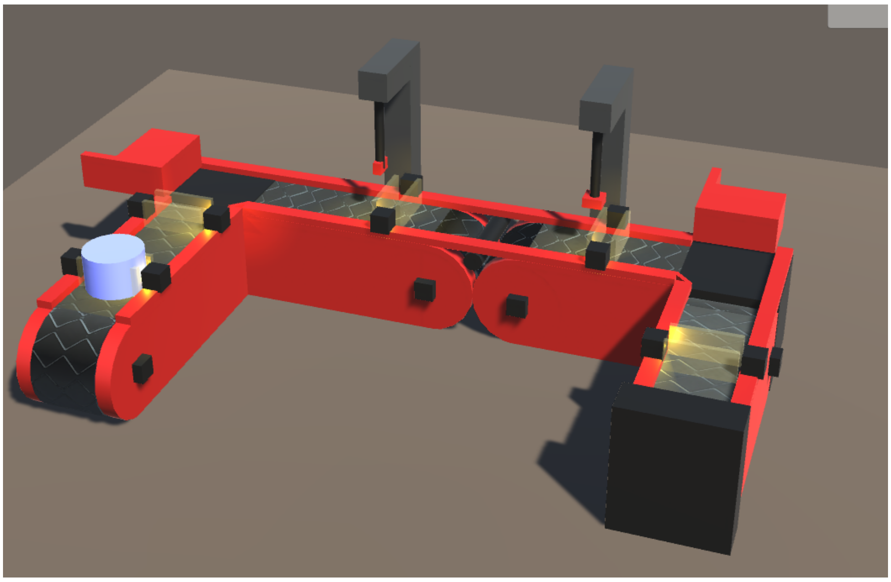


Figure 3.1: FTsim, the virtual lab of the training model by Ile and Lotric [7]

3.3 Testing

User testing was done with the help of the FTsim tool created by Ile and Lotric [7], a virtual copy of the Indexed Line training model that can be controlled using Siemens PLC software (Figure 3.1). This serves as a functional approximation of the training model, however there are physical aspects to the implementation of the real-life training model that will not come up testing with the virtual lab.

Tests were conducted with co-students selected based on the same considerations used when choosing interviewees previously. These were somewhat limited in time and scope. I was able to more comprehensive tests by completing full run-through of the assignment activities myself. This is feasible as I am a student in the target group. However, it is important to keep in mind that through my work with this project I have far more experience with the equipment than a common student would.

3.3.1 Considerations

What to test and why Before developing a test, it is paramount to identify what features you want to test[12][15][16]. The prototype should be tailor-made to target these selected features. On a basis of testing capabilities and critical features at this stage, the key co-student test aspect was previous skills and knowledge. Their ability to perform the activities in an assignment and complete them on time, will have a significant influence on what to involve in the assignment, to what extent and how much effort needs to be put into precursory preparation. In the run-throughs with myself as the lone test subject I was able to get a more complete view of the comprehensiveness of the assignment activities, possible pain points and ideas for possible activities.

Feasibility One also needs to consider what one realistically has the ability to test at the present time. Getting students to sit down for the full four hours of allotted time the resulting assignment will have is not feasible for a test without being able to provide some reward in return, particularly in the busy exam season when testing was commenced in this project. Preferably some additional time should be spent with the test subject afterwards in order to ask questions. I thus limited the test duration to 30 minutes, having to be efficient with this time. Testing was also inhibited by the expiry of my Siemens TIA Portal trial licence at the time of co-student testing, meaning I was unable to have them create program blocks. However, the PLCSim license was still valid allowing for manual control of FTsim by activating input and output variables in turn, see Figure 3.2. Limiting factors such as this, means the test will be merely a microcosm of a full run-through of the assignment. Nevertheless, when performed ingeniously such a small-scale preliminary test can provide valuable insights and a good indication of how users will experience the product.

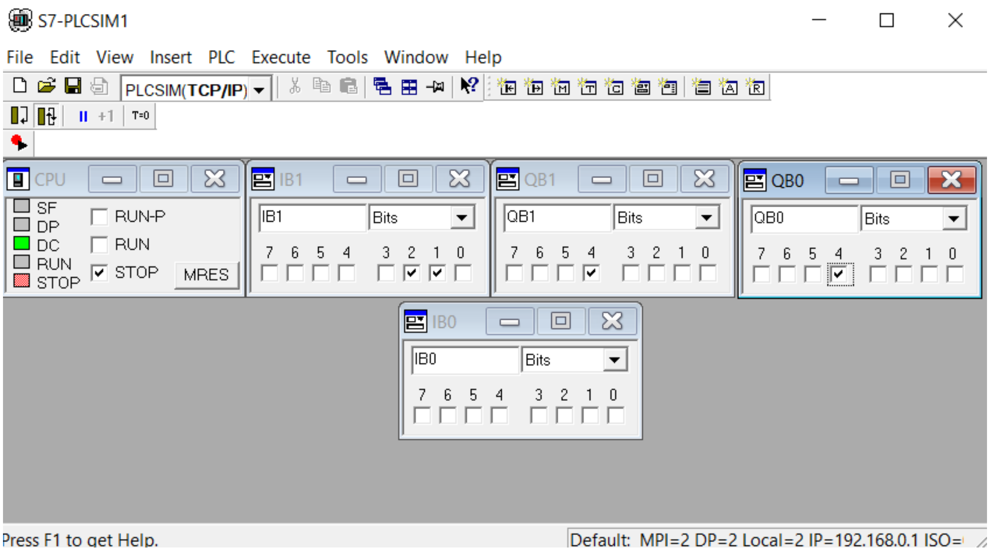


Figure 3.2: Siemens PLCSim interface allowing for manual activation of input and output variables

3.3.2 Test Design

When testing with co-students time was a significant limiting factor, curtailing both how many tasks they could complete and how much time they had to make themselves familiar with the equipment and related concepts. Keeping in mind that later tests were improved with the experience of previous ones, and every test unfolded differently in certain aspects, this is how they were conducted:

1. Tell students the context of the test and what you want out of it. You do not want them to go into a bug-testing mindset, as this is far from the complete implementation. They are simply to perform some actions.

2. Show a video of the physical training model in order for them to get a tangible idea of how it appears and operates.

3. Provide them with an overview of the actuators and sensors with locations and labels akin to Figure 2.4 and Table 2.1.

4. Ask them to in words and pseudocode describe the steps the process should include, of the type: "Phototransistor X is activated so move conveyor belt 1, stop it when...". Do it in a wizard-of-oz[1] style manner, enacting the actions they state in FTsim.

5. Show partial implementation of a ladder logic diagram for the process, and explain it's function. Ask them to write down a program block of the initializing steps in the same manner. Enact their programming in FTsim.

6. Conduct a short interview in the wake of the test, in the style of the interviews previously described, seeking to understand how they experienced the process.

3.4 Framing, Synthesis and Ideation

Both during, between and after the needfinding activities performed, it was required to concretize and make sense of the results, re-framing them and using this to create ideas for the implementation. Keep in mind this is a iterative process. Beckman and Barry [12] describe the framing phase as requiring abstract conceptualization. This prompted the need to use methods like 2x2 matrixes and mindmaps to visualize the results, enabling the extraction of important insights and finding contradictions between results and preconceptions. When developing this into concrete ideas and possible solutions, it was required to start converging by imposing constraints. Intensive brainstorming sessions were conducted to get as many ideas as possible, taking care to write down everything, as ideas that might seem outlandish at first often provide valuable innovations. The outcome from this was then whittled down to the viable ideas, which were then further explored, imposing the results from the needfinding process and what is technically feasible as constraints.

[1] Wizard-of-Oz: A test in which you "fake" the functionality for the user[13][16]

Chapter 4

Results and Suggestions for Implementation

In this chapter the results from the design thinking and general product development process are presented. It details the insights from the needfinding and testing activities, and based on this suggestions for the implementation and further work are made as to meet these imperatives.

4.1 Insights

The results from the design thinking process are presented here. Including the insights, needs and painpoints from the initial user inquiry, user observation and user testing.

4.1.1 Interview and Field Observation Insights

It was immediately apparent from the interviews that engineering students value seeing the physical result of their code or circuitry. Seeing actuators or other outputs respond to ones own input is viewed as satisfying. For this to be the case, they have to do a large amount of the work themselves, and understand what they are doing. In the words of one interviewee "Putting one or two lines of code in a huge .py file that I don't know what is doing does not make me feel like I accomplished something", it likely doesn't provide much learning either.

In addition to the theoretic foundation established in the courses, having actionable and tangible tasks promote deeper understanding. It gives intuition, and has the possibility of "aha-moments". However, for them to get proper understanding it is important that there is a relationship between the theory they learn and the lab they perform.

In technical assignments like this with many disparate activities, steps and pieces of equipment it is preferable for the assignment to be conducted in an orderly manner. Especially when the concepts involved are new to the student. Some interviewees report problems with previous assignments at NTNU where they have to spend a lot of time finding equipment and deciphering what they are to do from the assignment text. This can take time and attention away from the subjects they are to learn.

There is learning in troubleshooting malfunctioning equipment and hardware. However, this should be balanced against the amount of time it takes. If it consumes too much of the allotted time such that the students can't complete the original task, this knowledge from troubleshooting could be better attained elsewhere in a more time-efficient manner. Students find it particularly frustrating when the issues are invisible or not from personal error, quoting "I really dislike in electronics labs when something doesn't work and you have to check 20 cables and ICs". Frustration is an unsuitable state of mind for learning.

How students seek help when stuck or struggling with a task is highly dependant on the context. As the involved courses to a large degree features students in the 3rd year of the same study program one can assume that they know the others in class. This means they will have a lower threshold for asking help and comparing results with other groups. It can also have a positive influence on the cooperation within a given group. Students at NTNU also rely on getting help from teaching assistants and other resource persons present in the lab hours, but they ask less if they have previous experience of them being unhelpful. Furthermore, they often look to the web for help, but less so when working in groups. Looking for help in the assignment text is a common tool, but can be awkward in lab groups as reading is a individual activity. This holds especially true if they have to sift through a lot of text to find what they are potentially missing. This necessitates facilitating for the possibility of getting help from other people in the lab.

4.1.2 Testing Insights

Although somewhat limited in both scope and available time, the testing process provided interesting new insights, enforcing some and challenging other preconceived ideas. As a whole, it was of surprise how much output one can get out of even a small-scale user test. Another point of interest is how the tests got progressively better. This shows another important aspect of the iterative Design Thinking process. Namely that using experiences to constantly make minor improvements to both product and process, leads not only to a better product/prototype, it also produces tests more succinctly examining the concepts of interest. This holds true for interviews as well.

The testers maintained that they would find an assignment such as this enjoyable, reinforcing what was found in the interviewing process. They value seeing their software and schematic side inputs producing a visible and coherent output. On a general level the training model is somewhat of a sophisticated toy that is entertaining to control and watch. It is reasonable to assume that enjoyability promotes learning both during and after the assignment hour, in that students will gladly perform the learning activities and that it might inspire for further inquiry into the subject. Students will aspire to complete all the assignment tasks as the satisfaction of seeing a complete operation acts as an incentive carrot on a stick.

Students readily understood how the factory process of the training model should function. Meaning, with reference to Figure 2.4, it was apparent that an activation of phototransistor I7 should prompt the forward operation of the conveyor belt of Q5 and so on. They grasp how the positioning of the sensors should correspond to the activation of certain actuators. This is a positive sign, implying that the training model incurs tangible ideas in its simulation of full-scale factory operation. If students understand *what* they are supposed to do, they can focus on *how* to do it.

The students will have little previous experience with using PLCs. They will likely have learned about what they are and their function in a factory environment, but will not have handled a PLC or its corresponding software before. As for the involved programming languages it is varying, with the TPK4128 students reporting some experience with ladder diagrams as it is a part of that course. If the training model is to be implemented in both TPK4125 and TPK4128, one can base the assignment in the latter on the fact that the students will have previous experience with the equipment and concepts. One should then consider implementing it in TPK4125 first, to ensure that the first cohort performing the more advanced assignment has previous experience.

In addition to reinforcing the ideas stated elsewhere in this chapter, self-testing provided some technical insights that should be kept in mind. Firstly, getting Raspberry PI single-board computers to connect to the on-campus Eduroam network over WiFI is difficult. While this might seem like a small concern at first, it will serve as a major painpoint for the students performing the assignment if a satisfactory solution for this is not found. It was also apparent that extending the function of the control program such that it can handle multiple workpieces at the same time without collision requires a substantial increase in the amount of code.

4.2 Suggestions for Implementation

In this section recommendations and suggestions are made for the implementation of the assignment. Some of the suggestions were made by the users during interviewing and testing, some are synthesized from what the needfinding process uncovered and some are based on established knowledge or own experience with the assignment.

4.2.1 General Structure, Context and Execution

The base structure is that students control the Indexed Line with Two Machining Stations from fischertechnik[8] with a Siemens S7-1500 PLC[9]. With reference to Figure 2.4 this involves a workpiece being loaded on the left side of the model, being moved by conveyor belts and pushers to be processed by the machining stations and then through to the end, with pushbuttons and phototransistors creating sensor output of the position to be acted on. Implementing this alone with simple ladder logic control is a substantial and worthwhile task for the students. However, there are many different opportunities for expanding on this concept, including different methods of logic control, batchwise operation with collision prevention and using communication protocols like OPC-UA for remote control or cooperation between training models. It should be strongly considered to implement this as not one, but several consequent assignments, be that in both TPK4125 and TPK4128 or with several in TPK4128 alone. In this section many of these opportunities are proffered, along with considerations to be taken into account when selecting and implementing them.

Introduce with a simple "Hello World" After an initial setup, the students should be provided with a partially implemented "Hello World" task, showing them the basics of how the Training Model and other equipment works and operates. They should then get piecemeal tasks, gradually leading them to full autonomous processing of the workpiece through the factory line.

Make it analogous to actual factory situations When implementing the assignment, it should be sought to make the tasks analogous to real factory situations. Doing this can promote understanding of real-life situations, and conversely make it more intuitive to the students how the line should operate. The training model is well-suited to represent relevant issues from automation, but there is a substantial room of opportunity for involving further concepts from operations management, safety, logistics, manufacturing technology and more.

Make causality apparent The relation between the actions students perform and the output they observe from the equipment should be clear. This makes it easier to troubleshoot, promotes deeper learning and makes the results more satisfying.

Errors should be personal errors When students are introduced to new hardware and software as in this lab assignment, issues that don't stem from personal error should be prevented, and if they occur they should be detectable. If not, it can become a major pain-point leading to frustration and preventing students from finishing the assignment in the allotted time. This is accomplished in part by ensuring the integrity of the assignment structure and the equipment involved, and by making sure eventual errors are noticeable and that the teaching assistants are well-versed in handling them.

Make it foolproof If students are inexperienced with electronics or stressed, they might inadvertently perform actions that are harmful to equipment. There are likely several ways for students to harm the training model in setup, wiring or with code. Giving instructions in advance on actions that might be detrimental is certainly helpful. However, as a teaching assistant in TPK4125 I frequently observed students forgetting or neglecting to switch off their laboratory boards when rewiring, despite being repeatedly told to do so. Therefore, the best way to ensure a long life expectancy for the lab equipment is to, where possible, make harmful actions unlikely or impossible to perform. It is also prevented by avoiding stressful situations. This way of thinking is central to the modern HSE paradigm in factory environments.

Continue employing design thinking methods, preferably as a team It is plausible that the person that will implement this assignment will be well-versed in the technical details involved, but will have less experience with design thinking. However, the steps, methods and processes herein described and the corresponding sources should be enough to grasp the basics of Design Thinking and perform it. This should be employed in further work with the assignment. Test the implementation with users before providing it in class, observe the students as they perform the assignment, ask them for feedback and try to immerse yourself in their situation. This way one can continue to ensure that the assignment is correct for the users, and ensure ongoing improvement and innovation. Remember to always keep the context in mind. The size of groups, time aspects, students previous knowledge and space the assignment will happen in are all important factors that need to be considered.

Whoever continues this project should strive to do any needfinding work in teams, particularly prototyping and testing. While it might be unrealistic and resource consuming to have a interdisciplinary innovation team for all of this process, getting simply one extra point of view is valuable.

Don't introduce too many concepts at once The indexed line training model offers opportunities for learning about many different concepts that are of relevance to the involved courses and automation in general. However, there is a ceiling on how many new concepts a person can take in at once. By being too immoderate in selecting concepts, one can create a "jack of all trades, master of none" type situation where students get superficial understanding of many concepts, if that, but not the deeper understanding such an assignment could provide. It was apparent from the needfinding process that experiencing mastery is important, and this necessitates being able to finish the tasks in time. Avoiding the burden of time pressure, students are able to discuss and explore more, which could in reality provide more learning than forcing in an extra activity. One should then show restraint and consider:

- What concepts and skills are best taught with this assignment?
- What learning outcomes should be targeted?
- Can some of these be taught in a later assignment?

Additional activities could instead be given as optional tasks for especially interested or fast groups. In the likely event that the training model is used for several assignments, there will be ample time to progressively introduce more concepts.

Limit group size to at most three, preferably two When doing tasks like this one needs to take into consideration the physical size of the equipment. In the interviews several students and a professor stated that with bigger groups in NTNU mechatronics courses[1] they experienced situations where one or two group members worked, with the additional group members becoming passive bystanders. There is simply not space around the equipment and not enough disparate tasks for more than two to three students to contribute at the same time. This means worse learning for the surplus students.

4.2.2 Assignment Text and Course Learning Materials

Here are suggestions pertaining to the structure of the assignment text, and the theory provided along with the assignment and in relevant lectures of the parent course.

Introduce the relevant concepts and background theory beforehand Some of the technology and concepts inherent to the assignment will be new to students It is then important that the students are properly introduced to the concepts. This can either be done in the lectures leading up to the assignment, or in the assignment text itself. Preferably it is done in both, with the lectures and course reading materials providing a general understanding of the concepts, and the assignment text theory being more tailor-made to the tasks at hand. In order for students to learn from the lab they need to know what they are doing and what it means. If not, it is akin to blindly following a list of objectives without purpose.

[1] In the mechanical engineering study program this is not limited to Mechatronics (TPK4125) and Industrial Mechatronics (TPK4128), but also Product Development (TMM4121), Machine Design and Mechatronics (TMM4150) and Fuzzy Front End (TMM4245).

Ask the students to prepare, but in moderation Doing preparations before the assignment is positive for learning and making sure the students finish on time. However, it is not certain that students actually do it. Some will first start reading up on the assignment when the lab hours begin. The students observed recognize that doing preparation is valuable, however they forget to do it or don't prioritize time for it in their busy workdays. When this is said, a lot of students do preparatory work, and more would do it if one is deliberate in stating it is needed for the course. However, the provider of the assignment should have a realistic view of this and not rely too much on students preparations.

Provide required actions in a step-by-step structure This assignment involves a lot of steps, stemming from connecting up the factory, the PLC, initializing software and so on. It was apparent from the interview process that students often overlook or miss steps when they are provided as part of a "wall of text". Therefore the tasks to be performed, especially the ones for setup should be provided in a clear step-by-step manner, as to make sure they don't miss any, and that makes it easy to check back in case of troubleshooting. Test with students whether the instructions are understandable.

Include a feedback option In order to maintain continuous improvement, the assignment text should contain an optional opportunity for providing feedback at the end.[2] This will give useful user insights and information about painpoints that can be used to improve the assignment. It is useful to gain feedback directly after the experience of doing the tasks as it will be fresh in the memory of the students. Over time this will make the desired learning outcomes come through more clearly, and remove frustrations and confusing instructions that are not conducive to learning. In line with the ideas of design thinking, this is a way of performing iterative steps of testing and user information gathering. The educator arranging the assignments should also do field observations in the lab hours. Furthermore, it would be possible to conduct user interviews with some students during or after the lab.

Provide a list of common errors Interviewees made it clear that this was desired. Assignment of this kind often have common errors, or easy pitfalls. Listing up these errors can avoid too much time being spent on these, and free up the teaching assistants for other questions. This can also help in making the assignment foolproof. These errors are probably not readily apparent before the first implementation of the assignment, and should be garnered from the feedback and teaching assistant experience.

[2] Gensheimer *et al.* [24] suggest the same in their assignment implementation using FischerTechnik training models.

4.2.3 Additional Possibilities

This section features some creative ways of extending the assignment. Either as a part of the assignment, optional extra tasks or as possible future developments.

Look to other modes of logic control While useful, ladder logic is somewhat basic, and if multiple assignments are to be implemented it could be worthwhile to involve other forms of logic control. There is room for this within the curriculum of the course and the capabilities of the equipment. This could include languages such as the graphical Functional Block Diagram (FBD)[23], Instruction List (IL)[3], Sequential Function Diagrams (SFC) and Structured Text (ST)[26].

Have two training models interact In order to promote teamwork, and the exchange of understanding between groups, it should be considered implementing a part where two factories interact. This can teach the students about a broader factory context. For example, two groups can put their Training Models together, and have them interact through OPC-UA or similar. An additional mechanism needs to be created to transport the workpieces between the two factory lines, this offers new opportunities for extended learning. The easiest implementation of this is the student "acting" as a robotic arm or factory operator, and physically moving it themselves, but more advanced and creative solutions are also possible. One can implement some sort of miniature arm or loading platform moving the pieces between the models. Or, one can extend the factory "metaphor" further, making a miniature Automated Guided Vehicle (AGV) for moving the piece between them. This can be done autonomously or through remote control. Whichever way it's implemented, it offers opportunities to learn students about new subjects from the course learning objectives[4].

Create a virtual lab/digital twin Creating a Virtual Lab like Ile and Lotric [7] or Gil *et al.* [6] should be looked into. This can be operated in parallel with the physical lab, or as a replacement. It offers students flexibility, opening up for repetition or doing the lab at home if the students were busy at the time of the lab or if they couldn't finish the lab in the allotted time. It is uncertain how the Covid-19 pandemic will influence the future of education, but one possibility is an increased demand for digital laboratory work. The coming campus merger in NTNU Trondheim might also limit the space available for laboratory work on campus.

Control the training model remotely Another way to implement Industry 4.0-related technologies is to have the students control and monitor the training model remotely. This can for example be done by connecting a camera up to a Raspberry PI (RPi) single-board computer which can communicate with their laptops

[3] Known as Statement Lists (STL) for Siemens PLCs

[4] FischerTechnik offers a wide variety of other training models, and having disparate training model types interact would be even more interesting, but also more expensive and difficult.

through OPC-UA from another room. Furthermore, this can be done as an extension of the virtual lab concept, with students accessing the on-campus training model from home through the RPi.

Store the equipment in a proprietary container For ensuring that the required equipment is in place and in order, it is beneficial to create some sort of briefcase for storing the equipment. This makes it easier to store, find and easier for the students to get set up. This briefcase should preferably contain the training model, the PLC, wiring, a power supply and other eventual equipment.

Install stop-button and indicator-lights on training model The training model side equipment can be extended by implementing a stop-button, indicator lights showing different states or buttons for controlling the training model. This can be a useful tool in how the assignment is conducted, extend the factory analogy and, in the case of the stop-button, make it safer in the event of errors.

Extend the monitoring data A significant part of the Industry 4.0 paradigm is the handling of more sensor data[1]. Integrating sensors for more measured data like temperature, cycles and so on could better make it a simulation of an actual factory environment. If OPC-UA is included this can better and put its capabilities to use. Putting NFC-sensors[5] in the workpieces is also an intriguing possibility, and could allow for sorting between different types of objects. For example by having certain workpieces only be processed by one of the machining stations depending on their NFC-tag

[5]Near Field Communication (NFC) is a technology for wireless communication between two units over short distances.

Chapter 5

Discussion and Conclusion

In this chapter there is a discussion on the applicability of Design Thinking in this context and an assessment of the results and process. Finally, the conclusions of these questions along with an overview of the suggestions for further work is presented.

5.1 Discussion

This section features an evaluation of the process considering the results up to this point and what remains to be done on the path forward. It also considers the validity of the core hypothesis that design thinking is a fitting methodology for a task such as this. Furthermore, it features discussions on interesting aspects such how to utilize your own experience without getting tunnel vision, possible shortcomings of Design Thinking; both in general and how it is utilized here.

5.1.1 Assessment of Results: GAP Analysis

This thesis is a pre-study, and the practical work still remains to be done before the first students engage in this assignment as part of their lab work. It nevertheless serves as a foundation for further work. Following the suggestions and guidelines in this text should produce an assignment that students find engaging and that provides them with the desired learning outcomes[1]. Some of the suggestions are purposely general as to be translatable to other work, leaving a lot of the specifics to be found out in more hands-on work in designing the assignment. It is entirely possible that future work will invalidate some suggestions, they should be viewed as recommendations not stone-set directives. The inherent needfinding, testing and ideation activities, along with required considerations, are described in such a way that they can be continued.

[1]Agreeing with the statements of Ile and Lotric [7], Gil *et al.* [6]

It is not feasible to continue work before the required equipment is at hand, including the fischertechnik training model, Siemens S7-1500 PLC and Siemens TIA portal software license. Other equipment will also be needed, depending on the details of the selected implementation. After deciding what activities students are to perform, based on the suggestions given in this text, these activities will have to be put into structure, deciding how this and required theory will be enacted into the assignment text and the course in general. Then the physical implementation must be done. Depending on the extent this will include creating an interface for the training model and corresponding equipment, creating a containing unit for it, creating necessary software, as well as creating the means for students to easily access software on their computer, or a proprietary one provided as a part of the lab equipment. When all the requisite equipment and software is up and running, and the assignment structure and text is ready, quality assurance has to be done. This includes testing with users to see how they respond, as well as ironing out potential problems and pain points through extensive troubleshooting. It is paramount that the assignment should continue to evolve after it is implemented in a course, especially after the very first round a lot of issues should present themselves that were not previously apparent.

5.1.2 Designing for a Group You are a Member of

Often when doing design thinking or other types of user needfinding, firms and developers engage with users that are different from themselves. Such situations are also a strength of Design Thinking, as it seeks to close this gap. However, I am in the special situation that I am part of the group I am designing for. This offers both advantages and possible challenges.

First and foremost it gives an unique advantage in understanding the users and the context. I have completed both TPK4125 and TPK4128, meaning I understand both the experience of having these courses and the surrounding study situation. This is still relatively fresh in memory, and I can base my thinking on what students would appreciate more reliably on my own judgement than for example a professor could. Buchenau and Suri [27] stress the importance of experiencing the context you design for yourself, naming this Experience Prototyping and writing: "*...experience is, by its nature, subjective and that the best way to understand the experiential qualities of an interaction is to experience it subjectively.*"

However, it is paramount to not let ones own experience and preconceptions cloud openness to new ideas and ways of thinking. As detailed in the introduction, students are a varied group, individual students learn and experience concepts far different from each other. Much Design Thinking literature emphasizes the importance of letting the user set the agenda and not having your own notions produce leading questions[10][13][14]. This is a part of the design thinking process that might be easier to perform when you are further removed from the user. However, I managed to restrain myself, and gathered several surprising insights that either challenged my preconceived notions or elaborated on them.

In addition to having had the relevant mechatronics courses I have had courses in Design Thinking. This gives me a somewhat unique engineering education background. However, implementing all the suggestions proffered in this text would be beyond the scope of my capabilities in the time allotted for this project thesis, even if the required equipment was available. It is reasonable to assume that the person implementing this will be a university educator, PhD-level or at least have more available time. They will thus have better capabilities in the technical implementation, but possibly less in Design Thinking and needfinding activities. This collaboration of me using my experience to understand the users, and someone more technically adept performing the implementation, thus offers a valuable co-utilization of capabilities.

5.1.3 Applicability of Design Thinking in Creating Educational Tasks

In addition to doing preliminary work for the assignment, part of the contribution of this thesis is to explore the applicability of design thinking methodology in creating educational activities. It is hypothesised that it is indeed applicable.

This assumption is based on the nature of university engineering education. It is a fast-changing landscape with new technology and paradigms needing to be implemented into the education in order to ensure that future engineers have the required skills. In addition to this it features a large variance between the users. Students come from all sorts of backgrounds, and thus have different needs. When viewing university education as the educator being the product developer and student being the user, one finds that there is a substantial difference between the developer and user. Difference age cohorts learn differently, students today might be more technologically adept than students 30 years ago, however attention spans are shorter and there might be more distraction in their every day. There is also a significant difference in the knowledge base between the educator and student. Firstly on the grounds that the educator has spent a whole career developing his knowledge on the subject. Furthermore, someone capable of reaching the rank of professor in a subject will have a natural inclination towards easily grasping it. This can lead to the professor being out-of-touch with what the students already know, and how easy they learn. As they have a natural level of mastery of the subjects, they underestimate the difficulty other people will have in understanding it. These factors and the large disparity they entail, require the educator to engage with the students in order to be able to understand what they know and how they learn. One framework for doing this is Design Thinking.

With some exceptions, the design thinking process here described was successful at gathering understanding of user needs and how to best provide an assignment. The resulting insights and ideas are of great interest to the assignment(s), and some can be applied to creating other educational activities as well[2]. This understanding would be hard to get at without speaking to and seeking to understand the users. At the very least, it resulted in these truths becoming evident far quicker than they would by sitting at a desk. This holds true for me as a co-student, and would hold even more true for a university educator who is further removed from the student experience.

Regardless of whether design thinking is the right methodology, this thesis shows the importance of engaging with students needs and predispositions when designing educational activities. Design Thinking is simply one possible framework for this purpose, and one that is often effective. The greatest barrier for this is likely educators being comfortable and having the time to do in-the-field needfinding activities[3]. The Design Thinking process of this text is described in such a way that it can be continued by the person resuming this work, and it is recommended that they do so. However, this is not an absolute requirement and if they for some reason will not adopt Design Thinking, they should at the very least maintain the core ideas of doing user testing and attempting to see the assignment from the students point of view. Doing simply one single user test before providing an assignment is hugely beneficial to conducting none.

5.1.4 Possible Shortcomings

The informality of Design Thinking Design Thinking is sometimes criticized as being too informal or diffuse[29]. It is more a set of tools, guidelines and practices than a strict and rigorous framework. This can make it difficult to write about scientifically, but conversely makes it more practicable. The results of the interview and overall needfinding process herein described are by no means statistically representative. Care was made to engage users with different backgrounds, and also so called extreme users. However, the sample size was 12 at most. A survey with 50+ subjects and clearly defined questions would be more scientifically rigorous, but would fail to get at the underlying needs that Design Thinking does[12]. Design Thinking is a product development methodology and not a way of conducting ethnographic science. The resulting recommendations are suggestions made by the author based on the needfinding process, but can not be viewed as universal scientific fact. When seeking innovation the right questions will not be clear in advance. By allowing the user to set the agenda and being iterative and adaptive with questions one can get a deep and intrinsic understanding of their needs and get ideas for possible innovations. This way of improvising questions, in addition

[2]Albeit with a grain of salt depending on how dissimilar the subject is with regards to automation.

[3]Studies have found it challenging to implement Design Thinking in large organizations[28], but this is not what this text is advocating. It would be far too premature to say that NTNU should widely adopt Design Thinking, but merely doing more user testing is much more feasible, strongly recommended and should be looked into.

to the individual interviews being more time-consuming than a classical survey, means that it is difficult to extract conclusions of the kind "7/10 students want X". This is a central dichotomy to design thinking, where the same reasons that make it valuable and effective, are the same reasons that make it hard to make objective statements.

Lack of innovation team A significant shortcoming in the innovation process herein described is that design thinking largely entails working in teams, while I did this alone[3][4][5][12]. This lead to me losing out on the team benefits of getting other points of view on subjects, other backgrounds and the additional workforce. Design Thinking teams are preferably interdisciplinary, or at least with members possessing different capabilities. Beckman and Barry [12] suggests learning styles fitting the separate stages as seen in Figure 2.2b. These learning styles are contradictory, and thus it is likely that a single person team will be good at some stages and unfit for others.

Discussions and feedback with my supervisor and other resource persons has provided some of the team benefits. The work on the assignment can also be viewed as a collaborative work with the innovation team consisting of me, the supervisor and whoever will continue the implementation. The person continuing work will primarily work in the "Solutions" quadrant of Figure 2.2a, requiring a "Accommodating" learning style, learning from concrete experience and active experimentation[12]. This also draws on the co-utilization of capabilities discussed in Section 5.1.2.

With that said, the main benefits of working in innovation team come from working simultaneously on the same problems. This is lost when the collaboration is distributed in time. The process herein described would likely have benefited from teamwork, and for this reason one of the recommendations for future work is that multiple people with different backgrounds are involved, particularly when performing needfinding activities such as testing.

5.1.5 The Delicate Balance of Learning Through Troubleshooting

Troubleshooting emergent errors in practical assignments can improve student learning[30]. Firstly, in terms of them getting a deeper understanding of the involved concepts and new ones as well. Furthermore, troubleshooting is a form of problem-solving that is beneficial and highly valued both in later studies and engineering careers. It is a fact of life that unexpected problems will occur in any project of a meaningful size, and being able to handle them is a necessary skill. This is another way that an assignment such as this can contribute, as there is a diverse array of errors that can occur during the students implementation. However, it was very clear from the students interviewed and observed that too much of this can in turn be negative. If it is prohibitive of their process, this can frustrate and prevent them from completing the tasks in the allotted time. Hindering them from attaining the learning objectives and preventing an experience of mastery. There is thus a trade-off between time spent troubleshooting and time spent progressing with the subtasks of the assignment. Many of the suggestions given for the implementation seek to address this. Particularly when introducing students to many new concepts, it can be too much to absorb at once to have to do extensive problem-solving as well. One should consider if some of the troubleshooting lessons are better taught through other parts of the course. A common problem with practical electronics assignments is that errors are due to invisible or hard to find faults, or equipment malfunctioning. The fact that students learn by working through errors, should not be an excuse for having a less refined assignment setup. While a certain amount of learning through troubleshooting is definitely valuable, one should strive to make sure that the implementation is of such integrity that emergent problems are visible and due to personal errors on the part of the students.

5.2 Conclusion

The application of Design Thinking methodology in finding user needs and generating ideas for a laboratory assignment has been largely successful. A substantial gap between the product developer (educator) and user (student) is inherent to higher education, and thus measures need to be taken to bridge that gap, ensuring an understanding of what best provides students with the desired learning outcomes. Design Thinking is one possible framework for this, and the process therein has been described in this text such that it can be applied in future work with this assignment as well as by others wishing to create educational content pertinent to how their students learn. Regardless of design thinking, a bare minimum of testing with students is decidedly beneficial.

Below, a list of suggestions for further progression with the assignment is provided. This is with reference to extended descriptions of these points in both this chapter and Chapter 4. This is divided in three categories, with the first two serving as concrete recommendations based on the work done as part of this project. The contents of the last category are similarly devised, but are unfeasible to implement all at once leaving it optional which to select. The base structure is processing a workpiece through all the workstations of the Indexed Line training model using a PLC, with a recommendation of extending this through several consequent assignments.

Suggestions for the general structure, context and execution of the assignment:

- Introduce with a simple "Hello World"
- Make it analogous to actual factory situations
- Make causality apparent
- Errors should be personal errors
- Make it foolproof
- Continue employing design thinking methods, preferably as a team
- Don’t introduce too many concepts at once
- Limit group size to at most three, preferably two

Suggestions pertaining to the assignment text, and the theory provided in it and the surrounding course.

- Introduce the relevant concepts and background theory beforehand
- Ask the students to prepare, but in moderation
- Provide required actions in a step-by-step structure
- Include a feedback option
- Provide a list of common errors

Additional possibilities for the implementation, depending on whether or not it is feasible based on both available time for the implementer and the students capabilities in the allotted time for the assignment:

- Look to other modes of logic control
- Have two training models interact
- Create a virtual lab/digital twin
- Control the training model remotely
- Store the equipment in a proprietary container
- Install stop-button and indicator-lights on training model
- Extend the monitoring data

As this is a pre-study work remains before the assignment using the training model can be provided in a course. However, it serves as a groundwork for further development. From the needfinding activities performed it was apparent that engineering students would find such an assignment enjoyable, promoting intuition and inspiring for deeper and further learning. Adapting the provided recommendations should provide a strong tool for teaching students about automation, meeting both the desired learning objectives of the course and the skill requirements required by engineers in the Industry 4.0 paradigm.

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