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Learning Factory Configuration Tool: An Approach for Preserving the Value of Educational Learning Factories

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Abstract

Learning Factories (LFs) are existing and proven systems of transferring knowledge in an active and practical way. Using a physical production process as a learning tool facilitates a constructive and contextualised learning process. Due to the fourth industrial revolution, many new and innovative manufacturing process-improving technologies enter the market. Existing Learning Factories depreciate over time due to the fact that they are frequently constructed with clearly defined specific objectives in mind. Currently this is a great disadvantage of such capital intensive and rigid buildings. Therefore a tool that preserves and maintains the value of LFs must be developed. To this end, a literature study has been conducted on Active Learning Methods (ALMs), Learning Factories and the relationship to its Learning Subjects (LS). Second, the implementation of changeability is identified as a method for preserving the value. Which is accomplished through a modular design that is interoperable and independent of equipment types. When planning a factory reconfiguration, it is difficult to maintain an overview of all the elements, including the Learning Subjects offered, the products to be manufactured, the available budget, and the size of the factory floor. Therefore, the findings of the literature review are incorporated into a Learning Factory Configuration Tool (LFCT). This LFCT provides the user with a list of equipment based on the parameters provided. These parameters consist of the Educational Product (EP) that must be manufactured, the corresponding LSs, the available budget, and the size of the factory floor. The user then selects the appropriate equipment models manually from the resulting equipment list. The suggested equipment list has been converted into a Learning Factory simulation. It helps to test the feasibility of different production lines according to the LFCT-suggested equipment list. To accommodate the use and expansion of the database, an equipment input form for has been created. Both the simulation and input form have demonstrated their functionality and the tool operates as expected. In the future, essential decisions should involve key stakeholders, the database should be moved to the cloud to increase its reliability, and a filtering algorithm is required for the massive output resulting from the expanded database. The ultimate goal would be to have a physical Learning Factory that can collect factory data through the strategic placement of sensors. The collected data should be connected to the LF simulation. Then, using an algorithm for machine learning, this data can be used to automatically adapt and improve the Learning Factory or to recommend changes.

Keywords— learning factory, learning path, changeable learning factory, preserving learning factory value, learning factory configuration tool, learning factory equipment database

Nomenclature

AGV Automated Guided Vehicle

AI Artificial Intelligence

ALM Active Learning Methods

AM Additive Manufacturing

AOL Action Oriented Learning

AR Augmented Reality

CNC Computer Numerical Control

D&M Design and Manufacturing

DPM Design, Production and Management

EL Experiental Learning

EP Educational Product

FDM Fused Deposition Modeling

GBL Game-based Learning

HRM Human Resource Management

I4.0 Industry 4.0

IT Information Technology

JIT Just In Time

KPI Key Performance Index

LC Learning Course

LF Learning Factory

LFCT Learning Factory Configuration Tool

LP Learning Path

LS Learning Subject

MES Manufacturing Execution System

MP Manufacturing Plan

PBL Problem-based Learning

PjBL Project-based learning

RBL Research-based Learning

SMED Single Minute Exchange of Die

TPCK Technological Pedagogical Content Knowledge

TPM Total Productive Maintenance

TQM Total Quality Mangement

UT University of Twente

VC Visual Components

VSM Value Stream Map

Contents

1 Introduction

Currently, manufacturing is undergoing its fourth revolution. This is accompanied by numerous new technologies and techniques to enhance production in both the physical and digital domains[1]. This presents a challenge for companies to keep up with the manufacturing trend. Which is characterized by frequent changes in the market, decreasing batch sizes and a growing demand for customization[2][3]. To accommodate these changes of the manufacturing industry, the University of Twente (UT) will construct a new workshop. This building will house a Learning Factory (LF), where instructors will prepare students and (local) businesses for the future innovative manufacturing solutions.

The idea for a Learning Factory exists for a longer period already and many have been built since. LFs facilitate an active learning environment and can be utilised for instruction, training and research[4][5]. A real production environment allows students to immediately apply their acquired knowledge. This physical activity facilitates a constructive and contextualised learning process[1] and also improves the students connection to the labour market[3]. Besides these benefits, LFs have significant drawbacks, including the high cost of construction and the difficulty of reconfiguring the production layout after it has been constructed. It is also difficult to scale the factory to accommodate a fluctuating amount of students, and it is challenging to implement new technologies in a rigidly constructed Learning Factory[4]. Consequently, a variety of constraints diminish the value of an LF over time. As it is challenging to implement new LSs due to innovations in the market, while more Learning Subjects (LSs) become obsolete.

Therefore the research focuses on how the lifespan and value of engineering education of Learning Factories can be maintained and preserved. One method to do so, is by implementing changeability into the Learning Factory. In response to market demands, more and new LSs can be made available by swapping the equipment. As there are numerous parameters to consider prior to the acquisition and/or reconfiguration of LF equipment. A Learning Factory Configuration Tool (LFCT) must be developed to streamline the equipment selection process.

A literature review on the current state of active learning methods and learning factories is conducted to acquire the necessary background knowledge. The relationship between the learning factory and its learning paths, subjects, and courses is then investigated. Methods for extending the LF value are identified as a final result to the literature review. With the knowledge gained from literature, the LFCT is designed and developed. The results of the LFCT are converted into a simulation. Besides other advantages, it helps to show the feasibility of different production lines based on the LFCT-suggested equipment list. Finally, critical aspects of this study are discussed along with suggestions for future research.

2 Research Approach

2.1 Problem Definition

A new workshop is planned to be constructed at the University of Twente (UT). This building will house a Learning Factory (LF). The LF should provide insight and experience regarding new equipment, software, and production management tools. Students, staff and businesses will be involved to use it. The users of the LF gain new skills by performing Learning Paths (LPs). An LP is defined as a small task or action, that enables the user to learn a new skill. A combination of these leads the user to learn a new Learning Subject (LS). Learning Subjects can be taught in any area of interest. 3D printing, energy monitoring, machine learning and process improvement are LS examples within the scope of Learning Factories.

Typically, an LF has a static approach to studying and experiencing LSs[4]. However, as the industry progresses into the future, new or alternative LSs must be provided. Therefore, a static LF, despite being designed for multiple clearly defined specific targets, is incapable of meeting the evolving needs of the users. This lowers its value over time as research progresses. This diminishes its value as research progresses.

To increase the value, a dynamic LF must be constructed. With a dynamic LF, the idea is to have a basic factory floor plan that facilitates multiple important LSs. New LSs must be offered over time to keep up with manufacturing trends. By modifying the layout, routing tools, or equipment, it is possible to facilitate new LSs. A new LF every few weeks or months assists various users (e.g., staff, students, businesses, etc.) in meeting their needs.

2.2 Research Questions

The problem described in Section 2.1 can be solved by answering the following research questions:

Main Question:
"How can the lifespan and educational value of learning factories be preserved to support engineering education?"

Sub Questions:
1. *What is the relationship between a Learning Factory and learning subjects?*
2. *What factors should be considered when designing a Learning Factory with extended value?*
3. *What kind of tool could be used to preserve and maintain the value of Learning Factories?*

2.3 Research Method

To answer the Main Question, the following methodology is used. First, a literature review was conducted on the state of the art in Learning Factories and methods to increase the value of LFs. To broaden the knowledge, the topic of Active Learning Methods (ALMs) was initially investigated and defined.Then, the characteristics of Learning Factories were defined, research was conducted on existing examples, and the benefits and limitations of LFs were described. For Learning Subjects, similar to LFs, a definition was set up, and research was conducted on substantial LS topics. At last, research was performed on methods to preserve and maintain the value of learning factories, with a focus on changeability, modularity and interoperability. Changeability can be understood in different ways within the manufacturing industry. Prior to eliminating this ambiguity, a proper definition had to be defined. This can be further described as, under what circumstances do we use which -ility? (scalability, flexibility, reconfigurability etc.).

After removing the ambiguity, research was conducted on the current Learning Subjects provided by the University of Twente. This information was used to determine what equipment is necessary for teaching Learning Subjects. Second, research was conducted on existing LFs to determine which Educational Products (EP) can be manufactured in the learning factory. The EP is used to transform the theory from various LSs into a practical LPs for the Learning Factory. Using correlation matrices, the best EPs to offer in the LF were determined.

Then, the information obtained from this literature review was incorporated into a Learning Factory Configuration Tool (LFCT) that generates an equipment list to facilitate the production of the EPs and its corresponding LSs. With the LFCT, it is possible to evaluate the EP changes. Consequently, each change to the EP has a corresponding effect on the required equipment and the LF. A simulation is created to demonstrate the viability of various production lines based on the LFCT-suggested base equipment list. Use of the LFCT and simulation of the Learning Factory led to enhancements to both the configuration tool and the first iteration the simulated Learning Factory.

A summary of the research questions ans their corresponding method is shown in Table 1.

Table 1: Research questions and corresponding method.

Research Questions	Method	Description
1. What is the relationship between a learning factory and learning subjects?	Literature review	Here, knowledge is obtained through the reading of articles on both learning factories and learning subjects.
2. What factors should be considered when designing a learning factory with extended value?	Literature review	Read articles about changeability, modularity and integration.
3. What kind of tool could be used to extend the value of learning factories?	Literature review + Making the tool + Simulation	1. Design the tool based on the knowledge gained before and well-founded decisions. 2.Make the tool. 3.Test the tool, use the LFCT-suggested equipment list to create simulation of the LF and use that to show the feasibility of various production lines according to the base equipment list. 4. Describe what should be improved or researched for future usage of the tool.

3 Literature study

Active Learning Methods, Learning Factories, Learning Subjects, and methods for maintaining and preserving the value of LFs are researched in this section. It is necessary to understand the characteristics and most recent developments in these fields. This section lays the groundwork for the design and analysis of the tool to extend the value of LFs, which will be presented in subsequent sections of the report.

3.1 Active Learning Principles

According to A. Andersen et al. [6] learning paths must be given following the Technological Pedagogical Content Knowledge (TPCK) rule. This method combines Technological knowledge with Content and Pedagogical knowledge. Here the Technical aspect is the Learning Factory, the Content aspect is the Learning Subject and the pedagogical aspect is about teaching using experiments, videos, online tests, virtual classrooms, online forums etc.

As described above, the pedagogical aspect is a broad topic. Teaching is not like before when a teacher was just standing in front of a classroom and commanding everybody what to do. Currently teaching is much more centered around the students and facilitating their personal growth through group assignments. Nowadays, this can be supported by various technologies as a result of the innovation in communication technology.

Through time, multiple methods to teach, have been investigated and used. A learning factory environment enables many learning methods to be used. Abele et al.[4] has listed these so called *active learning methods* (ALM) below. It is important to note that most LFs are not specified to teach according to one ALM, but a combination of multiple ALMs.

3.1.1 Action Oriented Learning (AOL)

Action oriented learning is a principle that is designed to create more "complete" employees [7]. Learners are not only told about a profession, but also actively experience the profession. Both on a personal and group level. By working in teams, learners socially improve themselves and by evaluating together, individual values can be compared and discussed. AOL is done by following and repeating the 6 steps listed below throughout a project. This cycle is required, because it can happen that after evaluation, more processes are required before the end-product is there.

a) *To inform:*
Informing about the precise objective of the assignment. Setup requirements.

b) *To plan:*
Devising a working schedule and mode of execution.

c) *To decide:*
Setup the order in which the execution of work and cooperation is done.

d) *To realise:*
Carry out the job.

e) *To control:*
Fill in control sheet that encompasses the requirements, quality criteria and tolerances.
f) *To evaluate:*
Evaluate together with the instructor or teacher if all steps of planning, decision and implementation went in the best possible way.

If these steps are monitored and guided correctly, an environment is created in which the student/learner achieves self-awareness in dealing with a problem.

3.1.2 Experiential learning (EL)

Based on the learning the models of the Lewin, Dewey and Piaget. Kolb [8], describes learning as "The process whereby knowledge is created through the transformation of experience". Viewed from an experiential perspective, the focus is on the process of adaptation and learning, instead of content or outcomes. Where instead of a traditional teacher that sends the information, emphasis is laid on the role of the learner which gains knowledge through experience. an LF makes use of this by walking the learner through 4 steps [8][4]:

a) *Concrete experience:*
For example by performing a certain Learning Path, further explained in Section 3.3.
b) *Reflective observation:*
Then, the learner reflects on this experience.
c) *Abstract conceptualization:*
This is followed by analysis and interpretation of the experience.
d) *New active experimentation:*
The result of the analysis is then transformed into new knowledge, from which follow-up steps can be taken. Such that step one can be followed again.

3.1.3 Game-based learning (GBL)

Game-based learning uses game elements to activate the learning. This can also be described as gamification or serious gaming [9]. Gamification, is defined by Deterding et al. [10] as, "the use of game design elements in non-game contexts". The benefits of gamification are that you can explain LPs using a problem-solving and competitive character. Where learning and applying LPs, has a positive effect on the progression. This enhances the learning success, working performance and promotes the creativity of learners [9]. Learning can be made more interesting by varying the phases of tension, just like in games. This has a positive influence on the cognitive, behavioral and sociocultural engagement of the learners. On the other hand, if the requirements of the assignment are far above the abilities of the learners, thus unbalanced, gamification could also lead to stress, anxiety, boredom or disinterest. Therefore the flow-state must be properly controlled, which means that the learners are constantly motivated to continue playing [11]. This is best done by introducing clear targets, providing direct feedback and the possibility of adjustable requirements and capabilities. Teichmann et al. [9] have defined their own requirements regarding LF game-design, see Table 2.

Table 2: Serious game LF requirements from Teichmann et al. [9]

Design requirements:		Competence and content requirements:	
Attributes	*Characteristics*	*Attributes*	*Characteristics*
Objectives:	Encourage team work Convey and deepen knowledge Ensure capacity to act Technology acceptance	General skills:	Problem-solving capability Participation in transformation processes Independent decisions
Gamification:	Playful elements Social interaction Gaming experience	Competences:	Interaction competence Process competence Organization competence
Flow conditions:	Clear targets Direct feedback Adjsutable requirements and capabilities	Factory specifics:	Setting Didactical concept Topics

3.1.4 Problem-based learning (PBL)

Problem based learning is another teaching method. Using a realistic case, students have to come up with their own parameters to getting the right solution. The focus is more on the students knowledge development rather than designing the correct end-product. It is based on four basic learning principles [12] that are written below:

a) *Learning must be a Constructive process*
Teaching is not only about delivering knowledge, a student must be actively involved in the process of learning. This creates knowledge structures, where different concepts of knowledge can be linked to each other. To create a knowledge structure, students must be triggered to get their own experience or interpretation of the gained knowledge. Elaboration in the form of discussions or questions is helpful to link new information to the existing prior knowledge. The result is a deeper and richer understanding, and therefore better use, of the knowledge.

b) *Learning must be a Self-directed process*
During a course, assignment or thesis, learners should actively plan, monitor and evaluate the learning process. This keeps the learner directed towards the right learning goals and helps in achieving the targets quicker. Besides cognitive self-regulation, it is important to create motivation by letting the student know that all gained knowledge can be helpful in the future and that during the entire lifetime, learning is required. By understanding his/her own existing level of knowledge, a learner is able to form the scope, plan and monitor his/her own learning process.

c) *Learning must be a Collaborative process*
Students must be stimulated to interact with each other because these interactions may positively influence learning. Collaboration is built on four factors, the students have a common goal, share responsibilities, are mutually dependent and need to reach agreements through open interaction. (bron 8) Because of these factors, students are forced to elaborate, cooperate, give support or criticise others during a learning process. This helps the group with gaining a better understanding of the matter, compared to individual learning.

d) *Learning must be a Contextual process*
   It is important to teach in different contexts. So presenting a problem with different times, purposes and from different perspectives. Having experienced multiple perspectives of multiple problems helps in determining the critical features presented. This way the knowledge can be applied and transferred better to others in the project group.

These four learning principles can be converted into three characteristics of a PBL teaching method. These can be used while formulating learning courses and helps in ensuring student participation and maximizing knowledge growth with students.

* **Problems as a stimulus for learning**
  Problems that are realistic and presented in the context of the learning path, actively help in achieving a constructive and contextual learning process.
  Something to consider when designing a problem is that it is not too simple or close-minded and it that it is realistic. Students must be challenged to actively construct knowledge. A Learning factory facilitates making realistic problems.

* **Tutors as facilitators**
  Tutors facilitate and stimulate the learning process. Also, monitoring the educational progress of each student is important. They make sure that each student is actively involved by investigating deeply about their knowledge. This can be done by asking for clarifications, elaborating questions and application of knowledge. Instead of transferring knowledge, the tutor must encourage cognitive activities where students are challenged to gain more knowledge. This helps in achieving a Self-directed learning process.

* **Group work as a stimulus for interaction**
  To ensure a collaborative learning process, problems must be tackled in small groups. Small groups allow for easier and clear communication between students. Students learn collaboratively by being forced to interact and ask and answer questions to each other. Working together is something to be learned in tutorials and can be applied later in the work field.

  To prevent a group from getting into a negative spiral, it is important for the tutor to check the group's functioning on a regular basis. The assignment should be complex enough to force proper group integration and the tutor must give instructions in a way that students want to gain new knowledge by themselves. This way a good collaboration can be created. Also, peer assessment throughout the project helps in steering the group's behaviour in the right direction.

3.1.5 Project-based learning (PjBL)

Closely related to Problem-based learning, is Project-based learning (PjBL). In both methods, the learners work in groups on a shared goal. The difference is that the case of problem-based learning keeps a certain level of abstractness, while the case of project-based learning is more clearly defined. With project-based learning the teachers have set the requirements and desired end-product beforehand. The role of the teachers is more about providing guidance and feedback towards the end-product and within the context of the case. So compared to problem-based learning, the learners are less encouraged to coming up with their own parameters and are more stimulated towards performing the correct procedure [13]. The paper from M. Zarte and A. Pechmann [14] or the paper from P. Balve and M. Albert [15] show how Project-based learning can be used in an LF environment.

3.1.6 Research-based learning (RBL)

As the name suggests, Research based learning (RBL) is about performing research. So the focus is not on passing on information from teacher to learner, but about doing research on the unknown. The idea is that throughout a project, learners will reflect on their process and results [16]. This reflection then helps in setting new goals and are starting points towards doing new findings and results. The learners should be aware that it is not about the results, but about the deeper understanding of how the results are made. This knowledge can then be used to solve unanswered research questions. This is also closely related to problem-based learning. Where the difference is that students are stimulated to lead the research and teachers, besides facilitating the reflection and evaluation, also provide information and take actively part in the discussion [13]. A learning factory is a perfect environment for this type of learning because it offers room for experiments and failure. Figure 1, shows what classifications of research exist and how research-based learning distinguishes itself.

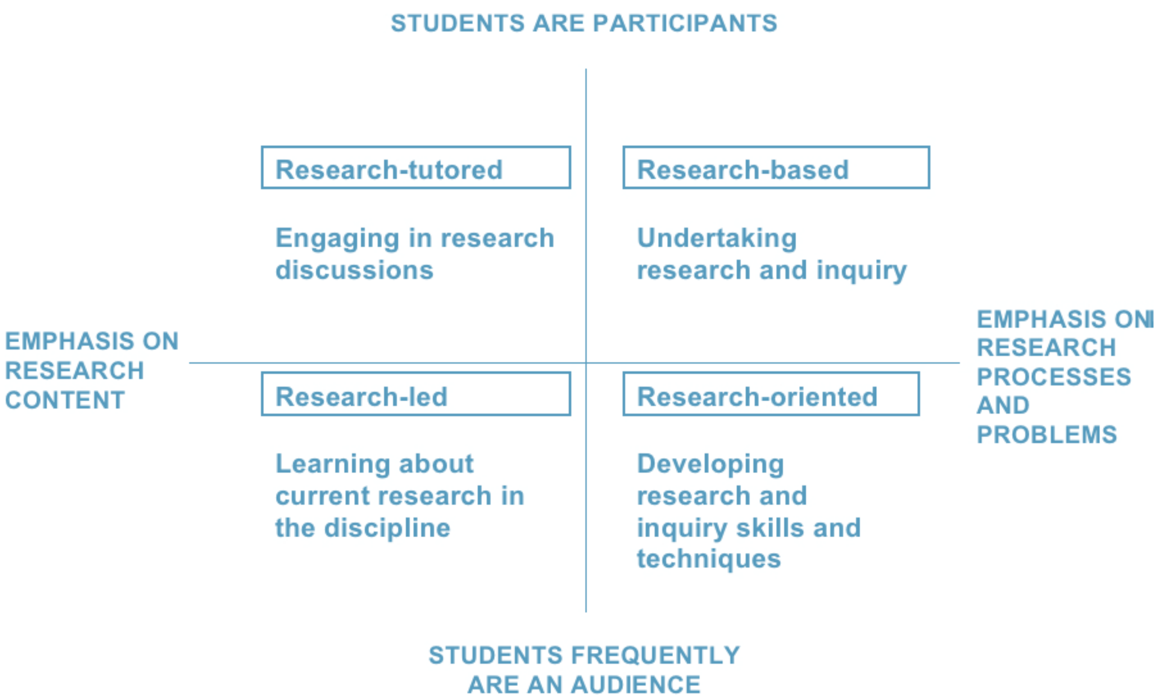


Figure 1: Research classifications by Healey [17].

3.2 Learning Factories

A Learning Factory (LF) is used to teach individuals (staff/students/companies) about a physical or digital topic within the Learning Factory. Physical topics may include the use of tools, equipment, machines, 3D printing[18], composite forming[19], co-bots[20], etc. The focus of digital topics, such as RFID tracking[21], A.I. video tracking[22], and digital twins[23], is on automation. A professor's work in an LF consists of instructing a Learning Subject (LS) as part of a larger Learning Course (LC). Consequently, an LC comprises multiple secondary LSs[4].

Learning Courses in Learning Factories can also be viewed from a tertiary perspective. Take an LS like lean for example, which can be further subdivided into lean transportation, lean production, and lean assembly. Also, an LS like sheet metal forming encompasses a variety of actions, such as plate cutting, plate folding, and plate welding. Correspondingly, it is necessary to have a term for the tertiary perspective. Therefore, a Learning Subject may be subdivided further into Learning Paths (LPs)[24][4]. This is illustrated in Figure 2 and summarized in Table 3. The ultimate goal is to teach as many and as valuable LSs as possible with the fewest LF modifications.

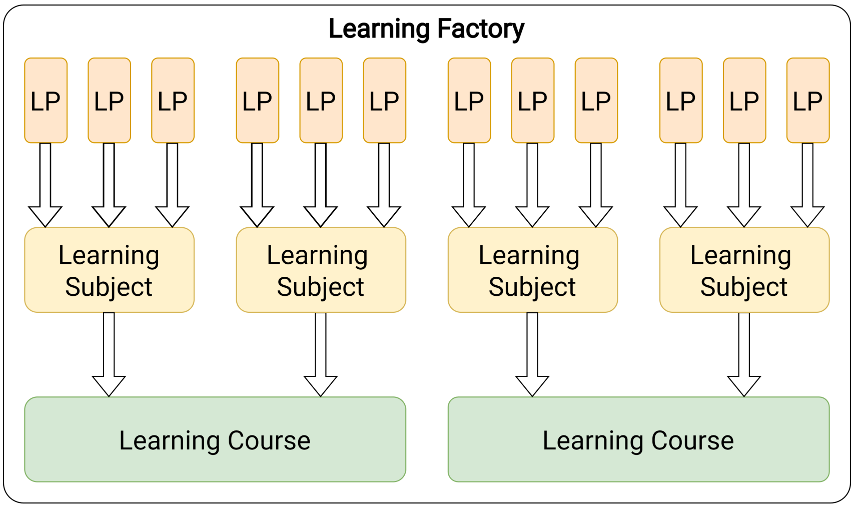


Figure 2: Learning Paths, Learning Subjects and Learning Courses are all part of the Learning Factory.

Table 3: Defining Learning Paths, Subjects and Courses.

Name	**Description**	**Example**
Learning Path (LP)	A small task or action, that enables the user to learn a new skill.	Lean assembly + lean manufacturing + lean transportation Plate cutting + plate folding + plate welding
Learning Subject (LS)	A combination of LPs that collectively enable the user to learn a subject within the field of manufacturing education.	Lean production/sheet metal forming
Learning Course (LC)	Multiple LS' that together form a course in manufacturing education.	Course: "Lean design of a Sheet metal parts factory"

3.2.1 Defining a Learning Factory

A Learning Factory (LF) is an environment where a physical product is manufactured and the manufacturing process is used for teaching purposes. For different target groups, it is possible to turn theoretical knowledge into practice within a small-scale factory. Target groups could be researchers, students and industrial companies. Both existing and new technologies can be developed, tested, demonstrated and evaluated here [25][26][4].

As discussed Section 3.1, the LF allows the target groups to take part in the implementation and improvement of production processes, while directly experiencing the results of their own actions [27]. It is a great way of gaining skills and competencies in dealing with unknown techniques and situations [26]. Later, these competencies can be used on an industrial scale too. Physically experiencing a learning process results in a better way of remembering the given information and also brings joy [28][29]. Curiosity and willingness to experiment are enhanced because there is less risk involved in the choices a practitioner makes in an LF [26]. The idea of practising in a small-scale version of the work field originates in the medical world. Here, students also gain practical experience during their research. Practical experience allows for better understanding and improves the research because it is relatable to real-world examples [1].

The LF can be divided into a physical and a digital domain. The physical domain is everything related to the actual manufacturing system. It consists of machining, assembly, logistics and IT system infrastructure. The digital domain consists of software for planning and modelling. Also, visualization and simulation tools are part of the digital domain. [1] LFs for research purposes or for education of students and training of professionals might differ [5][4]. Figure 3 from Abele et al. [1], shows a summary of the key characteristics of a Learning Factory. It also shows how an LF can be defined in a broad or narrow sense. As the scope of this research is to design and analyse a changeable learning factory that might be built on the UT terrain, the rest of the paper will focus on LFs in the narrow sense. The goal is to manufacture a **physical** product in a **real** Learning Factory **on-site**.

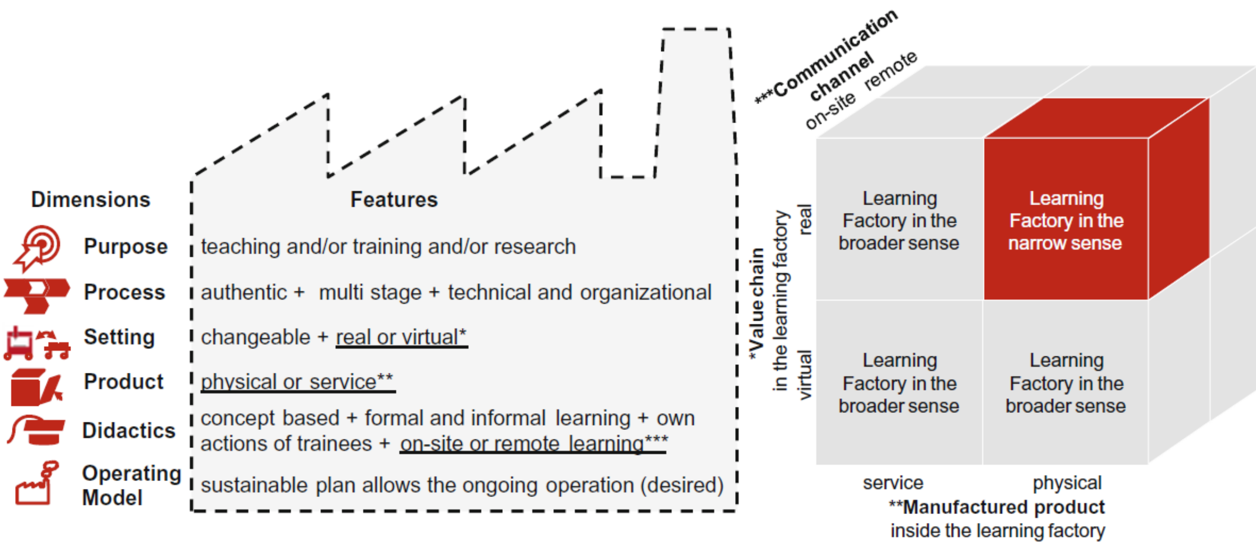


Figure 3: The key characteristics of Learning Factories in the narrow sense[1].

One method to describe learning factories is by using the framework made by Tisch et al[30]. This framework consists of 59 characteristics that are clustered in seven dimensions. A short elaboration of each dimension and its characteristics is given below. Note that these characteristics are examples of topics to highlight when describing an LF and not all 59 should be utilized every time an LF is described.

a) Operational model[30]
The operational model describes who operates the factory (academic institution, non-academic institution, profit oriented operator) and which trainers (instructors) provide the education (professor, researcher, student assistant etc.). It also explains about the different stages of funding. Initial funding to set up the factory, the method for continuous funding after it is built and the funding period. Additional funding can be gained using an open (club model, course fees) or closed (training program for single company) business model. Besides, it is possible to define where development of didactical concepts comes from (owned by the LF, externally assisted or external).

b) Purpose and targets[30]
LFs generally have a main purpose (education, vocational training, research etc.) and a secondary purpose (test environment, industrial production, innovation transfer etc.). There are various target groups for education and training (students, employees, unemployed etc.) and several target industries (construction, chemical, automotive etc.) that can be focused on in an LF environment. Either with a homogeneous or heterogeneous group constellation. And according to that, several topics for learning content or research can be identified (resource efficiency, automation, lean management etc.). The LF can take the role of research object or research enabler.

c) Process[30]
The process is used to describe the product, factory, order and technology lifecycle. Besides, more details are given on other functions (sales, HR, QM etc.) and processes within the factory. Important processes details are the material flow (continuous or discrete), process type (mass production, small series production etc.), manufacturing organization (work bench manufacturing, flow production etc.), degree of automation (manual, automated or hybrid), manufacturing methods (cutting, forming, additive manufacturing etc.) and manufacturing technology (physical, chemical or biological).

d) Setting[30]
The setting describes the learning environment (purely physical, physical and supported digital etc.), its scale (scaled downn or lifesize) and the work system level (work place, factory etc.). Additionally, enablers for changeability (modularity, mobility etc.) and the changeability dimensions (layout and logistics, product features etc.) can be described. Also IT-integration is possible in many ways (CAD, ERP, PLM etc.).

e) Product[30]
The product that will be manufactured in the LF, facilitates the transfer of knowledge. It can be described with characteristics like the materiality (physical product or service) and the product form (general cargo e.g. unique objects or bulk cargo e.g. sand). The product origin (own, external or hybrid development) and marketability of the product (available on the market, for demonstration purposes only etc.) is also of interest. Other product details are the number of products, number of variants, number of components and the further product use (re-cycle, sale, disposal etc.).

f) Didactics[30]
Besides the product, the transfer of knowledge is also determined by the didactics, or ALM, see Section 3.1. Tisch et al. [30] has defined 12 characteristics to define didactics. Starting with competance classes (technical and methodological, personal, social etc.) and dimensions of learning targets (cognitive, affective or psycho-motorical). The learning scenario strategy (instruction, demonstration etc.), type of learning environment (development or improvement of existing LF environment) and communication channels (on-site or remote) are several methods to transfer knowledge. The conditions to learn can be described by the degree of autonomy (instructed, self-guided or self-organized), the role of the instructor (presenter, moderator etc.) and the type of training (project work, workshop etc.). Further characteristics to elaborate on didactics are the standardization of trainings (standardized or customized) and the theoretical foundation (in advance, alternating with practical parts, afterwards etc.). Evaluation is also part of learning and is described by the evaluation levels (feedback of participants, transfer to the real factory etc.) and learning success evaluation (oral or written knowledge test, written report etc.).

g) Learning Factory Metrics[30]
To gain a better understanding of the operational scope a few metrics can be used. The number of participants per training or per year. Next about the training, the amount of standardized trainings (1-3, 3-6, more than 6 etc.) or the average duration of training (less than a day, 5 days etc.). More general could be the capacity utilization (1-100%), the size of the LF (m^2) or FTE in LF.

3.2.2 Changeable Learning Factories

A fully operating changeable learning factory, both in the physical and digital domain, does not exist yet. According to a research from Martinez et al. only a small amount of research papers give attention to changeability with respect to learning factories [31].

Abele et al. made a website[32] that includes a database of 21 existing LFs, see Figure 4. It is possible to browse through it using filters on 59 characteristics identified by Tisch et al. [30] and described above. In Appendix A.1, an overview of all the filter possibilities of each characteristic can be found.

Figure 4: Map of the 21 LFs on the website [32].

As shown in Figure 5 and 6 which correlates to Figure 59 in Appendix A.1, it is possible to filter on changeability enablers in the 'setting' -dimension. By filtering on 'modularity', 'physical LF supported by digital factory' and being able to make a 'physical product', which is the scope of the assignment, four results are found and listed below.

a) iFactory, Windsor, Canada [33]
b) LMS, Patras, Greece [34]
c) Process Learning Factory CiP, Darmstadt, Germany [35]
d) UNIMEP - SCPM, Santa Bárbara d'Oeste, Brazil [36]

Each of these LFs claims to be changeable. However are limited to, standardized machines of one manufacturer, for example in the iFactory[33] or limited to a set of multiple LPs in one LS such as lean manufacturing like the Process Learning Factory CiP [35]. This is not the idea for the Learning Factory at the University of Twente. The LF at the UT, should deliver value throughout its lifespan for any LS and should have freedom to choose any type of equipment relevant for engineering education.

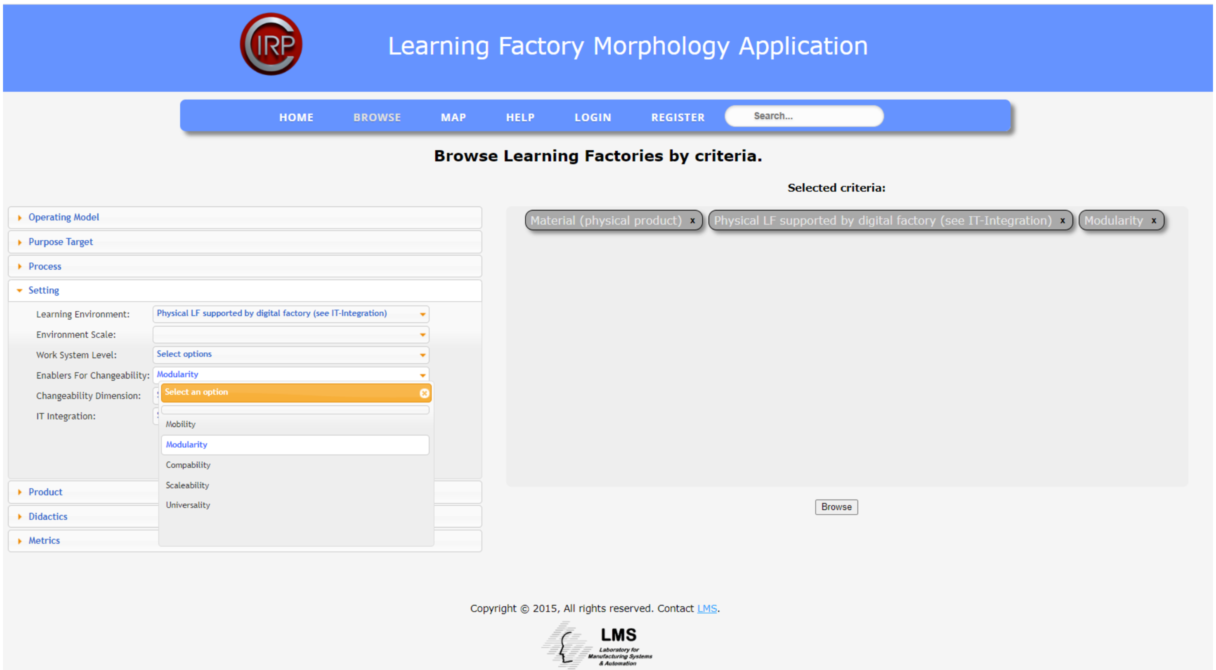


Figure 5: The filters applied in the LF-browser [32].

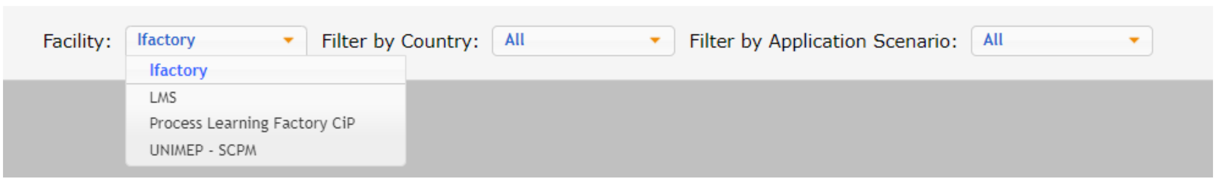


Figure 6: The results in the LF-browser [32].

3.2.3 Benefits and limitations of LFs

When an LF concept must be developed, it is important to understand what the benefits of an LF are and what limitations and obstacles must be dealt with. Tisch et al.[37] performed a study into this topic, which can be combined with the literature from Section 3.1. As such the benefits and limitations are listed below in Tables 4 and 5. These correspond to the core LF concept, described in Section 3.2.1 and indicated red in Figure 3. As told in Section 2.1 and approved by this list, there are many challenges to overcome and to improve about a regular learning factory. In Section 3.6, a solution is found to these problems.

Besides a core concept, Abele et al.[4] also illustrates other variations like, model scale LFs, physical mobile LFs, low-cost LFs, digitally and virtually supported LFs and LFs that produce a large series of a single product. Each have their own added benefits and limitations. These are shown in Appendix A.3, but to not distract from the main topic of the research, will not be further referred to.

Table 4: Benefits of Learning Factories[37]

+	Hands on experience and own actions of the learners and connected feedback[7][8][4][16][13].
+	A high contextualization of the learning environment[8][4][12].
+	Activation of the learners in practical learning tasks[4][8][9][16].
+	Use of realistic problem situations[9][12][14][15].
+	Motivational benefits of the immersive learning environment[11][12].
+	Possibilities for collectivisation of on-site learning processes[7][12][14][15].
+	Possibilities for the integration of thinking and doing[7][9].
+	Self-regulation and self-direction of the learners can be used appropriately[7][12].

Table 5: Limitations and obstacles of Learning Factories[37]

-	A large (financial) resource requirement for construction and operation.[37]
-	The mapping of only certain production processes and topics that represents a small part of complex manufacturing systems.[1][38]
-	The challenge in mapping large factory structures, e.g. entire factories or networks.[39]
-	The challenges with learning content that does not allow direct feedback from the learning environment to the learners' actions.[37]
-	The challenge with ad hoc representation of participants' ideas and solutions in the learning factory (changeability and flexibility of the factory environment).[40]
-	The difficulties with scalability, e.g. in the use of learning factories of educational purposes in lectures with many participants.[37]
-	The lack of mobility of the learning factory facility and equipment.[41]

3.2.4 Solving the learning factory limitations

Recognizing the LF limitations that are shown in Table 5, the following approaches according to literature can be used:

A large (financial) resource requirement for construction and operation.
Learning factories are capital intensive. Besides the space and necessary equipment, a factory also needs lightning, heating and ventilation. Additionally machine operators, instructors and maintenance engineers must be paid[37].

The mapping of only certain production processes and topics that represents a small part of complex manufacturing systems.
One way of increasing or adjusting for that, is having additional sensors or tools that are in the LF that allow for broader data collection. Therefore different mapping processes can be used[42][23][22].

The challenge in mapping large factory structures, e.g. entire factories or networks.
The entire factory is a complex environment with a number of different entities and actors that go into it. It has been suggested that Real-Time Locating System (RTLS)[42], is one way that can help to gain insight into the factory itself. You can additionally use optical systems[23] and artificial intelligence for machine learning [22] to try to track and monitor the larger factory.

The challenges with learning content that does not allow direct feedback from the learning environment to the learners' actions.
Its very important to make sure that the content is not only academically correct but also engaging as discussed in Section 3.1. An engaged student gets his own interpretation of the gained knowledge and is able to discuss or elaborate on that. This helps students to better understand the relationship between the Learning Path, the Learning Subject and the Learning Course[4][7][8][12].

The challenge with ad hoc representation of participants' ideas and solutions in the learning factory (changeability and flexibility of the factory environment).
Typically because learning factories are built for a specific target point, they are fairly rigid which makes it difficult to change[35][43]. If you are able to consider the opportunities for change[44][45], its possible to make it more flexible.

The difficulties with scalability, e.g. in the use of learning factories of educational purposes in lectures with many participants.
Similar to the problem described above, Learning factories are typically very rigid. It is hard to fluctuate the amount of equipment as equipment investments are meant for the long term[41]. To accommodate a growing number of students, an efficient and qualitative knowledge transfer methods should be devised.

The lack of mobility of the learning factory facility and equipment.
As a physical asset, you can not pickup and move the learning factory. What you can have, is pieces of equipment that are mobile[33]. Additionally you can implement some basic component modularity or simplicity or standardized connectors to be able to easily reconfigure/change the learning factory to increase the overall movement and motion that can be tracked[45].

3.3 Defining a learning path

As described in the introduction of this section, a Learning Path (LP) is a small task or action that enables the user to learn or perform a new skill [24][4]. If multiple LPs are combined, they can form a Learning Subject (LS), see Figure 7.

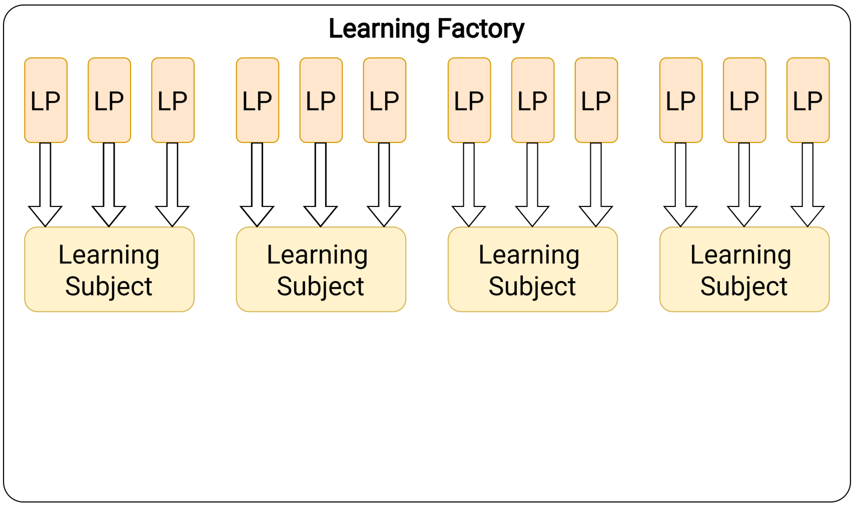


Figure 7: Multiple Learning Paths must be taken before a Learning Subject is understood.

From a learning factory perspective, the user fulfills an LP by performing a small action within the LF. This could for example help with learning to work with a type of equipment. For example if the subject is 3D printing, the following Learning Paths must be taken [1]:

a) Learn about the main Additive Manufacturing (AM) processes, the working principle and their benefits and limitations.
b) Learn about the processes and the supported materials within the field of AM.
c) Learn how to distinguish each AM process.
d) Learn about the economical aspects related to AM.
e) Learn about the design rules for an additive manufactured part. Identify the design constraints in AM and post-processing considerations.
f) Apply simulation tools in the design for additive manufactured parts.
g) Slice the part such that it can be printed in the desired speed and quality.
h) Analyse the printed part and test it for the desired application.
i) If needed, improve the printing process by iterating the slicing settings or the part design.

From this list it can be derived that not every LP has to be performed in the learning factory itself. A learning factory facilitates certain LPs for the user. In this case the equipment and test environment to learn about the practical implications of 3D printing.

[1]Inspiration from the subject information on the topic of Additive Manufacturing (AM) from the University of Twente [46][47].

3.4 Defining a learning subject

Learning Subjects can be best described as a topic within the field of manufacturing engineering. In a Learning Factory one or a series of products is made. The manufacturing process and the different types of equipment required for that, facilitate the user in performing many LPs and learning about multiple LSs[4]. Examples of LSs that can be offered in a Learning Factory are given below in Table 6.

Table 6: Learning Subject examples

Industry 4.0	**Manufacturing:**	**Other:**
Digital twins	Lean manufacturing	Energy and resource efficiency
Machine learning	Composite forming	Transportation
Process tracking	Laser manufacturing techniques	Inventory/supply chain management
Digital milk-run	Milling, grinding, turning, boring	Demand changes
Industrial automation	Sheet metal forming	Mass customization
3D printing techniques	Plastic manufacturing techniques	Working with a co-bot
Human-Machine-Interface	Metal casting techniques	Bolt and joint connections

Most LFs are focused on Lean manufacturing and Industry 4.0, see Figure 8. This overview is established by counting key topics in an overview of 64 existing Learning Factories made by Abele et al. in the book *Learning Factories: Concepts, Guidelines, Best-Practice Examples*[48]. Note that, some subjects overlap, for example cyber-physical production systems is part of the I4.0, but has been given its own category. A comprehensive summary of the numbers is shown in Appendix A.2.

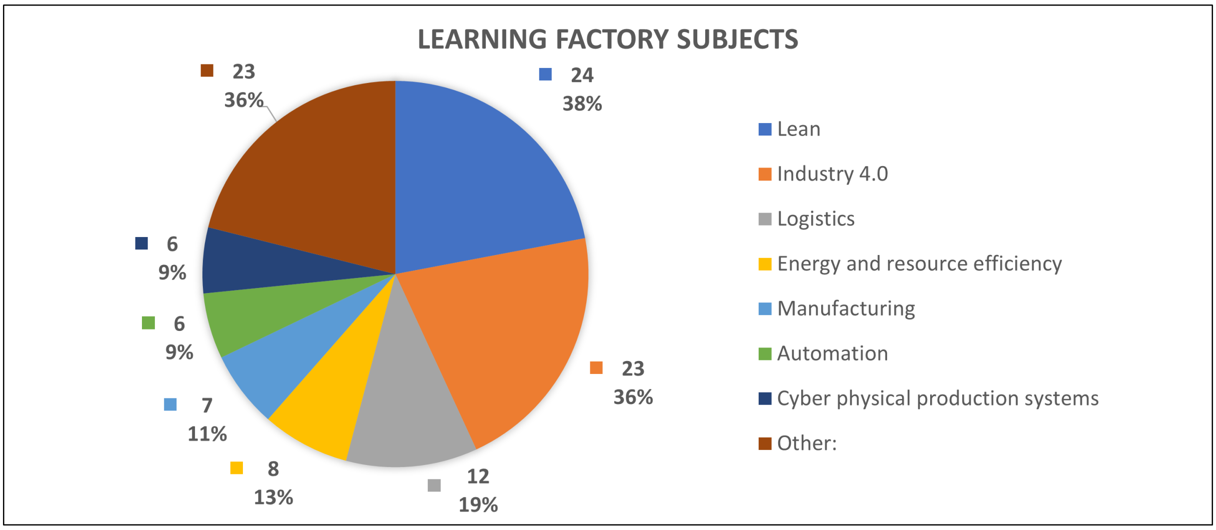


Figure 8: Overview of key learning subjects of 64 existing Learning Factories [48].

An overview of existing Learning Factories equipped to teach on Lean or Industry 4.0 subjects is given in Table 7.

Table 7: Learning Factories that contain subjects on Lean and Industry 4.0[48].

Learning factory	**Location**	**Lean**	**Industry 4.0**
AAU Smart Production Laboratory	Aalborg, Denmark		X
Alberta Learning Factory	Alberta, Canada	X	X
Anglo American Training Center	Johannesburg, South Africa	X	
AutoFab	Darmstadt, Germany		X
CETPM Akademie	Ansbach, Germany	X	
Demonstration Factory	Aachen, Germany		X
E3-Forschungsfabrik	Chemnitz, Germany		X
ESB logistics	Reutlingen, Germany		X
Festo Learning Factory Scharnhausen	Scharnhausen, Germany	X	X
FMS Training Center	Tampere, Finland		
iFactory, iDesign, iPlan	Windsor, Canada		X
IFA-Learning Factory	Hannover, Germany	X	
Lean Academy	Winnenden, Germany	X	X
Lean Laboratory	Gjovik, Germany	X	
Lean Manufacturing Laboratory	Luxembourg, Luxembourg	X	
LEAN-Factory	Berlin, Germany	X	
LeanLaboratory	Gratz, Austria	X	X
Learning Factory aIE	Stuttgart, Germany	X	
Learning Factory at the Campus	Heiligenhaus, Germany		X
Learning Factory for Global Produktion	Karlsruhe, Germany	X	X
Learning Factory Split	Split, Croatia	X	
Lernfabrik 4.0	Baden Wurttemberg, Germany		X
Lernfabrik für Schlanke Produktion	Munich, Germany	X	
Lernfabrik für vernetzte Produktion	Augsburg, Germany		X
Live Training Center	Bruchsal, Germany	X	
LPS Learning Factory	Bochum, Germany	X	X
Model Factories	30 locations worldwide	X	X
Move academy	Herzogenaurach, Germany	X	
MPS Lernplatform	Sindelfingen, Germany	X	
MTA SZTAKI Learning Factory Györ	Györ, Hungary		X
Process Learning Factory CiP	Darmstadt, Germany	X	X
SEPT Learning Factory	Hamilton, Canada		X
Smart Factory	Kaiserslautern, Germany		X
Textile Learning Factorie 4.0	Aachen, Germany		X
The PuLL Learning Factory	Landshut, Germany	X	
Value Stream Academy	Several locations	X	
VPS Center of the Production Academy	Munich, Germany	X	

Lean and industry 4.0 are terms often used to describe processes in the field of manufacturing, especially when describing LF education programs. Unfortunately, terms like these are not very specific, but instead are an umbrella term to cover a lot of topics. Therefore, the following pages will provide a brief explanation.

3.4.1 Lean

The consumer demand for customized products became popular in the late eighties. However, the resulting complicated control systems and production planning made mass production of goods very difficult. In a search to more efficient manufacturing, inspiration was taken from Japanese car manufacturer Toyota, which was far more efficient than western car manufacturers[49]. The origin of this lies in the scarcity of resources after the second world war. The core principle of lean is to reduce and eliminate non-value adding activities, thus waste. Using the acronym DOWNTIME, eight types of waste are identified and listed below [50].

a) Defects - Production or services that are out of specification that require resources to correct.
b) Overproduction - Producing too much of a product before it is ready to be sold.
c) Waiting - Waiting for the previous step in the process to complete.
d) Non-utilized talent - Employees that are not effectively engaged in the process.
e) Transportation - Transporting items or information from one location to another, that is not required to perform the process.
f) Inventory - Inventory or information that is not used in the short term.
g) Motion - People, information or equipment that make unnecessary motion due to for example the workspace layout, ergonomic issues or searching for misplaced items.
h) Excess-processing - Any activity that is not necessary to produce a functioning product or service.

Following this principle, a company can react much better to customer demand with fewer resources. Driven by a research program of the Massachusetts Institute of Technology, lean manufacturing became a known term in the early nineties due to the work of Womack et al. [49]. It was adopted a lot in the car industry, but since then it evolved and also became popular in other industries like, aerospace, food, medical healthcare or the textile industry [51].
According to Taj and Morosan[52], lean is defined as A multi-dimensional approach that consists of production with minimum amount of waste (JIT), continuous and uninterrupted flow (Cellular Layout), well-maintained equipment (TPM), wellestablished quality system (TQM), and well-trained and empowered work force (HRM) that has positive impact on operations/competitive performance (quality, cost, fast response, and flexibility). In total Bhamu et al.[51] have identified 18 lean management tools, listed in Table 8, that assist with removing waste from a company. Without going into further detail, it shows how broad the application of lean is.

Table 8: 18 lean tools identified by Bhamu et al.[51].

1	Value Stream Mapping (VSM)	10	Single Minute Eexchange of Die (SMED)
2	Kanban	11	Multifunctional teams
3	Just In Time (JIT)	12	Production smoothing (Heijunka)
4	Total Productive Maintenance (TPM)	13	Visual control
5	5S	14	Supplier relationship (Andon)
6	Cellular manufacturing	15	Poke Yoke
7	Continuous improvement	16	Standardized work
8	Total Quality Management (TQM)	17	Simulation
9	Kaizen	18	Automation (Jidoka)

Lean Learning Subjects
The tools listed in Table 8, can be identified as Learning Paths. And a combination of tools may result in completing an LS like Lean Management, or Lean Production. Some tools are applicable by persons on the production floor while other tools help with managing the production planning. In the end, they all do the same thing and that is identifying and/or removing non-value adding activities.

3.4.2 Industry 4.0

Nowadays the world of manufacturing is going through its fourth industrial revolution. In this revolution, manufacturing evolves from automated production from the 20th century to a cyber-physical production system from the 21st century. It is called cyber-physical because it means that production is now increasingly based on computer-based algorithms. This revolution is driven by data gathering, cloud computing, inter connectivity, AI and machine learning, digital twins, cyber-security and many other topics that in the end lead to more autonomous manufacturing systems. The production systems, machines and storage facilities now communicate autonomously and exchange information. The gathered information triggers further actions and reconfiguration to different situations happens without human interference [53]. Industry 4.0 (I4.0) is a term introduced by the German government that defines a strategy for improving German manufacturing industry and secure its global competitiveness. Nowadays it is a widespread term to describe all kinds of innovations in fields like like described above that lead to better functioning cyber-physical systems.

The road towards an I4.0 proof factory is complex and there is not one solution that fits all. In general, G. Schuh et al.[53] have identified 6 steps a company must take, to be a mature industry 4.0 proof factory. Figure 9 shows the industry 4.0 maturity index made by G. Schuh et al. Each of these 6 steps is elaborated on the next page.

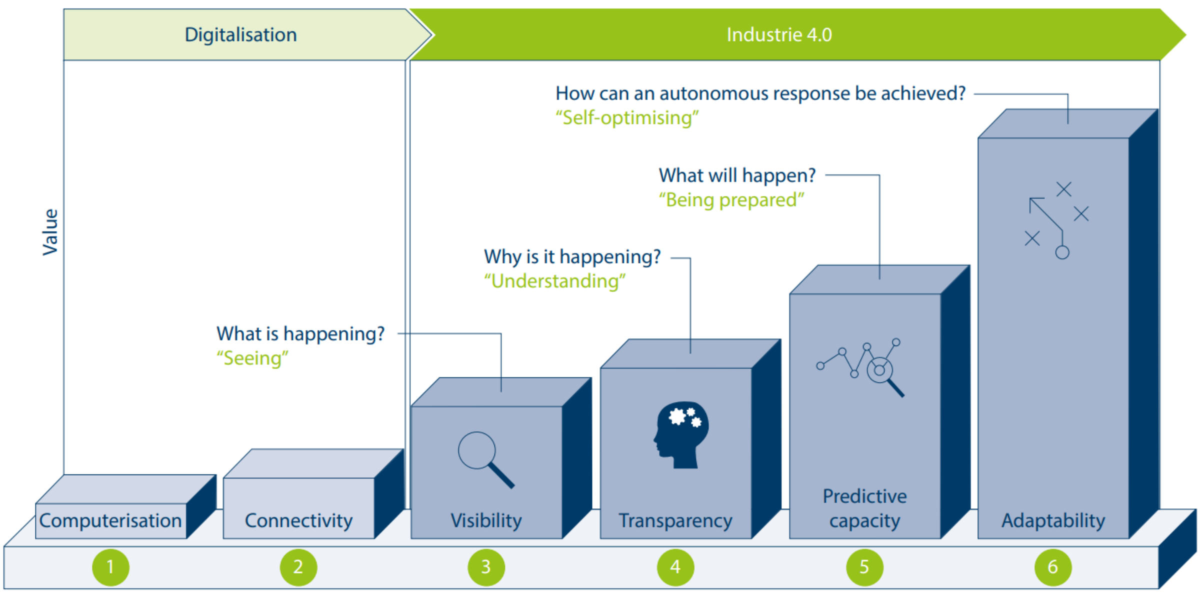


Figure 9: The Industry 4.0 Maturity Index [53].

Step 1: Computerization - Initially a company must digitize itself first before advancing on the industry 4.0 path. Therefore the basic requirements for industry 4.0, and part of industry 3.0, are computerization and connectivity. Most companies operate already on this level. The computerization stage compromises companies that use different isolated types of information technology (IT) to perform repetitive tasks more efficiently. Production data is not shared between different compartments. An example of a computerization upgrade could be to replace manual input of a computer numerical control (CNC) milling machine, with an automatic input[53].

Step 2: Connectivity - The next stage is connectivity, which builds bridges between different isolated IT systems. An example of connectivity, is the engineering office that sends a design to a remote shop floor. After a production step, an automatic confirmation is sent into the Manufacturing Execution System (MES). The availability of sensors also enables older machines to be connected digitally. These are initial steps of connecting production systems to the internet[53].

Step 3: Visibility - This stage is all about gathering real-time data. Bundling all real-time data makes it possible for factories to create a digital-twin. This allows to make dashboards and provides insight in Key Performance Indicators (KPIs). This way it is possible to adjust the production planning and inform customers and suppliers on time for any production variations. A problem is that in most companies, much data is still isolated within different departments and a few individuals actually analyze the data and make decisions[53].

Step 4: Transparency - With all the gathered data it is becoming hard to see linkages and understand why events are happening. Big data applications help the company by combining data and to reveal problems by searching for mutual events and dependencies. These are then contextualized to help with decision making[53].

Step 5: Predictive capacity - Using the real-time data, the company already has a digital twin. Now, the company is able to simulate the digital twin into future scenarios. This will help to anticipate the future and enables appropriate decision making[53].

Step 6: Adaptability - The ultimate goal of industry 4.0 is an adaptive process without human interference. This is possible with good predictive capacity, which allows a company to delegate decision making to IT systems. It is important to review this properly for any decision making event. An example of an adaptable process can be individually customized goods that are ordered online. The production system automatically adapts its configuration to enable production of that custom product. Another way could be a delivery failure and the system automatically changes the sequence of produced goods. Such that the goods independent of the failed-delivery can be produced first[53].

Industry 4.0 Learning subjects

There are many partial solutions that, combined together, allow a factory to reach the 6th level of adaptability. Each partial solution can be seen as learning subject. Figure 10, made by Roland and Berger[54], gives an impression of Learning Subjects related to Industry 4.0.

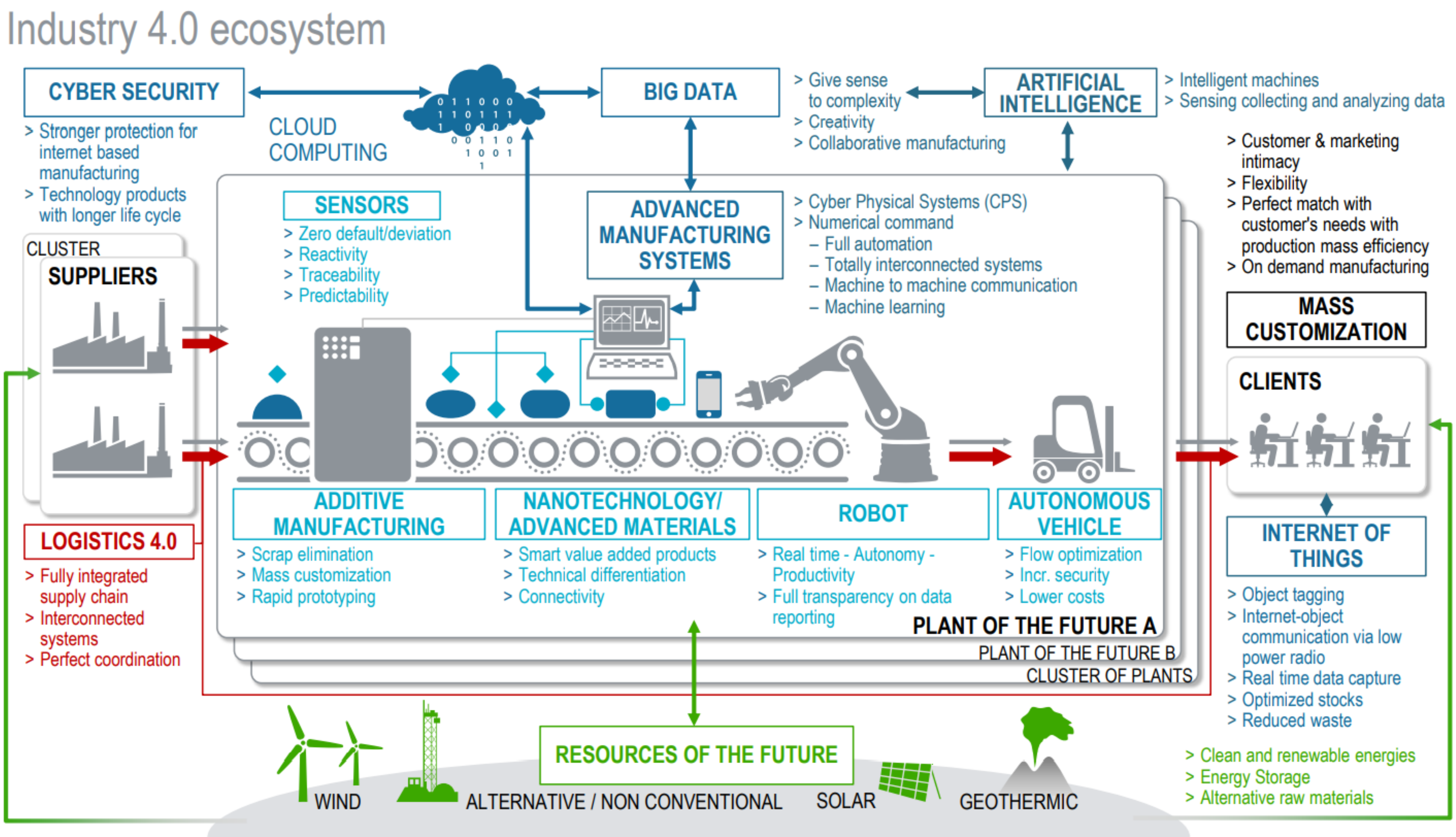


Figure 10: The Industry 4.0 ecosystem [54].

3.5 Defining a Learning Course

A Learning Factory is able to facilitate teaching of multiple Learning Courses (LCs)[4], see Figure 11. An LC is built out of different learning subjects. With regards to an LF this means that you can design courses that are multidisciplinary and focus on multiple LSs at the same time.

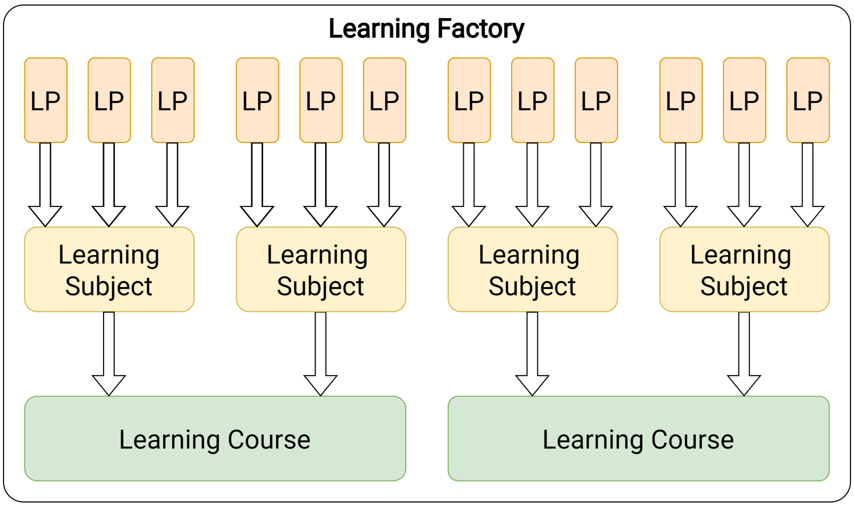


Figure 11: A Learning Course exists out of multiple Learning Subjects. A Learning Factory is able to facilitate multiple Learning Courses.

According to the literature from Section 3.1, an engaging course should be designed to get a better student understanding on a topic. One LS on it itself may not be appealing, but combined with other LSs and using the LF, it could be. As explained in Section 3.2.1 and Table 4 on page 15, a learning factory can facilitate the user in combining knowledge of multiple (theoretical) LSs into practical use cases. These practical use cases can be offered by manufacturing Educational Products (EPs) in the LF.

Subjects like stochastic modelling and machine learning on itself contain a lot of theoretical background knowledge which can be made visible with real examples in the learning factory. For example when stochastic modelling is combined with a subject like predictive maintenance and machine performance data. Or machine learning combined with a subject like image processing and AR glasses or a robotic arm. Through manufacturing the EP, it shows the practical application and limitations of these LSs and helps the user to get a grasp of reality rather than a theoretical proof of concept.

3.6 Methods to preserve and maintain the value of Learning Factories

As summarized in Table 5 on page 15, there are many limitations for Learning Factories. The main drawback is the combination of the large initial investment costs and the difficulty to change the layout of the factory and/or the educational model after construction. The knowledge and innovations in manufacturing technology are continuously exposed to change. This makes it possible for the value of the LF to diminish over time. To maintain and preserve the value, it is important for a learning factory to be changeable and offer as many LSs, with the least amount of change, as possible. Therefore, it is important to understand how changeability, "modularity and interoperability", can be leveraged in the most effective manner.

3.6.1 Changeability

In this section, the topics of changing systems and changeability in manufacturing are explored. Because changeability can be interpreted in several ways, a proper definition must be defined first, along with other -ilities that are used in the context of manufacturing. Then, a method for describing change in learning factories is determined and demonstrated. This section is finalized with a recommendation for changeability in learning factories.

Defining changeability

Nowadays, more sustainable systems must be designed. Not only in terms of climate, but also in economics and space. This is best done by robust system design, which allows a system to deal with internal and external changes and thus create a higher value for stakeholders throughout its lifetime. In short, robustness is the most commonly used term to describe the ability of a system to change, while at the same time value towards stakeholders has remained the same or is increased.

Change can be defined as the transition over time of a system from state i to state i+1 [55], see Figure 12.

When going from i to i+1, three elements are present.

1) The agent of change,

2) the mechanism of change and

3) the effect of change.

These state change elements are further explained in Table 9 on page 26.

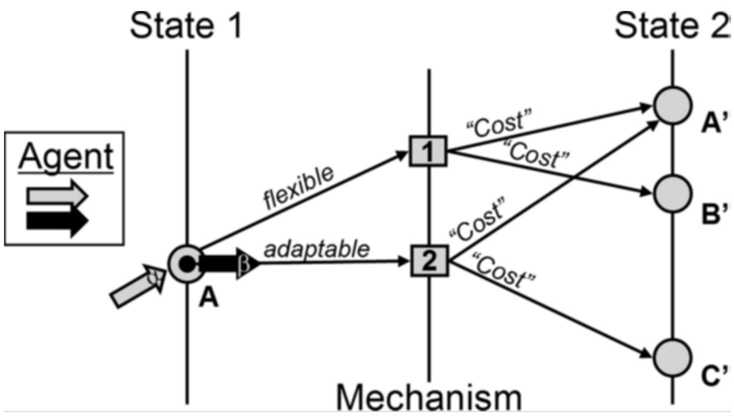


Figure 12: State change graphic [55].

Table 9: Explanation of state change elements [55].

$\alpha \mid \beta$	1) Agent of Change / Change driver	Initiator, or force, for the change to occur.
1 | 2	2) Mechanism of change	The path taken from state i to state i+1
A' – A B' – A C' – A	3) Effect of change	The actual difference between the origin and destination states.

Change agents can be either an internal (adaptable) or external (flexible) influence on the manufacturing system [55]. An example of a change agent within a learning factory could be an instructor, student or, on a higher level, a university or company. Where the LF instructor or academic staff is an internal change agent, and students, universities or companies are external change agents in the LF. The change effect could be the addition of a machine to the factory production line.

The change mechanism could be the student or professor which takes a route from making space, acquiring the machine up till the placement of the machine. Each step comes at a cost of time and money.
The research from Ross et al. is taken a step further by Colombo et al. [56]. Colombo et al. describe an engineering change in the form of 7 different features as displayed below in Figure 13.

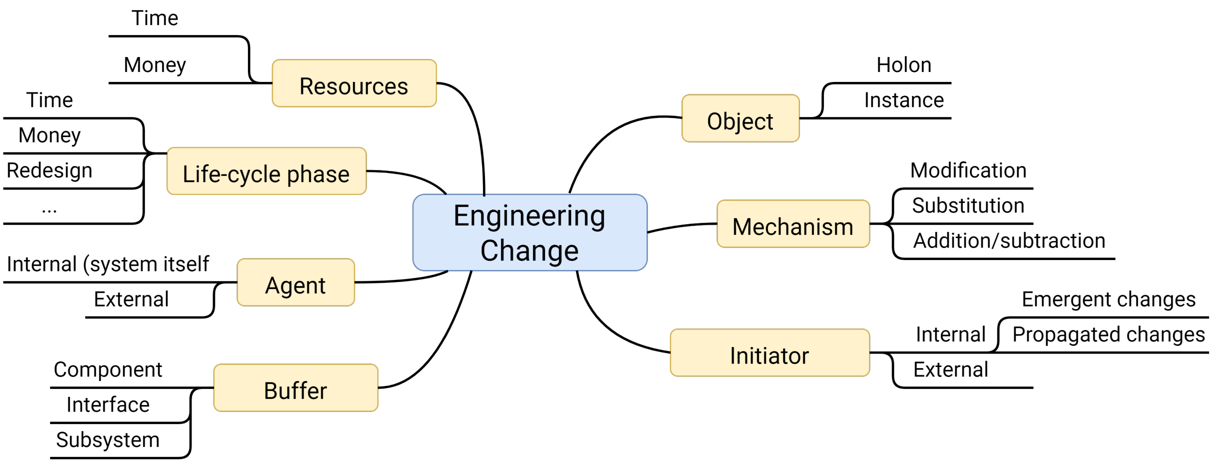


Figure 13: Change features graph [56].

Starting with the change-Resources for change, being money and time. Then the change-Life-cycle phase, which describes where in the lifecycle a change occurs. For example during design, utilization (use) phase or redesign (after-use) phase. Similar to the model of Ross et al., it consists of a change-Agent which could be either internal or external. The change-buffer (absorber)[57], which can be described as a component, interface or subsystem. This is a part of the system that can be modified without generating further changes.

Then the change-Object, which can be a holon (system representative) or instance (the actual system). This can be described using the following example. When a change is made during the design phase, so no physical system has been built yet, a change is made to a holon. When a change is made during the operation phase, a literal change to the physical system must be made. Which is called a change to the instance. The change-Mechanism is also described by Ross as the path form one state to the other, see Table 9. Colombo et al. have identified three change-mechanisms: modification (a change in components or interface parameters), substitution and addition/removal. The initiator consists of internal and external changes. Where internal changes is further divided into emergent and propagated changes. Table 10 below describes further what the change-Initiator is about.

Table 10: A few examples that show that change can be initiated either external or internal to the technical system.

Change type	**Initiator**	**Examples**
Initiated change	Reason external to the technical system.	Change in requirements Market shifts Innovations
Emergent change	Reason internal to the technical system	Ambiguous communication Errors in design Defects Wear Inadequate design processes, methods or tools
Propagated change	Undesired modifications due to other changes inside the system.	Due to a change in one requirement, a second requirement also has to change.

Changeability and other -ilities

Other -ilities that are likewise to changeability might be used to describe the same effect. To keep them apart, a summary of all -ilities and their definitions is given below.

Table 11: Definitions of other -ilities.

Adaptability Internal change Ross (2007)[58]	A LF becomes more adaptable if either the cost of change are lowered or the cost threshold is increased. An example of adaptability is that a professor can repair machine with some manual setting changes.
Flexibility External change Abele (2019)[4] and Ross (2007)[58]	Flexibility allows a rapid planned conversion of the factory environment within trainings. An example of flexibility is that a machine repairs itself with a software update.
Reconfigurability Sullivan (2018)[59]	The ability to change components arrangement and links reversibly.
Extensibility Weck et al. (2012)[60] Colombo et al. (2016)[56]	To accommodate new features after design. Allows systems to fulfill new functions or new sets of functions.
Scalability Ross (2007)[58]	A scalable change is a change from a machine type with a certain production capacity, to a machine type with a better production capacity. An LF is considered scalable if the cost for change is acceptable.
Modifiability / modularity Ross (2007)[58]	Modular design is that the cost of additional modules is relatively low. Thereby increasing the likelihood that the cost for change is acceptable.
Value Robustness Ross (2007)[58]	A robust learning factory preserves its value for stakeholders across various future scenario's. This could either be one system option which performs sufficient in two different scenarios. Or it could mean that you can change your system without a lot of cost from one option to the other, when a scenario is changed.
Transformability Brunoe (2019)[61]	The manufacturing system's ability to change significantly from producing one product type to an entirely different product type.
Agility Colombo (2016)[56] Sullivan (2018)[59]	Ability to change quickly. The only *ility* that does not concern monetary expenditures. Agility designates the ability of a system to be changed in an acceptable amount of time.

Method to describe change

Now that each -ility is defined, it is possible to describe change within the domain of manufacturing. Colombo et al. have defined a method to do this easily by taking 4 basic steps, see Figure 14.

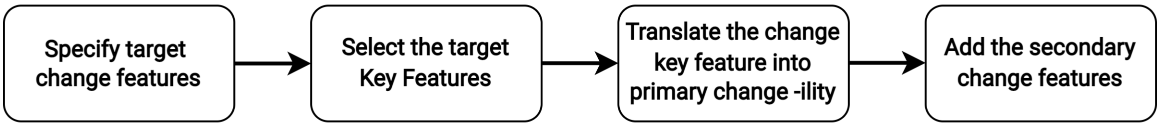


Figure 14: The 4-step method to describe a change situation [56].

Step 1: Specify the target change features.
Stakeholders need to specify what kind of change they want to ease with the change ility. The seven features of engineering (Figure 15) allow the stakeholders to orient across the different dimensions of a change.

Step 2: Select the target Key Features.
The key features and their primary change -ility are shown in Figure 15.

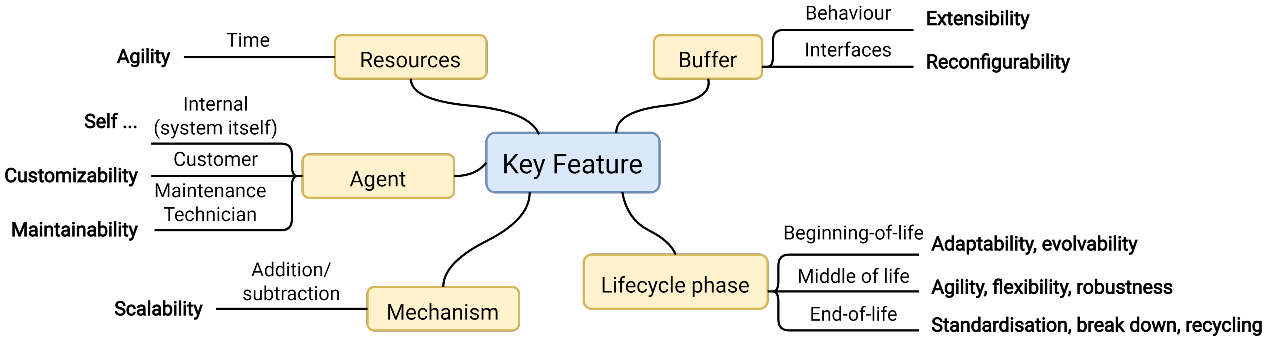


Figure 15: The key features and corresponding primary change -ility.[56]

Step 3: Translate the change key feature into primary change -ility.

Step 4: Add the secondary change features.
To further remove ambiguity and wrong use of changability features and/or -ilities, Cascini et al made a table to couple expressions to the right secondary feature and/or ility, see Table 12 page 30.

Table 12: Standard expressions used to describe a change situation.

Secondary Features	**Standard Expression**	**Name (-ility)**
Buffers	"thanks to changeable..."	Interfaces/components/Subsystems
Lifecycle phase	"during"	Design/Utilization/ Redesign phase
Mechanism	"via"	Modification/Substitution/ Addition/Removal
Agent	"self-" or "provided by"	Customer/Technician/Designer/...
Initiator	"to deal with changes from..."	The system itself/ Requirements/Market/...
Resources	"limiting..." "Agile" (for time) or	... consumption

3.6.2 Describing change in Learning Factories

In the section above, the method to describe change situations is defined. In this section some examples are given that can be applied specifically to change situations within a Learning Factory.

Example 1: To increase the Learning Factory lifespan, it must be able to cope with changes during the utilization phase. An example why change can be initiated is a change to the Learning Subject requirements. This change can then be described by the following sentence:

"*Adaptability* of the Learning Factory by *modification* of some components, to deal with *a change in requirements for the Learning Paths of students* during *the utilization phase.*"

Here the primary change feature is adaptability. The mechanism is "modification". This is activated by the change agent (external initiator) "change in requirements". The lifecycle phase is "the utilization phase".

Example 2: To make sure that the Learning factory is able to provide teaching of multiple learning paths, changes must be made by the instructor to certain equipment or the floor plan. A sentence that can describe this is as follows:

"*Agile Reconfigurability* of the Learning Factory during *the utilization phase* by *addition/removal/relocating* of equipment to deal with *regular changes in Learning Path demands.*"

Here, the primary change feature is "reconfigurability". The mechanism is "addition/removal/relocating". The change initiator is the "changing demand of learning paths. The lifecycle phase is "the utilization phase". "Agile" indicates the resource is time. The buffer is "the equipment and corresponding interfaces". The change agent, the person that provides the change, is specified in the text above and is the "instructor".

Example 3: After three years, a machine in the Learning Factory does not work anymore due to wear. A technician must repair this.

“A *maintainable* Learning Factory that can be repaired by a *Technician* to deal with *defects or damage by wear*.”

The key feature is ”maintainability”. The change agent is ”the technician” and the resource is time and money because he/she gets paid per hour. The initiators are defects and wear.

The value of changeability in manufacturing
Due to faster changing customer demand, the rise of customer-specific products and shorter product lifecycles, the requirements for manufacturing systems become increasingly complex. This evolution of manufacturing systems has been To cope with the new flexible market needs, new innovative technologies and solutions for manufacturing must be developed. A promising part of the solution lies in changeable manufacturing [25].

Changeability in manufacturing has many benefits. It allows you to produce a wider range of products with less space and costs. For example, by keeping parts of a production line the same and only changing a few key machines,see section 3.6.3). Also, if tools or equipment become more technologically advanced, parts of a production process could be applicable for change. Especially if you incorporate expected changes into the development process of a production line, see Section 3.6.4. Therefore, by incorporating changeability, the stakeholder value is maintained and kept high throughout the systems lifecycle [59].

When is changeability applicable?
Fricke and Schulz [45][44], have identified the core principles when changeability is applicable in manufacturing. These principles are listed below:
• The architecture is used for different products with a common basic set of attributes .
• The system has a stable core functionality but variability in secondary functions and/or external styling.
• The system has a long lifecycle with fast cycle times of implemented technologies driving major quality attributes (i.e., functionality, performance, reliability, etc.).
• The architecture and system are subject to a dynamic (that is, rapidly growing and strongly changing) marketplace with varying customer base and strong competition.
• The architecture and system are highly interconnected with other systems sharing their operational context.
• The system requires high deployment and maintenance costs.
• It is a complex and highly unprecedented system, with unknown market.

When is changeability not applicable:
Incorporating changeability into a system architecture may not be cost efficient for systems, which
• are highly expedient, short life systems without needed product variety,
• are highly precedent systems in slowly changing markets and no customer need variety,
• are insensitive to change over time,
• are developed for ultrahigh performance markets with no performance loss allowables.

3.6.3 Modularity types

Change could be initiated due to innovation in manufacturing techniques, other equipment,for which a quick reactive change of the factory is required. Modularity allows the factory setup to be changed and therefore enables a large amount of LSs. Not just now, but also in the future. Therefore, a modular LF is important to continuously provide high value towards the stakeholders. Fricke and Schulz [45] have distinguished six types of modularity. Besides a written explanation below, they are also graphically shown in Figure 16. A modular LF can be organized using one or a combination of these modularity types.

a) **Component Sharing modularity**
From an LF perspective, this works by having a single component or module that is kept within different factory floor plans.

b) **Component Swapping modularity**
From an LF perspective, this works by having a basic factory floor plan that has one varying component at a time.

c) **Fabricate to Fit modularity**
From an LF perspective, this works by having one or multiple components within the factory floor plan that are scalable.

d) **Mix modularity**
From an LF perspective, this works by having one basic factory floor plan that has multiple varying components at a time and they are not scalable.

e) **Bus modularity**
From an LF perspective, this works by having one basic factory floor plan that allows addition of one or multiple varying components. Each component has a standardized interface to position it correctly on the factory floor.

f) **Sectional modularity**
From an LF perspective, this works by having multiple varying components that have standardized interfaces. They are not limited to certain places in the factory and can be attached and detached to other components anywhere in the factory.

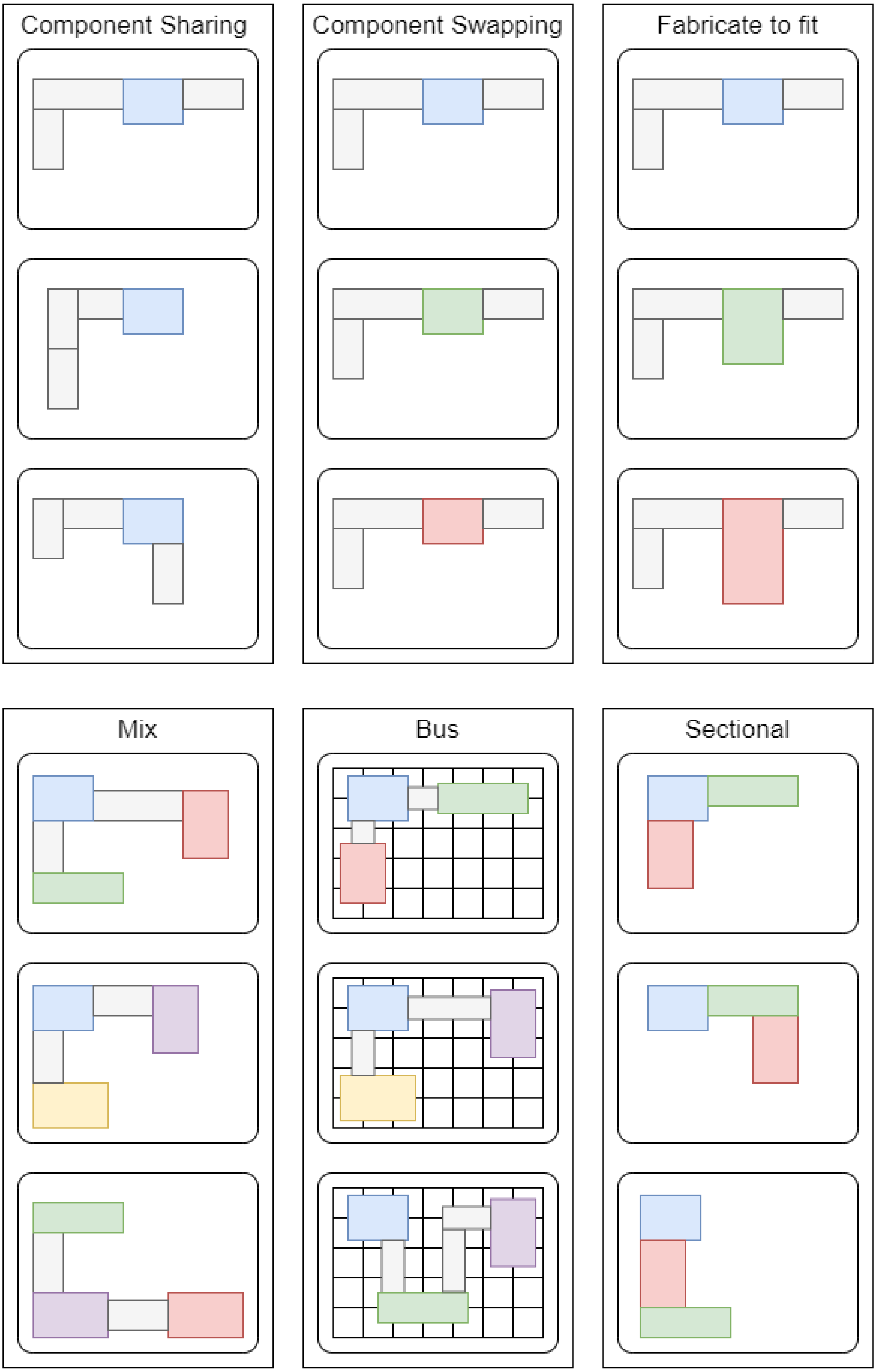


Figure 16: The six modularity types.

3.6.4 Interoperability

Interoperability is used to describe how each of the systems/equipment within the Learning Factory is connected and how that affects the modularity. To properly describe interoperability, understanding the relationship between lower level system -ilities is critical, as expressed by Fricke and Schulz[45]. The relationships and justifications expressed below aim to help support understanding the potential value implications for a learning factory.

Integratability:
"*Applying generic, open, or common/consistent interfaces.*"[45]
As changes occur you might need to move the equipment or change the configuration of the factory. By taking integratability/integration into account with components or connectors its easier to relocate equipment. Another example could be, that all equipment uses the same standardized data output format. This way, data analysis is easy and continuous, even when equipment is swapped. Standardized procurement towards suppliers, ensures more efficient ordering and streamlines warehouse management.

Autonomy:
"*Objects, which are capable of providing basic functionality necessary to ensure their independence from the embedding systems.*"[45]
In an LF this is useful when you want a system to operate on its own independently of the Learning Factory floor plan. An example of this can be an Automatic Guided Vehicle (AGV), that does not necessarily follow a predefined path, but autonomously takes the shortest route and stops automatically when encountering a human.

Non-hierarchical integration:
"*Linking units across the total system, with no respect to any type of modularity or encapsulation.*"[45]
An LF usage example could be cloud storage of data. As such, you can get any information of any machine with less effort.

Decentralization:
"*It strengthens the capability of the system to rapidly adapt itself towards its environment and to respond autonomously to changing requirements*"[45]
An LF example could be that certain functions of equipment are uncoupled, such that easy switching is possible. For example the functionality of a pick-and-place robot. You can keep this attached to a milling machine, to automatically pick up raw material and put it into the machine. But if you have an independent pick and place robot, you can also use it for other tasks as well.

Redundancy:
"*Enables capacity, functionality, and performance options as well as fault-tolerance.*"[45]
An LF example could be that you install fail-safes into machines, such that any student can use it. However this limits the range of the machines performance.

3.7 Key factors to extend the value

As described in Section 3.2.1, major drawbacks of conventional learning factories are the high investment costs, static (not changeable) approach towards introducing new learning subjects/machines, difficulty to scale towards dynamic user needs and the lack of mobility. The literature suggests that these problems can be managed through the use of changeability. Within this context, modular design that is interoperable, independent of types of equipment, is a principal property to preserving value.

Recognizing that changeability is not suitable for every possible learning factory, it is important to reflect on the limitations of changeability. Therefore below, each limitation, listed in Section 3.6.2, is mentioned and followed by a proposed LF requirement:

Incorporating changeability into a system architecture may not be cost efficient for systems, which

• *are highly expedient, short life systems without needed product variety.*
This means that changeability is not applicable if the system is build quickly, not durable and for specific purposes only. Therefore the objective is that the LF and a variety of manufactured products adds as much value to the stakeholders as possible, both in knowledge and materialistically.

• *are highly precedent systems in slowly changing markets and no customer need variety.*
Due to developments in industry 4.0, more applications are entering the market with a faster rate. The learning factory should therefore be able to cover a broad range of Learning Subjects.

• *are insensitive to change over time.*
The LF will be highly sensitive to change over time. By combining modularity and interoperability in the LF design, it allows for quick changes of equipment. This results in a low floor space occupation while keeping the sensitivity to change low. Depending on the available floor space, it may also allow for two learning factories, which has the advantage that one can still be operated while the other is being reconfigured. This also lowers the sensitivity to change over time.

• *are developed for ultrahigh performance markets with no performance loss allowable.*
It is not expected that the company produces for ultrahigh performance markets with no performance loss allowable. Therefore a key requirement is that the Educational Product is manufacturable, such that the LF is able to produce it to a reasonable quality with reasonable equipment.

4 Learning Factory Configuration Tool

As concluded in Section 3.7 there are multiple factors to implement when an extended value of the learning factory must be achieved. Up till now, a lot is theoretically determined. Key factors are changeability through modularity and interoperability. And requirements for production technology are to enable a broad range of Learning Subjects and Educational Products, whilst maintaining a small space using reasonable equipment.

In reality it is difficult and time consuming to keep an overview of all important factors every time a change of the factory is required. Therefore in this Section, the literature research is converted into a Learning Factory Configuration Tool (LFCT). The tool should help the user with indicating the right equipment for the right LSs and EPs.

To determine what technology is required in the LF a large comprehensive study is done on three factors, the LSs that must be offered, the EPs to accommodate the LSs and the required equipment. Here a problem arises, as each factor requires information of the other two. To clarify this problem, a circularity diagram is shown in Figure 17.

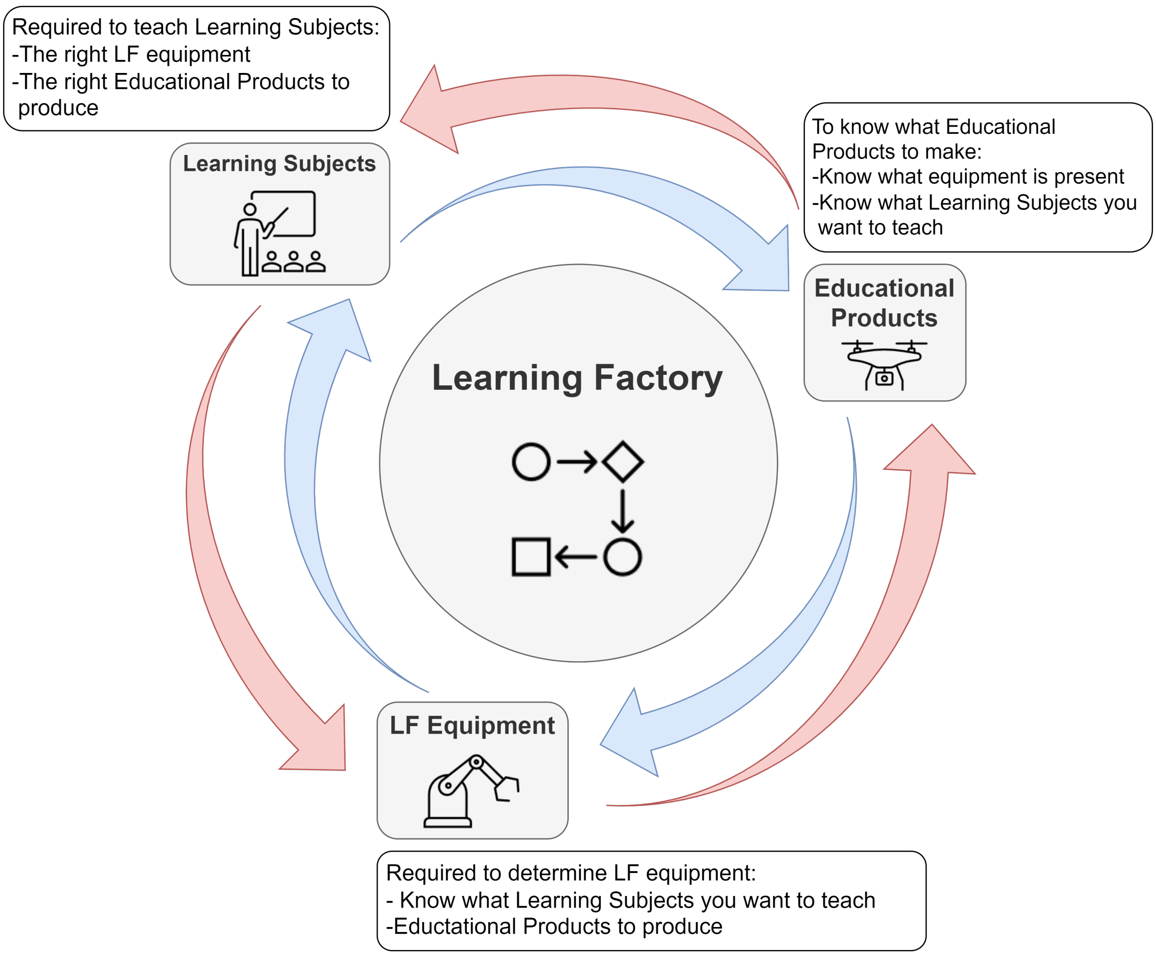


Figure 17: Circularity between Learning Subjects, Educational Products and available LF equipment

4.1 Equipment Selection

As explained on the previous page, a circularity problem occurs when having to select equipment for the LF. Therefore, a two-way approach is chosen, of which the roadmap is shown in Figure 18. In Section 4.1.1, the equipment is selected based on the product that is manufactured. In Section 4.1.4, the equipment is selected based on the Learning Subjects that must be offered. The result of these studies is combined into the LFCT. This is done, by determining for each type of equipment, if it is required for either an LS or an EP. Then the EPs are coupled to the right LSs. As such the EP, determines the LSs and accordingly also the required equipment. This will be further explained and demonstrated in Section 4.3.

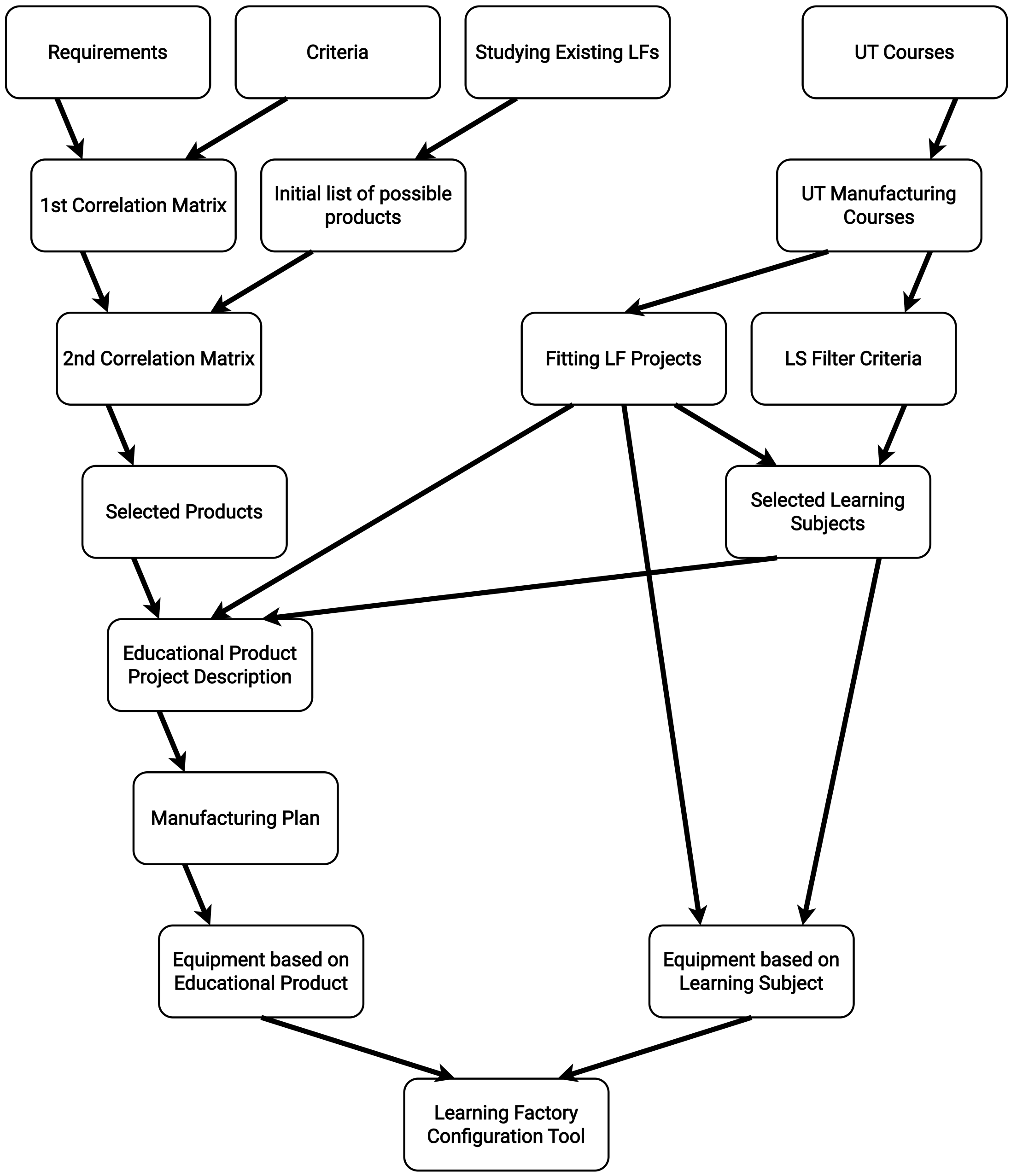


Figure 18: The method used to determine what equipment is required in the Learning Factory.

4.1.1 Selecting Educational Products

One way of defining an Educational Product is by examining EPs from existing LFs. The other way is by looking into the Learning Courses, Subjects and Paths and related LF applications. In the end both methods are used and combined, like shown in Figure 18.

Step 1: Investigating existing LFs.
To begin, an overview has been made of the LFs summarized in the book of Abele et al. [4]. In total 31 learning factories were analysed and compared in Table 13. The first two columns show the name and location of the LF, the third column the size in square meters, the fourth column, the EPs that are made and the last column contains important details on manufacturing and the offered LSs. The overview obtained by this investigation strengthened the understanding of EP possibilities with a certain LF size. It also gave insight in the combination between EP and LSs. Colour coding is done according to the possible LF size. More information on that follows in Section 4.3.2.

Table 13: Overview of 31 existing Learning Factories.[4]

Name	City	m^2	Product	Important details
Integrated LF	Bochum	N/A	Percussion drilling machine	To improve collaboration during product development
Teaching Factory	Patras	N/A	N/A	Non-geographically anchored learning environment
MAN LF	Berlin	45 / 50	Integrally geared compressor	Disassemble, maintenance (fix or improve parts), assembly
LF for Electronics production	Nürnberg	200 / 810	PCB / MID / Power Electronic Component / Opto-MID	SMT production / Printed Electronics and Optics / Power Electronics / 3D-MID technology
MPS, iCIM, CP Factory	/	2 to 50	Single-acting cylinder / micro-controller / deskset / electronic device	Reusable model products
MPS Lernplatform	Sindelfingen	3000	Various products (for ex.: roof control units / sun visors / covers / floor mats / room tears / assembly of small model cars etc.)	Actually usable products
IFA learning factory	Hannover	2000	Helicopter and components	Changeable / Factory planning / Lean production / PPC
LPS LF	Bochum	1800	Bottle cap / bottle cap holder / various make-to-order products	Complete value stream / individualization of products possible
DFA demonstration factory	Aachen	1600	E-GO-kart / body of E-LIFE car	Complete production and assembly of E-GO-Kart / welding of E-life body
Pilot Factory Industrie 4.0	Wien	900	Custom FDM 3D printer	Batch size 1 process / AGVs / Co-bots
E-drive center	Nürnberg	867	Electric motors	various measuring methods for magnetic fields
ETA factory	Darmstadt	810	Control plate hydraulic pump / gear-shaft combination	Energy efficiency and flexibility
ESB logistics learning center	Reutlingen	700	City scooter and accesoires	collaborative design/engineering/visualization and simulation with cloud software
VPS center of the Production Academy	München	600	Engines (3/4 cylinder, petrol and diesel)	Lean production / Low-Cost Intelligent Automation (LCIA) / Augmented Reality / Product disassembled and returned to lifecycle
LF for Innovation, Manufacturing and Cooperation	Heillbronn	570	Desk Wind turbine / Vacuum Engine / Pop pop boat / multi-purpose office tool / mendocino motor / sand pendulum / connect four 3D / Lighthouse	Change product every semester / Automated small parts warehouse with AGV
Process LF CiP	Darmstadt	500	Pneumatic cylinder / Electric gear drive	High volume production which can be partly disassembled and reused / High mix assembly of which all parts can be disassembled and reused
DIE Lernfabrik	Braunschweig	450	Divers	Energy and resource efficiency
LEAN-factory	Berlin	400	Pharmaceutical Tablets (bottled/blistered)	Lean management / continious replicated pharmaceutical production
Learning Factory aIE	Stuttgart	350	Desk tool set	FESTO manufacturing modules
LMS Factory	Patras	300	Radio-controlled car / Gearbox /	In final step, product performs dynamic tests and quality is examined
Smart Mini-Factory	Bolzano	250	Pneumatic Cylinder, Pneumatic Impact Wrench	3D virtual data model of het lab / multistage connected by Co-Bots and Robots
FESTO learning factory	Scharnhausen	220	Pneumatic valves / valve terminals	workplace-oriented trainings
iFactory	Windsor	200	Family of deskset / family of belt tensioner	modular and reconfigurable / automatic storage and retrieval system (ASRS)
Learning and innovation factory	Wien	200	Slot car	Product and process planning / optimization and assembly / test design on race track
Learning Factory Global Production	Karlsruhe	200	Electric drive	Research in the context of global production
Smart Factory	Kaiserslautern	200	Various products (for ex.: customized business card holder)	Creates and implements innovative factory systems (industry 4.0: RFID tracking / flexible transport / augmented reality etc.)
LF für schlanke Produktion	München	150	Gear box	lean philosophy and methods / compete in minimizing production costs of unsatisfactory starting situation
MTA SZTAKI LF	Gÿor	150	recyclable dummy workpieces (3d printed)	3D printed parts -¿ recyclable / Human robot collaboration
LF für vernetzte produktion	Augsburg	91	Remote-controlled cars	Digitalization / Paperless production
AutFab	Darmstadt	50	Automatic assembly of relais	6 axis industrial robot / automatic optical inspection
Smart Factory MTA SZTAKI	Budapest	30	reusable identical workpieces with recyclable cardboard inserts	Reusable and recyclable parts / Product tracking using NFC tag

Step 2: Setting up product requirements and selection criteria.
The product requirements and characteristics, which are listed in Table 14, are used to determine which product is the most important. These requirements and criteria are based of experience, validated in Sections 3.6 and 3.7 and supported by UT faculty. This is not intended to be a complete and comprehensive set of requirements and criteria, it is rather a initial set of considerations to help facilitate the first range of EPs for the LF. It is suggested that multiple actors (instructors, students, teaching staff etc.) take part in an open discussion, when establishing the criteria in the future.

Table 14: EP requirements and criteria.

	Product requirements:	**Reasoning**
1	Value adding	The objective is that the LF and its EPs, add as much value to the stakeholders as possible, both in knowledge and materialistically.
2	Broad LS coverage	The objective is to be able to teach as many LSs as possible.
3	Manufacturing facility size	The objective is to strive for the smallest area possible or a fixed amount of square meters.
4	Manufacturable	The EP must be manufacturable with the available equipment.
	Selection Criteria:	**Reasoning**
1	Resource availability	If the required resources are plenty available, less costs are made.
2	Volume that needs to be produced	Depending on the situation, it must be possible that a varying amount of parts can be manufactured.
3	Recycleability	It is important that the produced part can be disassembled or returned to the cycle in a later stage.
4	Amount of components	More components result in more production steps.
5	Assembly steps	If more assembly steps are needed, it potentially leads to more assembly locations which results in a larger LF floor.
6	Complexity of components	If many components are also complex, the production process can become very slow and also the LF layout more complex.
7	Part variability	Options to vary, gives insight in producing for mass customization.
8	Size of product	Large product require more inventory space, but it also depends on batch size. (eg. batch size one)
9	Individualization possibilities	Adds to criteria 6, a personal product can be kept by the maker.
10	Availability of technology	The parts and components that will be used in the EP, must be able to be sourced either locally/nationally or within the EU trading block.
11	Affordability	The EP that is produced must be reasonably affordable.

Step 3: Determine what the most important criteria are.
A correlation matrix has been made to determine what criteria weigh the most for the Educational Product selection. Then if an EP approves to many criteria, it also approves to the basic EP requirements. The correlation matrix is shown in Figure 19. The triangle on the top shows how different criteria are correlated, for example the strong positive correlation (++) between the 'amount of components' and 'assembly steps'. If one of these increases, the other does that as well. On the other hand it can also strongly negatively correlate (▾), like the 'complexity of components' and the 'affordability'. This shows that it is impossible to score good on every criterion and sometimes trade-offs need to be made. Then the top row, which shows for each criterion if the goal is to minimize (▾) or to maximize (▴) the performance on that criterion or to hit a certain target (**x**). The matrix between the requirements and the criteria allows the user to describe if a criterion has a weak (▴), moderate (**O**) or strong (Θ) relationship. This determines the weight for each criterion. As you can see, 'complexity of components' and 'part variability' have relationships with all requirements. With two strong relationships at hand, they are the most important criteria and each score a relative weight of 13.3 out of 100. Note that, similar to establishing the criteria, also the grading within the correlation matrix must be done using an open discussion with the actors mentioned before.

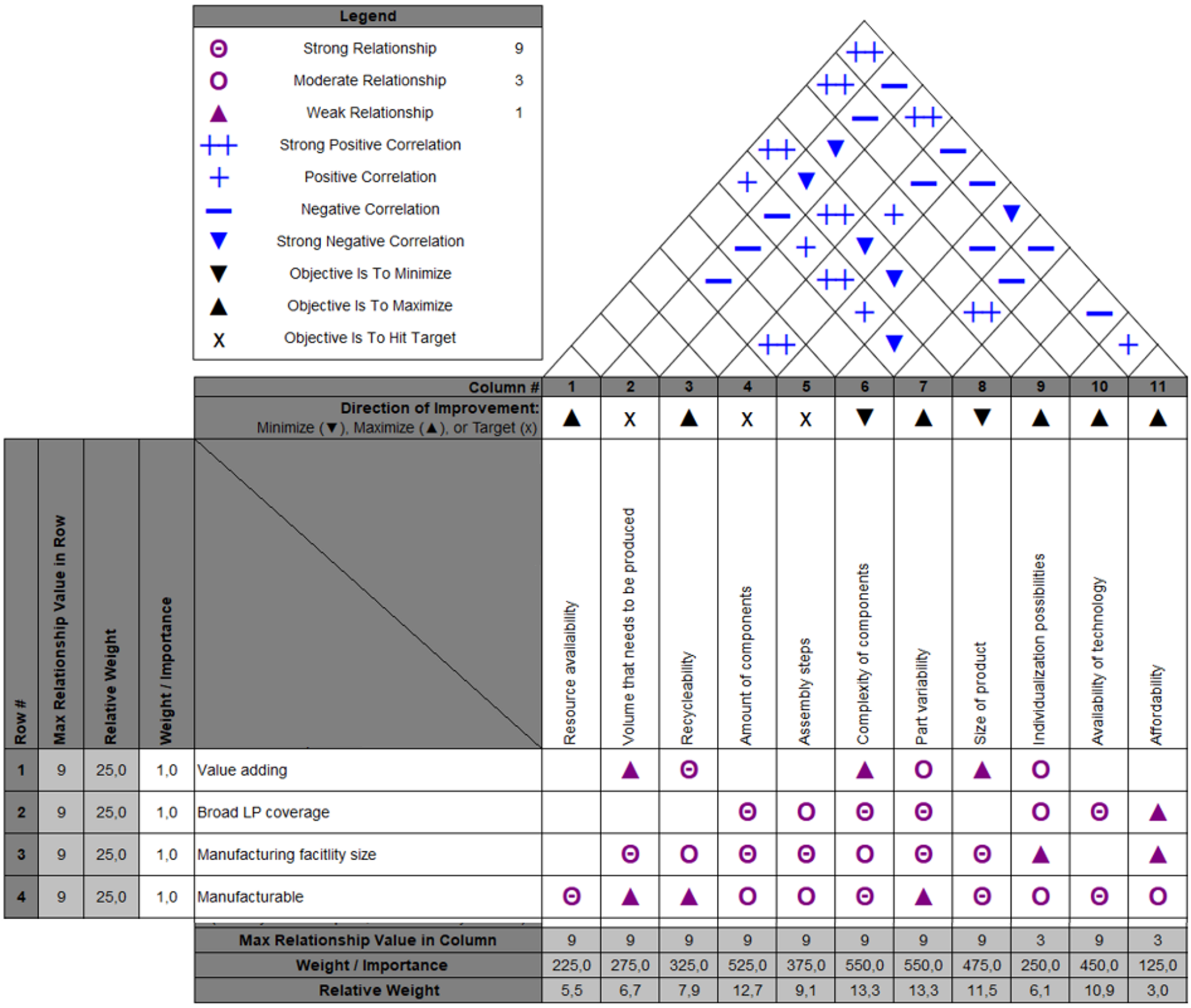


Figure 19: Requirements and criteria correlation matrix.

Step 4: Determine the Educational Product based on the criteria.
Following up on the matrix from step 3, the EPs were given a score for each of the criteria. This second correlation matrix is shown in Figure 20. For this step the upper correlation triangle and first row are removed. Now only the matrix between the criteria on the left and the eleven products at the top is important. By analyzing the LFs from Table 13 and slightly more focused on the smaller factories, eleven products were assumed suitable for the learning factory. Divided by the thick black line, two categories have been rated: actual products and product types. The criterion are coupled to each product, by filling in a score of weak (▲), moderate (**O**) or strong (Θ). Again on the bottom rows it shows how each product performs and here it can be seen that a few EPs stand out, see Table 15.

Table 15: Educational Products and their corresponding (relative) Weight.

Educational Product	**Weight / Importance**	**Relative weight**
Card Holder	692,7	12,5
Drone	525,5	10.3
Mechanical Component	622,4	11,2
Topology Optimized part	744,8	13,4

Row #	Max Relationship Value in Row	Relative Weight	Weight / Importance		Electric cross motor	Card holder	Pneumatic cylinder	Custom 3D printer	Drone	Car	Mechanical components	Hydraulic components	Electrical components	Housing / large parts	Topology optimized part
1	9	5,5	225,0	Resource availaibility	▲	Θ	O	O	▲	▲	Θ	Θ	O	Θ	Θ
2	9	6,7	275,0	Volume that needs to be produced	O	Θ	O	▲	O	▲	O	O	O	▲	Θ
3	9	7,9	325,0	Recycleability	O	O	O	O	O	▲	O	O	▲	O	Θ
4	9	12,7	525,0	Amount of components	O	Θ	O	O	Θ	▲	Θ	Θ	Θ	Θ	Θ
5	9	9,1	375,0	Assembly steps	O	Θ	O	▲	O	▲	O	Θ	O	Θ	Θ
6	9	13,3	550,0	Complexity of components	O	O	O	Θ	Θ	Θ	Θ	▲	O	Θ	Θ
7	9	13,3	550,0	Part variability	▲	O	▲	Θ	Θ	Θ	Θ	Θ	Θ	▲	▲
8	9	11,5	475,0	Size of product	O	Θ	Θ	O	O	▲	O	O	Θ	▲	Θ
9	9	6,1	250,0	Individualization possibilities	O	Θ	▲	Θ	O	O	▲	▲	▲	Θ	▲
10	9	10,9	450,0	Availability of technology	O	Θ	O	O	O	O	Θ	O	O	▲	Θ
11	9	3,0	125,0	Affordability	O	Θ	O	▲	O	▲	O	O	Θ	▲	Θ
				Max Relationship Value in Column	3	9	9	9	9	9	9	9	9	9	9
				Weight / Importance	262,4	692,7	330,3	458,8	572,7	347,3	622,4	504,8	515,8	489,1	744,8
				Relative Weight	4,7	12,5	6,0	8,3	10,3	6,3	11,2	9,1	9,3	8,8	13,4

Figure 20: Criteria and EP correlation matrix.

As 'mechanical component' is not very concrete, it is determined to change this into a gearbox design and assembly project. As shown in Table 13, gearbox type of products are already made in existing LFs too. The 'Topology Optimized part' is combined with a custom 3D printer. That is because this type of product can have many variations in terms of dimensions and working principles. So there is a lot of variability possible. Secondly, the structural parts are small and have clear mechanical functionalities, which should result into not too complex products. Both are very important criteria as described in Step 3.

4.1.2 Project Descriptions for Educational Products

Now that the Educational Products are selected, equipment must be determined for manufacturing. For this purpose a project description is written first, followed by a manufacturing plan. While writing this thesis, information had to be gathered and used on multiple fronts simultaneously. Therefore, the project descriptions are inspired by the selected EPs form Section 4.1.1, from the LSs selected in Table 22 in Section 4.1.4 and fitting LS projects from Table 24 in Section 4.1.4. The diagram in Figure 21 is made, to clarify the method described above.

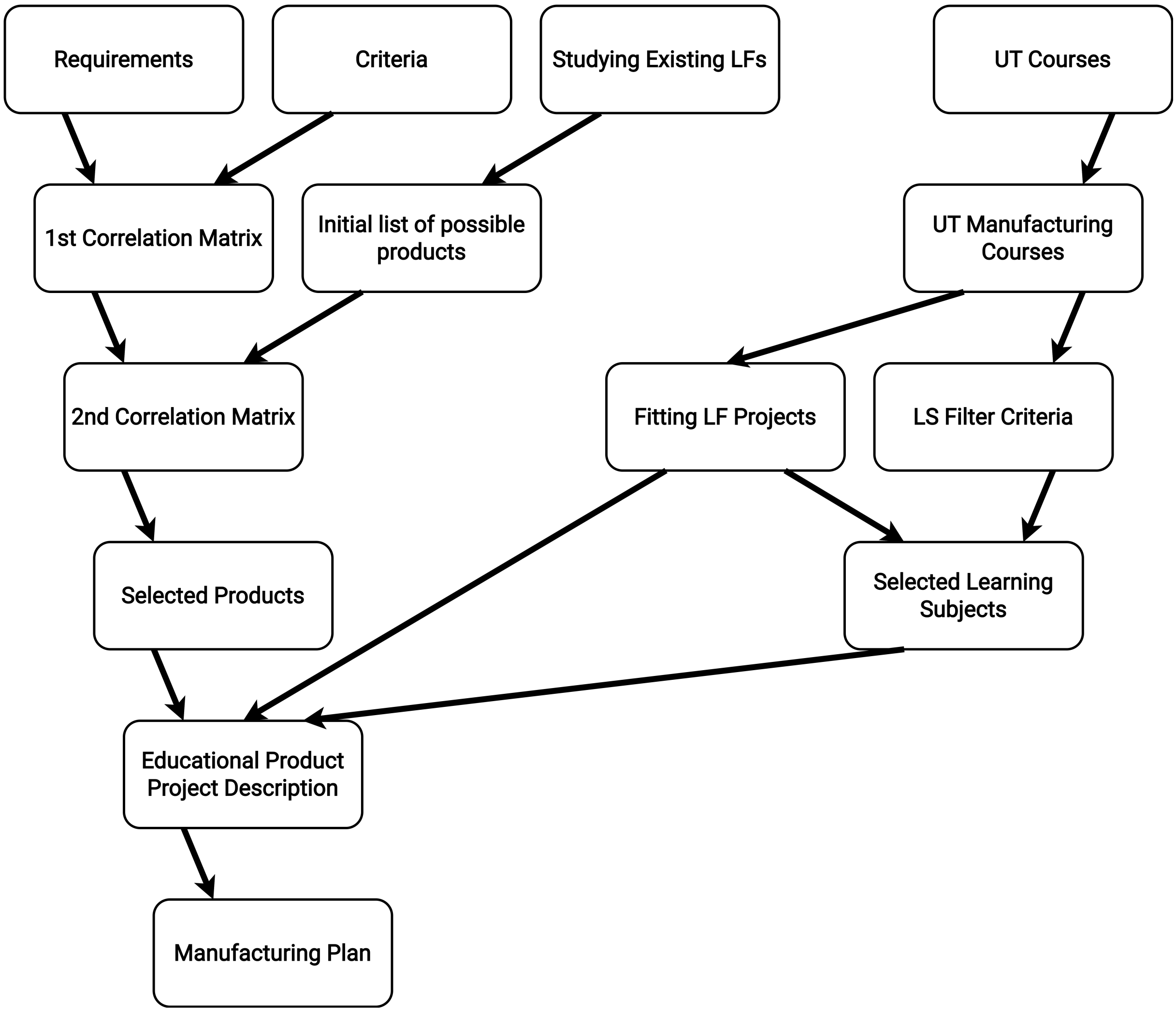


Figure 21: Diagram showing the method used to determine the project descriptions for Eucational Products.

EP1: Card holder assembly

Design and assemble a personalized card holder, see Figure 22. It consists of a metal casing, card push mechanism, varying covers, buttons and customizable colours.
Mass customization fits the Industry 4.0 scope and can be achieved using the following variables:
- Amount of casings (amount of cards)
- Leather covers (texture and colour)
- Closing system (none or button or band)

Mass production is possible and card holder is a functional accessory for each student and employee of the UT.

Figure 22: A variety of Card Holders [62].

EP2: Topology optimized printer

Design and assemble a topology-optimized 3D printer, for example the one in Figure 23. An FDM (Fused Deposition Modeling) 3D printer can be a cartesian, delta, polar or SCARA (Selective Compliance Assembly Robot Arm) type.
Each type comes with different mechanical challenges to the connecting components. The assignment is to manufacture and overcome the mechanical challenges using topology optimization. The LF will be used to print the parts and assemble the 3D printer. Various performance tests will be done to validate the topology optimized solution.

Topology optimizations and 3D printing are examples of industry 4.0 applications.

After manufacturing a disassembly step is involved.

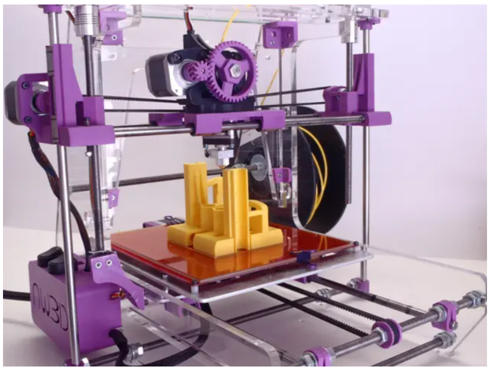


Figure 23: An example of a 3D printer with customized structural parts [63].

EP3: Gearbox assembly

A complex gearbox, for example shown in Figure 24, has to be assembled and consists of many production steps. The production process has to be improved to most efficiently make this gearbox.

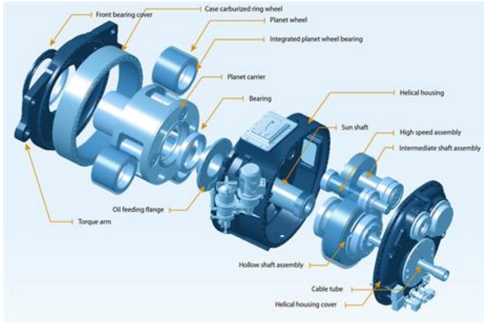


Figure 24: An example of a complex wind turbine gearbox [64].

Different lean and digital tools can be applied to increase the production efficiency. Automated systems can be used to transport parts from production step to production step.

After manufacturing a disassembly step is involved.

EP4: Gearbox design

A simple gearbox, like shown in Figure 25, has to be designed using a selection of different performance requirements. The gears, case and shafts should be designed for classic milling, turning, grinding or injection moulding. The bearings, screws and bolts are procured standard parts.

Figure 25: An example of a roughly designed custom gearbox [65].

Image processing techniques can be used to track the different custom objects through the factory. Automated systems can be used to transport parts from production step to production step.

After manufacturing a disassembly step is involved.

EP5: Drone assembly

A modular drone, like shown in Figure 26, has to be made using standardized components. The drone design and equipment selection are dependent on the project task. After manufacturing the drone, a control script must be written and calibrated, followed by performing a flight test.

Figure 26: An example of a small modular Drone [66].

To hold all the standardized parts and sensors, a custom frame must be designed. This frame should be designed for 3D printing, as it will be printed in the factory before assembly. Here, topology optimization can be used as well.

After manufacturing a disassembly step is involved.

4.1.3 Devising a Manufacturing Plan

Now that the project descriptions are known, a method must be found that helps determining what types of equipment are required to fulfill the project. For that purpose, a Manufacturing Plan (MP) is devised. An MP gives information on the required parts and factory equipment. The first step is to understand how a product is manufactured and what parts go into it. Then, write down a step by step guide on how to go from nothing to a finished product. By doing so, write down each part that goes into the process and what type of equipment would be required for performing a manufacturing step. At last state for each part is it procured or self made. Two examples of MP's are Table 16 and Table 17. The other MPs can be found in Appendix B.1.

Table 16: Manufacturing Plan: Card holder assembly

	Production steps:	**Required equipment:**
1.	Select aluminium case	Inventory space
2.	Select leather	Inventory space
3.	Engrave leather	Laser cutter
4.	Cut leather	Laser cutter
5.	Assemble case	Assembly station
6.	Knit button or elastic band to leather	Knitting machine
7.	Adhere leather to case	Glue
8.	Perform quality check	Quality station
	Parts	
	Procured:	**Self made:**
	Anodized aluminium case	Leather engraving
	Leather covers	
	Inner fabric that prevent cards falling out	
	Card push plastic	
	Card push spring	
	Elastic bands	

Table 17: Manufacturing Plan: Drone assembly

	Production steps:	**Required equipment:**
1.	Selection of required equipment	Inventory space
2.	Picking the equipment	Inventory space
3.	Frame design and production	3D printer or laser cutter
4.	Assemble the whole	Assembly station
5.	Calibrate the control system	Programming software
6.	Test the drone	Test environment
7.	Apply drone for the right project requirements	Test environment
	Parts	
	Procured:	**Self made:**
	Propellers	Drone frame/housing
	Motors	
	Vision cameras/sensors	
	Thermal cameras/sensors	
	Leakage cameras/sensors	
	Control Board	
	Battery	

4.1.4 Equipment based on Learning Subjects

As explained in Section 3.4, most existing learning factories enable to teach Lean or Industry 4.0 courses. Few LFs teach about additive manufacturing or sustainability. However, new LFs might require you to do so as well. Because the LF will be built on the campus of the University of Twente, it is also critical that it adds value to the courses given there. Therefore, this Section is about investigating what subjects the University of Twente offers and what the future trends in manufacturing technology are. The goal is to select at least two subjects related to Lean, two subjects related to Industry 4.0 and 6 other subjects related to manufacturing. To do this, a set of criteria is setup and listed below.

a) *Does it already require a existing infrastructure?*
It is important to know if a subject already uses existing infrastructure. If that is the case, it probably does not need the Learning Factory for the same goal or it at least has a lower priority. Chances are that the LF can support it, but the LF has a better value when supporting a subject which does not make use of existing infrastructure already.

b) *Are practical exercises used?*
If an LS uses practical exercises, it could very well be that the LF can support or improve that practical experience. It is expected that mostly simulation or calculation exercises are used. The LF environment can be used to test and validate the results of the simulation or calculation.

c) *Is it related to Lean or Industry 4.0?*
If the subject is related of Lean or Industry 4.0 it can probably be very well integrated into the factory. As the main focus of the LF is on Lean or Industry 4.0 applications.

d) *Are there LF possibilities?*
If the LS, does not use of existing infrastructure, it could still be that there are LF possibilities. It is therefore important to imagine for each subject how to incorporate it into an LF environment. This can help with selection later on.

The method for determination of important LSs is not fully comprehensive, but in accordance with the instructor, this can be used to potentially identify the courses that could benefit of an LF. The information of the courses will be gathered from the corresponding *Osiris*[67] pages. For future work, it is also important that stakeholders sit down and determine together what subjects are most important.

Step 1: Gather the courses related to manufacturing.
The University of Twente has seven mechanical engineering master tracks. Design and Manufacturing (D&M) is one of them and part of the Department of Design, Production and Management (DPM). The DPM department is responsible and main user of the Learning Factory. Therefore when selecting courses, first the D&M track is examined. A UT master track has Core courses and Elective courses. As such the search starts with the Core D&M courses, then the Elective D&M courses and at last courses form other master tracks. In total 29 LSs at the UT are offered that can be linked to manufacturing. These are listed in Table 18 and selected from *Course overview 2022-2023*[67]. Note that the courses here, as defined by the UT, are not Learning Courses as defined in Section 3.5. The difference is that, a course at the UT, is focused around one subject, which makes it function more like how LSs are defined in Section 3.4. A course at the LF, see Section 3.5, combines multiple LS into an overarching project that comes together and is given context by the EP from Section 4.1.2.

Table 18: University of Twente Mechanical Engineering master subjects list.

Core D&M master subjects:	**Source:**
3D printing	[46]
Design Production and Materials	[68]
Design of Production and Inventory systems (Lean)	[69]
Frontiers in Design and Manufacturing	[70]
Maintenance Engineering and Management	[71]
Manufacturing Facility Design	[72]
Modelling of Technical Design Process	[73]
Elective D&M master subjects:	
Adhesion and Bonding Technology	[74]
Biomechanics of Human Movement	[75]
Composites Forming	[76]
Computational Optimization	[77]
Cost Management and Engineering	[78]
Design for Additive Manufacturing	[47]
Design Principles for Robotics and Mechatronics Mechanisms	[79]
Governing Product Development	[80]
Lean Six Sigma Green Belt	[81]
Life-cycle Strategy	[82]
Multiscale Functional Materials for Engineering Application	[83]
Multiscale Mechanics	[84]
Simulation	[85]
Stochastic Models in Operations Management	[86]
Stochastic Models in Production and Logistics	[87]
Other ME master subjects:	
Machine Learning in Engineering	[88]
System Life-cycle Management	[89]
Automated Production Systems	[90]
Industrial Robotic Systems	[91]
Image Processing and Computer vision	[92]
Basics for Process Simulation	[93]
Process Equipment Design	[94]

Step 2: Research the Learning Subjects and Learning Paths of each manufacturing course.
Each of the 29 master courses of the University of Twente has been analyzed to find out which Learning Subjects and Learning Paths it contains. A section of this analysis is found in Table 19. The entire view of this table can be found in Appendix B.3.

Table 19: UT Course, Learning Subject and Path description.

Courses Core:	**LSs**	**LP's**	**Short LP's**
3D printing	3D printing, theory, application and state of the art 1 Basic Additive Manufacturing theory 2 AM economical aspects 3 Research on state of the art in AM	1. Know, Explain and compare individual AM processes from the range of additive manufacturing processes available. 2. Understanding the basic working principles, benefits and drawbacks, that apply to individual groups of AM processes. 3. Understand and explain what processing alternatives there are for certain material groups. 4. Understand, explain and use design rules for additive manufacturing. 5. Understand the economical aspects related to Additive manufacturing. 6. Explore the current state of the art related to Additive manufacturing.	1. Basic 7 Additive Manufacturing processes theory. 2. AM process distinction 3. AM materials understanding 4. AM design rules 5. AM economical Aspects 6. Research on state of the art in AM
Design Production and Materials	Composites, basic theory, design and manufacturing. 1. Basic continuous fibre-reinforced composite ply theory and calculations. 2. Laminate loading, deformation and failure analysis. 3. Design an object that is able to perform according to the requirements. 4. Choose manufacturing technology and strategy.	1. Derive the properties of a continuous fibre reinforced composite ply as a function of its constituents and their fractions. 2. Determine and analyse the stress – deformation relation of a continuous fibre reinforced composite ply for varying fibre orientation. 3. Derive and analyse the loading – deformation relation of a laminated plate. 4. Classify the way composite materials fail and quantify first-ply failure in a laminate. 5. Choose and advise on manufacturing technologies (for a given set of requirements on the part to be made). 6. Design a lay-up for plate- or cylinder-like composite structures given the loading requirements.	1. Basic theory continuous fibre reinforced composite plies. 2. Stress - deformation under varying fibre orientation. 3. Loading - deformation derivation and analysis. 4. Composite material failure classification. 5. Composite manufacturing technologies. 6. Design laminate according to the given load.
Design of Production and Inventory systems	1. Understand the basics of production system design, control and modelling, containing the topics. 2. Apply methods ,(mathematical) models and techniques with respect to the afore mentioned topics, to make design decisions concerning production and inventory systems.	1. The structure of production systems. 2. The behaviour of production systems. 3. The standard production system decision hierarchy. 4. Forecasting of market demands. 5. Long-range, medium-term and operational planning. 6. Production and inventory control systems. 7. Shop-floor design and operation. 8. Mathematical models and techniques that enable decision making on the LA's 1-7 above.	1. The structure of production systems. 2. The behaviour of production systems. 3. The standard production system decision hierarchy. 4. Forecasting of market demands. 5. Long-range, medium-term and operational planning. 6. Production and inventory control systems. 7. Shop-floor design and operation. 8. Mathematical models and techniques that enable decision making on the LP's 1-7 above.

Step 3: Filter courses based on selection criteria.
Table 21 shows a section of the selection process, further shown in Appendix B.4. After all subjects were rated, a selection of a top 10 was made using the criteria introduced above. If a primary criterion was met, the course was indicated with a red colour and automatically excluded. If a secondary criterion was met, the course was indicated with an orange colour, which implies that the subject has a *low priority* status. The primary and secondary filter criteria are shown in Table 20.

Table 20: LS Filter Criteria

Filter reason:	Result:
No information found	Automatically excluded
Nothing to do with LF	Automatically excluded
Not Industry 4.0 or Lean	Automatically excluded
It does already involve a lab	Low priority
The lab possibility is hard to involve	Low priority
The LF is not crucial to make the course better	Low priority

Table 21: Section of LS rating.

Modelling of Technical Design Process	No	Yes, a group assignment to analyze a production design and development process (DPPD).	Yes, both lean and industry 4.0	Yes, by including the LF constraints in the design process.
Elective DPM master subjects:	**1: Does it already require a existing infrastructure?**	**2: Are practical exercises used?**	**3: Is it part of Lean or Industry 4.0?**	**4: Are there LF possibilities?**
Adhesion and bonding technology	No	No, only conceptual	No	Yes, by applying various adhesion and bonding techniques in the assembly phase and see how that affects the production process
Biomechanics of human movement	Yes, a movement analysis lab	Yes, simulations of muscle mechanics on joints and gathering dynamic formulations from actual human movement data.	Yes, industry 4.0	Maybe testing human movement in an assembly process and see how a supporting robot can be designed based on the required mechanics of the human.
Composites forming	No	No, only a research assignment	Yes, industry 4.0	Yes, by applying various composite forming techniques and see how that affects a production process.
Computational optimization	*No information*	*No information*	*No information*	*No information*

Step 4: Finalize Learning Subject list.
Then, after these filters are applied, a selection of eleven subjects is left, as shown in Table 22. As can be seen, these subjects are all indicated green which means that none of the filter criteria of Table 20 applied. Here, it should be noted, that *Frontiers in DM* [70], is an open research assignment. So depending on the research direction, the LF is useful or not. Therefore, there are actually 10 selected LSs applicable for further equipment selection. These are described in Table 23 on the next page. The LSs that did not make to the final selection, are also listed and can be found in Appendix B.5.

Table 22: Selected Learning Subjects and possible LF incorporation.

Courses	**Criteria**			
Core DPM master subjects:	**1: Does it already require existing infrastructure?**	**2: Are practical exercises used?**	**3: Is it part of Lean or Industry 4.0?**	**4: Are there LF possibilities?**
Design of Production and Inventory systems	No	Calculation excercises	Yes, lean production	Yes, by designing or analyzing the LF on the logistics.
3D printing / Design for additive manufacturing	No	Simulation excercices are used	Yes, industry 4.0	Yes, seeing the practical side of having a 3d printer on your shop floor and how that affects the production line.
Frontiers in Design and Manufacturing	No	No, only a research assignment	Yes, industry 4.0	Yes, by exploring how new technologies could improve the LF.
Maintenance Engineering and Management	No	Yes, an assignment to perform various maintanence analysises. And guest lectures where analysises are applied.	Yes, lean production	Yes, by practically doing analysis on the existing LF.
Elective DPM master subjects:				
Lean six sigma green belt	No	A project about the analysis and improvement of a production process.	Yes, Lean	Yes, by using an actual production process that purposely has errors that can be improved.
Stochastic models in operations management	No	Yes, mathematical excercices.	Yes, industry 4.0	Yes, by using data from the factory to use in stochastic calculation models.
Stochastic models in production and logistics	No	Yes, mathematical excercices.	Yes, industry 4.0	Yes, by using data from the factory to use in stochastic calculation models.
Other ME master track subjects:				
Machine learning in engineering	No	Yes, some practical excercises to apply machine learning methods.	Yes, industry 4.0	Yes, by using data from the factory to use in machine learning models.
Automated production systems	No	Yes, an assignment to design a real-world automated production system.	Yes, industry 4.0	Yes, an assignment to change the existing Learning Factory in an automated production factory.
Industrial robotic systems	No	Yes, an assignment to design and program an automated industrial robot and corresponding sensors.	Yes industry 4.0	This could work very well with for example a Cobot in the LF.
Image processing and computer vision	No	Yes, an assignment to apply image processing and computer vision skills in Matlab image processing software.	Yes, industry 4.0	Yes, a project which involves image processing and tracking of objects throughout the factory.

Table 23: Final course list and corresponding LSs and possible LF incorporation

2 Lean Courses:	**Type:**	**Learning Subjects:**	**Possible LF incorporation:**
Lean six sigma green belt	Elective	Lean Six Sigma Green Belt	Yes, by using an actual production process that purposely has errors that can be improved.
Design of Production and Inventory systems	Core	1. Understand the basics of production system design, control and modelling on the topics mentioned as LP. 2. Apply methods ,(mathematical) models and techniques with respect to the LPs, to make design decisions concerning production and inventory systems.	Yes, by designing or analyzing the LF on the logistics.
2 industry 4.0 Courses:			
Industrial robotic systems	Other	Design automation by using industrial robot cells.	This could work well with for example a cobot in the LF.
Image processing and computer vision	Other	Image processing and computer vision, theory and application.	Yes, a project which involves image processing and tracking of objects throughout the factory.
6 DPM Courses:			
3D printing / design for additive manufacturing	Core	Info on state of the art in Design and Manufacturing	Yes, seeing the practical side of having a 3d printer on your shop floor and how that affects the production line.
Maintenance Engineering and Management	Core	Maintenance Engineering and Asset Management performance indicators, application and analysis tools.	Yes, by practically doing analysis on the existing LF.
Stochastic models in operations management	Elective	Stochastic models in operations management	Yes, by using data from the factory to use in stochastic calculation models.
Stochastic models in production and logistics	Elective	Stochastic models in production and logistics	Yes, by using data from the factory to use in stochastic calculation models.
Machine learning in engineering	Other	Machine Learning in Engineering	Yes, by using data from the factory to use in machine learning models.
Automated production systems	Other	Technical and engineering aspects of automated production systems.	Yes, an assignment to change the existing Learning Factory in an automated production factory.

Step 5: Exploration of Projects and corresponding equipment.
Now that the final 10 subjects are known, further exploration towards LF-fitting projects is done. Inspiration is taken from personal experience and gathering basic information about subjects online. Following up on that, the required types of equipment are determined. A section is shown in Table 24, the full table can be found in Appendix B.6. The information, known at this point, has also been used for specifying EP descriptions from Section 4.1.2 on page 43.

Table 24: Exploration of projects and corresponding equipment for each Learning Subject

Learning Subject	**Projects**	**Equipment/ required data**	**Comments**
5. 3D printing	1. Learning to design for 3D printing. Practically learn how various 3D print settings affect the process. (Speed, width, temperature etc.) 2. By actually having a part produced with a 3D printer and see how that affects the production process. 3. Learn how different materials affect the printing process and what is mechanically possibile for end products. 4. A project that is about improving a current part production, which is possible due to the rapid prototyping ability of a 3D printer.	Fused Deposition Modeling (FDM) printer. 3D printer enclosure Multiple nozzles with different sizes + extra nozzles and feeder tubes Automatic bed leveling sensor Filament rolls that differ in material, size and colour	Easy to use, many possibilities and not too expensive To be able to print ABS, it keeps the hot air inside and prevents ABS from warping. Also to prevent harmful fumes to spread around the printing area. For different widths For replacements due to wear Manual bed leveling is a time-consuming process To support many applications
6. Maintenance engineering and management	1. By practically doing analysis on the existing LF using wear and performance data of machines. 2. Check machine performance and use AR to do the right maintenance.	Wear rate of used tools Wear sensors for tools Wear rate of dynamically moving parts Wear sensors for dynamically moving parts Leakage sensors Thermal sensors Performance data QR code on each machine AR vision glasses	Wear rate for performing a production step Sensors that detect wear Wear rate for performing a production step Sensors that detect wear Sensors that detect gas/fluid leakages Sensors that detect thermal leakages Amount of times used, tells when to intervene Could be used by maintenance engineers. As every machine is different, AR could be used to do the right maintenance steps or fix all kinds or defects.

4.2 Equipment Selection Criteria

The required equipment is known, for both the EP and the LSs, see Sections 4.1.3 and 4.1.4. As such, a method must be designed to determine what model of the same type of equipment is the best.

For the selection of equipment, a few criteria are described and summarized in Table 25 on page 55. Each criterion has been given a weight percentage and score which is valuated below and approved in accordance with the instructor.

Technical difficulty for individual operations:
This has to do with the ability for new users to operate the equipment. Easy operation for students implies that with little or no explanation, an LF user can continue with his/her work. Medium difficulty would be that a factory employee has to give an explanation and demo beforehand. Very difficult would be if a training is required or a professional has to do it for the user, which lowers the understanding of the equipment in relation to the production process. Additionally, the personnel raises the operational costs significantly.

Size:
Size is an important criteria as that directly influences the layout of the factory and required amount of square meters. To simplify the selection process, the size is rated as fitting on a workstation, the size similar to a workstation and larger than a workstation. For a workstation the size is determined to be 1800x900 mm. Which is in accordance to the workstation located on the first row of the database in Table 26.

Costs:
Costs should also be considered in the decision. To distinguish the different types of equipment, cost is considered cheap when it is below € 1000, reasonable between € 1000 and € 3000, expensive between € 3000 and € 10.000 and very expensive above € 10.000. These values are chosen to distinguish between most types of small and medium size equipment. For larger equipment and heavy machinery, this method always results in *very expensive*. For these types of equipment, costs are complex to define. You have to consider many parameters to properly decide what model you want to buy, for example:

a) The amount of products, will it make thousands of products or once in a while a few products?
b) Reliability, how much products can it make with the same quality?
c) Precision, at what quality do you need to produce?
d) Durability, how long will it run before maintenance or a new purchase is required?
e) Depreciation, how much does the machine depreciate over time?
f) Cost of installation and tooling, besides the basic procurement price, some extra costs are made as well.

Movability:
To enhance the changeability of the factory, a high movability rating is preferred. For example if a piece of equipment is portable or can be put on wheels. Other ways of transporting like pushing or lifting are also sufficient. If a piece of equipment is too heavy or very location dependent, it can be considered stationary and it receives a low movability rating. Although it lowers the changeability of the factory, some pieces of equipment are necessary anyways, which does not mean that the entire factory is not changeable anymore. Therefore, this criterion has a relative lower weight.

Amount of projects to fit:
As described in Section4.1.2, a selection of possible projects is made. As the name suggests, if the piece of equipment fits to more manufacturing projects, it is more useful. However, this does not say that in the future other projects can not be done in the LF. Therefore, this criterion has a low weight compared to the others and is the least important.

Table 25: Equipment distinction criteria

Criterion	**Weight**	**Score**		
Technical difficulty for individual operations:	32.5%	Low	L	9
		Medium	M	3
		High	H	1
Size:	25%	Fits on workstation	S	9
		Size of workstation	M	3
		Larger than table	L	1
Costs:	17.5%	Cheap $\leqslant$ € 999	€	9
		Reasonable € 1000 - € 2999	€ €	3
		Expensive € 3000 - € 9999	€ € €	1
		Very expensive $\geqslant$ € 10000	€ € € €	0
Movability:	15%	Can be put on wheels	W	9
		Movable	M	3
		Stationary	S	1
Amount of projects to fit:	10%	5	5	9
		3	3	3
		1	1	1

Demonstration of equipment selection
The criteria described above can be used to determine what will be the best option when choosing between similar equipment-models. An example is shown in Table 26. As indicated by the score on the most-right column, some types of equipment, like a milling machine, would never be chosen based on the selection criteria. However within the same equipment-type, the right equipment-model can be chosen.

Table 26: Equipment selection based on criteria.

	EP1	EP2	EP3	EP4	EP5	Required technologies:	Length (mm)	Width (mm)	Height (mm)	Cost (€)	Projects to fit	Size	Cost	Technical difficulty for individual operations	Movability	SUMPRODUCT
						0. Standard factory technology					10%	25%	17,5%	32,5%	15%	Score
						Assembly workstation										
[95]	X	X	X	X	X	Mobile mechanically height-adjustable workstation	915	1849	2107	6580	5	M	€ € €	L	W	6,1
[96]	X	X	X	X	X	Mobile non-height-adjustable work-station	1077	1654	2341	2850	5	M	€ €	L	W	6,45
[97]	X	X	X	X	X	Mobile non-height-adjustable multi-ple bins workstation	846	1272	1820	2900	5	M	€ €	L	W	6,45
						Quality workstation										
[95]	X	X	X	X	X	Mobile mechanically height-adjustable workstation	915	1849	2107	6580	5	M	€ € €	L	W	6,1
[96]	X	X	X	X	X	Mobile non-height-adjustable work-station	1077	1654	2341	2850	5	M	€ €	L	W	6,45
[98]				X		Granite table top	450	300	75	250	1	S	€	L	M	7,3
						Inventory rack										
[99]	X	X	X	X	X	Small modular inventory rack (1m)	1038	400	2000	175	5	M	€	L	M	6,6
[99]	X	X	X	X		Medium modular inventory rack (3m)	3042	400	2000	495	4	M	€	L	M	6,3
[99]	X					Large modular inventory rack (5m)	5046	400	2000	765	1	M	€	L	M	5,8
						Inventory rack with bins										
[100]	X	X	X	X	X	Tiny inventory rack on wheels with 36 bins (0,6 m)	660	520	1325	250	5	M	€	L	W	7,5
[101]	X	X	X	X	X	Small modular inventory rack with 42 bins (1,4 m)	1420	335	1972	460	5	M	€	L	M	6,6
						Transport carts										
[102]	X	X	X	X	X	Transport cart	1411	954	722	1050	5	M	€ €	L	W	6,45
[103]	X	X	X	X	X	Cart with 5 drawers	1483	955	1340	4215	5	M	€ € €	L	W	6,1
	EP1	**EP2**	**EP3**	**EP4**	**EP5**	**2. Conventional Manufacturing**					10%	25%	17,5%	32,5%	15%	Total score
						Milling Machine										
[104]		X		X	X	Desktop — 177x228x89 work volume — 10 - 28 kRPM	500	530	492	6500	3	S	€ € €	M	M	4,15
[105]		X		X	X	Small industrial — 300x280x300 work volume — 20 kRPM	2100	1000	2050	24990	3	M	€ € € €	M	M	2,475
[106]				X		Small industrial — 762x460x460 work volume — 15 kRPM	2200	2805	3000	150000	1	L	€ € € €	M	S	1,475
[107]				X		Medium industrial 5 axis — 800x550x550 work volume — 10-30 kRPM	3000	2000	2650	41990	1	L	€ € € €	H	S	0,825
[108]				X		Medium industrial — 700x700x500 work volume — 15 kRPM	3995	2750	3000	500000	1	L	€ € € €	H	S	0,825
[109]				X		Large industrial 5 axis — 3810x1016x1067 work volume — 20 kRPM	7320	3050	3450	386995	1	L	€ € € €	H	S	0,825
[110]				X		Large industrial bridge-style — 1500 x 5100 — 22 kRPM	5140	12200	5000	2000000	1	L	€ € € €	H	S	0,825
						Laser Cutting Machine										
[111]	X			X	X	Desktop 400x400 work area — 350 mm/s	800	500	250	1160	3	M	€ €	L	W	5,85
[112]	X			X	X	Small industrial 1400 x 900 work area — 500 mm/s	1980	1270	930	7320	3	M	€ € €	L	W	5,5
[113]				X		Large industrial 2500 x 1300 work area — 1200 mm/s	3000	1700	1000	17500	1	M	€ € € €	L	W	5,125
						Injection moulding machine										
[114]	X			X	X	Desktop 310 °C — 146x146x150 work area — 29.57 cm3 shot size	876	254	254	5000	3	M	€ € €	L	W	5,5
[115]	X			X	X	Desktop 310 °C — 222x222x223 work area — 59.15 cm3 shot size	1092	305	305	10000	3	M	€ € € €	L	W	5,325
[116]	X			X	X	Desktop 500 °C — 200x125x150 work area — 29,50 cm3 shot size	1300	400	450	5400	3	M	€ € €	L	W	5,5
[117]	X			X	X	Desktop vacuum moulder 160-340 °C— 200x200x130 work area	466	274	315	615	3	M	€	L	W	6,9
[118]				X		Small industrial —250x250x200 work area — 48 cm3 shot size	1500	700	2500	6000	1	M	€ € €	L	W	5,3
[119]				X		Medium industrial xx°C —635x635x425 work area — 217 cm3 shot size	4000	1200	1500	20000	1	M	€ € € €	L	W	5,125
[120]				X		Large industrial (Approximation)	8000	2400	2000	60000	1	M	€ € € €	L	W	5,125

4.3 Configuration Tool Explanation

In this Section, the LF Configuration Tool (LFCT) will be explained and demonstrated. The LFCT information architecture is shown in Figure 27. The blue rectangles indicate a manual input is required. The black rectangles show that information is processed automatically. In short, the LFCT can be divided in 4 sections:
1. Equipment database input: the user adds equipment-models to the database. Dimensions and cost are specified and each model is coupled to the right LF budget and LF size.
2. Admin input: the admin couples the right LS to the right EP. Also the right equipment-type to the right LS and EP.
3a. Configuration dashboard step 1: the input parameters are the required EP and corresponding LSs. Then, the user selects the available budget and size.
4. Automatic data coupling: the tool formulates a list of desired equipment-models based on the user input from the configuration dashboard. That is done using the data couplings made in the first two sections.
3b. Configuration dashboard step 2: the user gets presented a list with possible equipment models. At last the user has to manually select between different equipment-models of the same equipment-type followed by the required amount.

The LFCT will be more elaborated on in the rest of this Section.

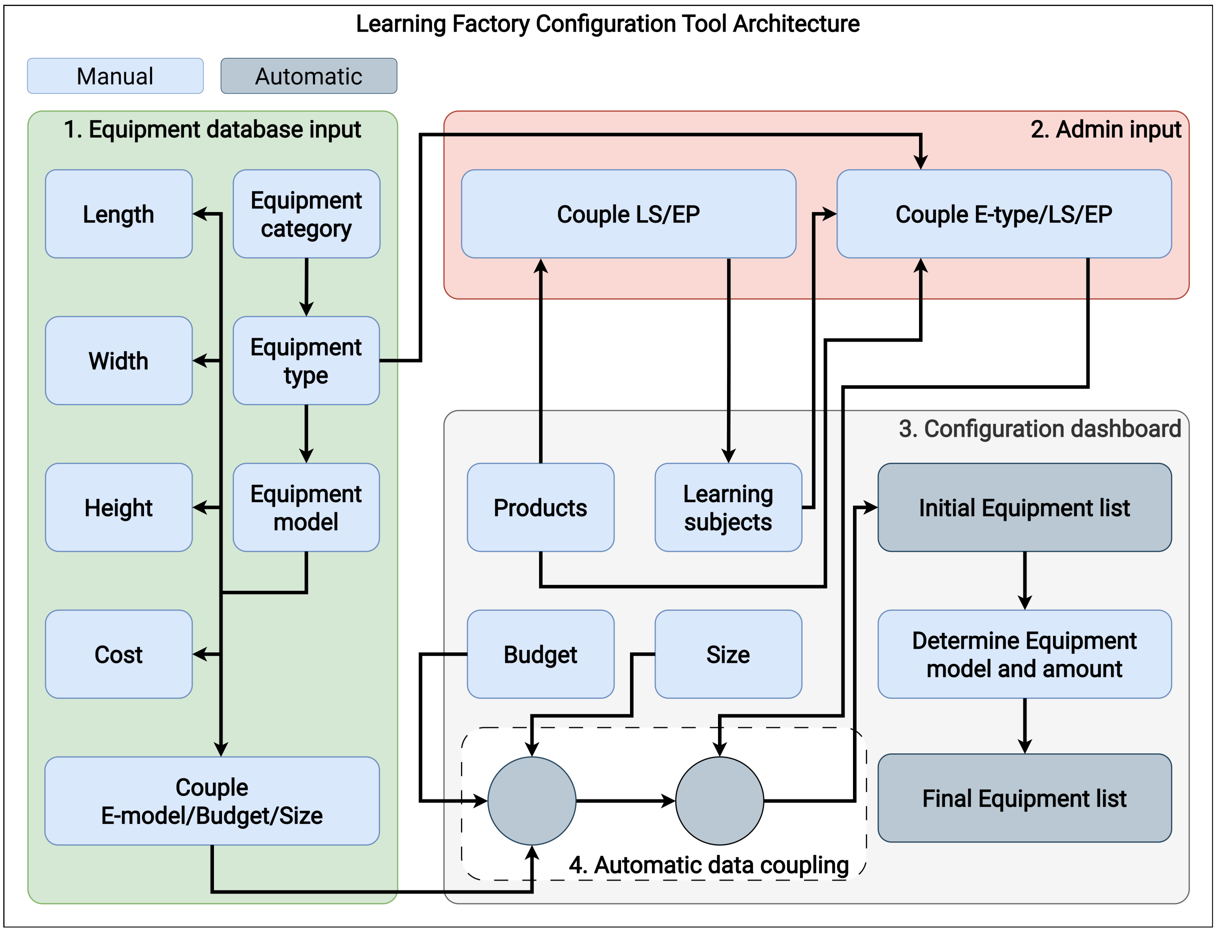


Figure 27: Learning Factory Configuration Tool architecture.

4.3.1 Step 1: Equipment database.

The configuration tool starts with the database. Based on the given input parameters, the equipment list gets pulled from the database. As can be seen in Table27, The database is divided into a primary, secondary and tertiary level. The primary level describes the equipment-category (e-category) and, as listed below, there are 5 in total:

1) Standard factory equipment: generally always available in the factory.
2) Conventional factory equipment: this is equipment that you see in conventional factories like heavy machinery.
3) Industry 4.0 equipment: equipment that has affinity with industry 4.0 like a 3D printer and AR glasses.
4) Software: anything similar or related to software programs.
5) Product-specific equipment: all types of equipment that would only be useful for specific projects.

The secondary level contains the equipment-type (e-type) and the tertiary level gives a more specific description of the single equipment-model (e-model). Next to the e-model description, the database also contains information about the width, length and height of each e-model. Based on the criteria from Table 25, it also indicates the cost and size level. The full database is shown in Appendix C.1.

Table 27: Equipment Database

	1. Standard factory equipment	**Length**	**Width**	**Height**	**Cost**		**Size**
	Assembly workstation	**(mm)**	**(mm)**	**(mm)**			
[95]	Mobile mechanically height-adjustable workstation	915	1849	2107	€ 6.580	€ € €	M
[96]	Mobile non-height-adjustable workstation	1077	1654	2341	€ 2.850	€ €	M
[97]	Mobile non-height-adjustable multiple bins workstation	846	1272	1820	€ 2.900	€ €	M
	Quality workstation						
[95]	Mobile mechanically height-adjustable workstation	915	1849	2107	€ 6.580	€ € €	M
[96]	Mobile non-height adjustable workstation	1077	1654	2341	€ 2.850	€ €	M
[98]	Granite table top	450	300	75	€ 250	€	S
	Inventory rack						
[99]	Small modular inventory rack (1m)	1038	400	2000	€ 175	€	S
[99]	Medium modular inventory rack (3m)	3042	400	2000	€ 495	€	M
[99]	Large modular inventory rack (5m)	5046	400	2000	€ 765	€	L
	Inventory rack with bins						
[100]	Tiny inventory rack on wheels with 36 bins (0,6 m)	660	520	1325	€ 250	€	S
[101]	Small modular inventory rack with 42 bins (1,4 m)	1420	335	1972	€ 460	€	S
	Transport carts						
[102]	Transport cart	1411	954	722	€ 1.050	€ €	S
[103]	Cart with 5 drawers	1483	955	1340	€ 4.215	€ € €	M
	2. Conventional manufacturing						
	Milling machine						
[104]	Desktop | 177x228x89 work vol. | 28 kRPM	500	530	492	€ 6500	€ € €	S
[105]	Small ind. | 300x280x300 work vol. | 20 kRPM	2100	1000	2050	€ 24990	€ € € €	M
[106]	Small ind. | 762x460x460 work vol. | 15 kRPM	2200	2805	3000	€ 150000	€ € € €	L
[107]	Medium ind. 5 axis | 800x550x550 work vol. | 30 kRPM	3000	2000	2650	€ 41990	€ € € €	L
[108]	Medium ind. | 700x700x500 work vol. | 15 kRPM	3995	2750	3000	€ 500000	€ € € €	L
[109]	Large ind. 5 axis | 3810x1016x1067 work vol. | 20 kRPM	7320	3050	3450	€ 386995	€ € € €	L
[110]	Large ind. bridge-style | 1500 x 5100 | 22 kRPM	5140	12200	5000	€ 2000000	€ € € €	L
	Turning machine						
[121]	Small ind. | 290 mm between centers | 230 mm turning diam.	1702	1843	2200	€ 120000	€ € € €	M
[122]	Small ind. | 600 mm between centers | 270 mm turning diam.	2100	900	600	€ 29920	€ € € €	M
[123]	Medium ind. | 750 mm between centers | 480 mm turning diam.	3050	4175	2200	€ 200000	€ € € €	L
[124]	Medium ind. | 850 mm between centers | 380 mm turning diam.	2500	1800	1800	€ 45000	€ € € €	L
[125]	Large ind. | 3000 mm between centers | 750 mm turning diam.	5300	2300	2200	€ 130000	€ € € €	L
[126]	Large ind. | 1500 mm between centers | 650 mm turning diam.	5530	2995	3000	€ 600000	€ € € €	L

4.3.2 Step 2: Equipment selection based on budget and size.

When making the database of Table 26, it became apparent that the best way to differentiate parts was on size and budget. The other criteria were, technical difficulty for individual operations, movability and amount of projects to fit. Almost everything can be operated by students except complex machinery like CNC-milling machines, for which there is an instructor anyway. Most small and medium sized equipment is movable and the amount of projects to fit is variable. At this moment in time, summer 2022, it is not yet known what will be the available size and budget for the LF factory on the UT. Therefore, a model has been written that determines, based on the available budget and space, what pieces of equipment can be bought. Further quantification these variables is described below and shown in Table 28.

Table 28: LF preliminary budget and size definitions.

Budget	**€**	**Size**	**m^2**
Small	€ 499.999 ⩽	Small	200
Medium	€ 500.000 - € 999.999	Medium	300
Large	⩾ € 1.000.000	Large	800

Budget
In accordance with the professor at the UT, the following budget quantities are used. As the budget is *just* variable in the total configuration tool, there is not a lot more to say about this. If the university wants to use other numbers, that is fine too and does not influence the functionality of the tool. This becomes clear later in this section.

Factory Size
For the size determination, the preliminary plan for the cube building and corresponding floor space is used[127]. As can be seen in Figure 28, indicated by the red rectangles and from left to right, the building has 3 available floor spaces on 3 different floor levels. The first floor has the maximum floor space available which is 40m by 20m = 800m^2. The second floor uses two times a small section of the total available space. These are considered as 'small' and correspond to 10m by 20m = 200m^2. The 'medium' value, is determined to be 15m by 20m = 300m^2 and corresponds to the space available on the third floor. Similar to the budget, size is also *just* a variable. However, in this case it is actually based on the available information.

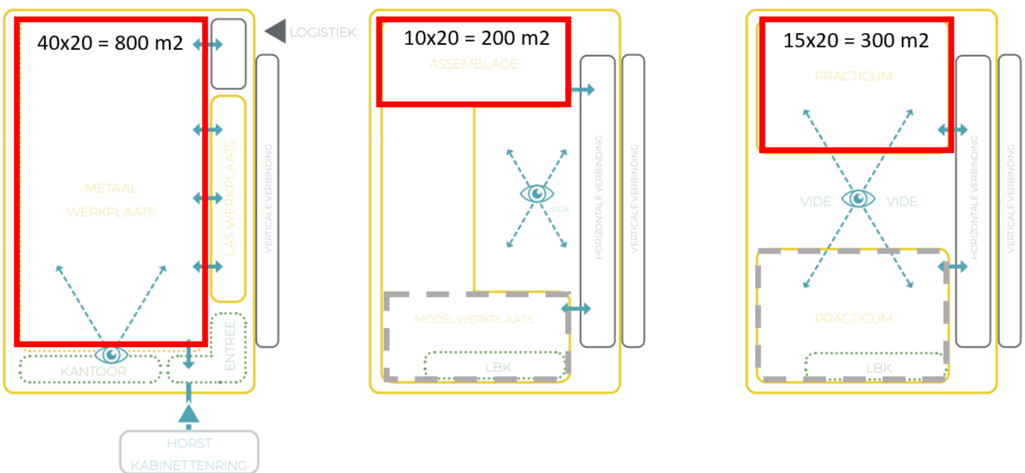


Figure 28: From left to right the first, second and third floor of 'The Cube' [127].

4.3.3 Step 3: Coupling the equipment to the right budget/size scenario.

For this part, the equipment database must be coupled to the right budget/size scenarios. In total there are 9, (3 budget x 3 size) possibilities. For each piece of equipment, the decision is made if it fits to one of these scenarios. As can be seen in Table 29, the cell is blue if the cell can be filled by the user. If a '1' is placed inside the cell, it automatically turns green, indicating it is coupled. In the LFCT, this window is found directly to the right of the database from Table 27 on page 58. So normally it is clear what equipment model corresponds with which row. The user can continue with the next step, if this decision is made for each piece of equipment.

Table 29: Equipment Database Coupling to Budget and Floor space scenarios.

Budget ⩽ € 499.999			Budget € 500.000 - € 999.999			Budget ⩾ € 1.000.000		
200 m^2	300 m^2	800 m^2	200 m^2	300 m^2	800 m^2	200 m^2	300 m^2	800 m^2
1. Standard factory equipment								
Assembly station								
1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1
Quality station								
			1	1	1	1	1	1
1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1
-	-	-	-	-	-	-	-	-
Inventory rack								
1	1	1	1	1	1	1	1	1
	1	1		1	1		1	1
		1			1			1
Inventory rack with bins								
1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1
Transport carts								
1	1	1	1	1	1	1	1	1
	1	1	1	1	1	1	1	1
2. Conventional manufacturing								
Milling machine								
1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1
							1	1
				1	1		1	1
							1	1
								1
								1
Turning machine								
			1	1	1	1	1	1
1	1	1	1	1	1	1	1	1
							1	1
				1	1	1	1	1
						1	1	1
							1	1

4.3.4 Step 4: Coupling the equipment to the Learning Subjects and Educational Projects

For this step, a matrix is used like shown in Table 31 on page 62. As the title suggests, it enables the user to couple each type of equipment to the appropriate Learning Subject and Educational Project. As visualized by the diagram in Figure 18 on page 18 and the LFCT architecture on Figure 27 on page 57, two methods of coupling equipment are made. For the LSs, this is determined from Table 24, where possible equipment from the third column is coupled to Learning Subjects from the first column. Similarly for the EPs, the project description and manufacturing plans from Sections 4.1.2 and 4.1.3 are used as guidance. Note that the second column contains LS:*0. Basic Factory Technology*, this is used for selecting the standard factory equipment of the first primary category shown in Section 4.3.1. Similar to step 3, the cell is blue if the cell can be filled by the user. If a '1' is placed inside the cell, it automatically turns green, indicating it is coupled. This connects the equipment to the right LS or EP.

4.3.5 Step 5: Coupling the Learning Subjects to Educational Products

In this step, the user connects the right LS to the right EP, see Table 30. Here, the same colour coding is used as in Section 4.3.4 and 4.3.3. Coupling is done by typing a "1" in the cell connecting the LS to the EP. This allows the LFCT to work in two ways:

1) Through direct coupling between Equipment and LS or EP, like done in Table 31.
2) By indirect coupling through one of these initial couplings and a further coupling between LS and EP from Table 30.

This is required, because equipment connected to an LS, on itself, does not grant a full operating EP. So by directly connecting EPs to LSs, this is secured. Also the other way around, it could happen that an EP on itself does not grant full coverage of an LS. The technical details of this principle is explained in Appendix C.2.

Table 30: Coupling the right LS to the right EP

If LS is involved in project: type '1'	Card Holder	3D Printer	Gearbox assembly	Gearbox production	Drone					
0. Basic factory technology	1	1	1	1	1					
1. Lean six sigma green belt	1		1							
2. Design of production and inventory systems	1	1	1	1	1					
3. Industrial robotic systems	1		1							
4. Image processing and equipment				1	1					
5. 3D printing		1			1					
6. Maintenance engineering and management	1		1	1						
7. Stochastic models in operations management	1		1							
8. Stochastic models in production and logistics	1		1							
9. Machine learning in Engineering	1		1		1					
10. Automated production systems	1		1	1						

Table 31: Equipment Database Coupling to Learning Subjects and Educational Projects

If Equipment is involved in LS or EP type: "1"	**0. Basic factory technology**	**1. Lean six sigma green belt**	**2. Design of production and inventory systems**	**3. Industrial robotic systems**	**4. Image processing and equipment**	**5. 3D printing**	**6. Maintenance engineering and management**	**7. Stochastic models in operations management**	**8. Stochastic models in production and logistics**	**9. Machine learning in Engineering**	**10. Automated production systems**	**Card Holder**	**3D Printer**	**Gearbox assembly**	**Gearbox production**	**Drone**
1. Standard factory equipment																
Assembly workstation	1											1	1	1	1	1
Quality workstation	1											1	1	1	1	1
CMM	1						1		1		1		1	1	1	
Inventory rack	1			1								1		1	1	
Inventory rack with bins	1	1										1	1	1	1	1
Transport carts	1											1	1	1	1	1
2. Conventional factory equipment																
Milling machine															1	
Turning machine															1	
Grinding machine															1	
Laser cutting machine	1											1			1	1
Injection moulding machine	1												1		1	1
Kanban board		1										1		1		
3. Industry 4.0 equipment																
FDM printer	1					1							1			1
AGV											1	1		1	1	
Cobot				1						1	1	1		1		
Conveyor belts				1							1	1	1	1		
AR glasses		1			1		1					1		1	1	1
Industrial cameras					1		1			1		1		1		
Industrial sensors					1		1			1		1	1	1		
Pick-to-light system		1										1		1		
4. Software																
Machine performance data	1		1				1	1	1	1		1		1		
Production performance data	1		1				1	1	1	1		1		1		
3D object recognition software										1	1					
AI software to process virtual object into picking instruction				1						1	1	1		1		
3D print slicer software						1							1			1
3D object design software	1					1						1	1	1	1	1
Pick-to-light software		1										1		1		
AR software		1			1		1					1		1	1	1
Digital Kanban Boardsoftware		1										1		1		
5. Project-specific equipment																
Knitting machine												1				
Hobbing machine															1	

4.3.6 Step 6: Input parameters of the LF Configuration Tool

This is where the User Input Dashboard from Figure 29 can be used. Directly visible on the top are the blue buttons. As before, this implicates that the user can do something with that. When the blue button is pressed, it changes to green and activates the EP as input. Followed directly by the matrix below that shows what LSs are present for that project. The user is also able to add additional LSs, which can be seen on the matrix on the bottom left. Figure 30 shows that LS 7 is also activated. Therefore, the LS turns active on the bottom right matrix, which shows both the LSs activated by the EP and the additional LSs, added by the user. Centered and to the right of the 'additional LS matrix', the user is able to select the budget and size of the LF.
So in short, first the EPs are selected, then optionally more LSs and finally the right LF budget and LF size.

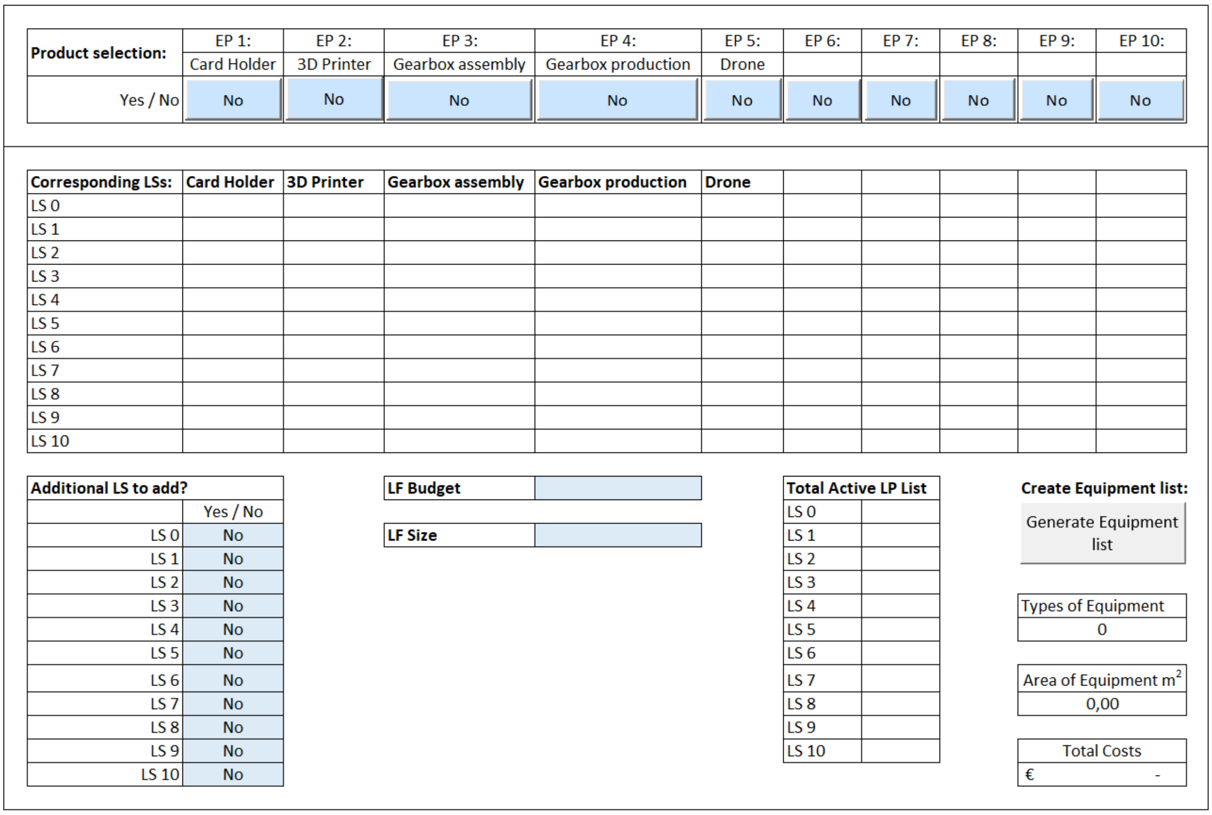


Figure 29: Empty Learning Factory Configuration Tool dashboard

Product selection:	EP 1: Card Holder	EP 2: 3D Printer	EP 3: Gearbox assembly	EP 4: Gearbox production	EP 5: Drone	EP 6:	EP 7:	EP 8:	EP 9:	EP 10:
Yes / No	No	No	No	No	Yes	No	No	No	No	No

Corresponding LSs:	Card Holder	3D Printer	Gearbox assembly	Gearbox production	Drone					
LS 0					Active					
LS 1					Not Active					
LS 2					Active					
LS 3					Not Active					
LS 4					Active					
LS 5					Active					
LS 6					Not Active					
LS 7					Not Active					
LS 8					Not Active					
LS 9					Active					
LS 10					Not Active					

Additional LS to add?	Yes / No
LS 0	No
LS 1	No
LS 2	No
LS 3	No
LS 4	No
LS 5	No
LS 6	No
LS 7	Yes
LS 8	No
LS 9	No
LS 10	No

LF Budget	Large
LF Size	Small

Total Active LP List	
LS 0	Active
LS 1	
LS 2	Active
LS 3	
LS 4	Active
LS 5	Active
LS 6	
LS 7	Active
LS 8	
LS 9	Active
LS 10	

Create Equipment list:	
Generate Equipment list	
Types of Equipment	14
Area of Equipment m^2	20,53
Total Costs	€ 83.046,00

Figure 30: Filled, Learning Factory Configuration Tool dashboard

4.3.7 Step 7: Generating the Equipment List

Now the button called 'Generate Equipment list' must be pressed. The VBA code is shown in Appendix C.3.1. Using the input parameters from the last step, the LF configuration tool is now able to generate an equipment list from the database. Using the couplings made Sections 4.3.3, 4.3.4 and 4.3.5, the equipment list is fitted to the correct LF budget, LF size, LSs and EPs. The technical explanation of this process is given in AppendixC.2.

The result is given in Tables 32, 33 and 34. Now the user is able to select which e-models he/she wants and specify the required amount. Again the blue cells can be edited by the user. If the user selects 'No', the amount-cell automatically turns empty. The result list also shows the cost per type of equipment and, based on the width and length, the total floor area it would cover. The total sum of these numbers is given in the UI-dashboard, see Figure 30.

Table 32: Resulting equipment list, part 1.

1. Standard factory equipment	Length (mm)	Width (mm)	Height (mm)	Cost	To Buy?	Yes/No		Amount	Total cost	Total Area (m)
Assembly workstation					-					
Mobile mechanically height-adjustable workstation	915	1849	2107	€ 6.580,00	To Buy?	Yes		4	€ 26.320,00	6,77
Mobile non-height-adjustable workstation	1077	1654	2341	€ 2.850,00	To Buy?	Yes		4	€ 11.400,00	7,13
Mobile non-height-adjustable multiple bins workstation	846	1272	1820	€ 2.900,00	To Buy?	No				
Quality workstation					-					
Mobile mechanically height-adjustable workstation	915	1849	2107	€ 6.580,00	To Buy?	Yes		2	€ 13.160,00	3,38
Mobile non-height adjustable workstation	1077	1654	2341	€ 2.850,00	To Buy?	No				
Granite table top	450	300	75	€ 250,00	To Buy?	No				
CMM					-					
Inventory rack					-					
Small modular inventory rack (1m)	1038	400	2000	€ 175,00	To Buy?	Yes		4	€ 700,00	1,66
Inventory rack with bins					-					
Tiny inventory rack on wheels with 36 bins (0,6 m)	660	520	1325	€ 250,00	To Buy?	Yes		2	€ 500,00	0,69
Small modular inventory rack with 42 bins (1,4 m)	1420	335	1972	€ 460,00	To Buy?	No				
Transport carts					-					
Transport cart	1411	954	722	€ 1.050,00	To Buy?	No				
Cart with 5 drawers	1483	955	1340	€ 4.215,00	To Buy?	Yes				
2. Conventional manufacturing					-					
Milling machine					-					
Turning machine					-					
Grinding machine					-					
Laser cutting machine					-					
Desktop 400x400 work area — 350 mm/s	800	500	250	€ 1.160,00	To Buy?	Yes		1	€ 1.160,00	0,40
Injection moulding machine					-					
Desktop 310 °C — 146x146x150 work area — 29.57 cm3 shot size	876	254	254	€ 5.000,00	To Buy?	No				
Desktop 310 °C — 222x222x223 work area — 59.15 cm3 shot size	1092	305	305	€ 10.000,00	To Buy?	Yes		1	€ 10.000,00	0,33
Desktop 500 °C — 200x125x150 work area — 29,50 cm3 shot size	1300	400	450	€ 5.400,00	To Buy?	No				
Desktop vacuum moulder 160-340 °C— 200x200x130 work area	466	274	315	€ 615,00	To Buy?	No				
Small industrial xx°C —250x250x200 work area — 48 cm3 shot size	1500	700	2500	€ 6.000,00	To Buy?	No				
Kanban board					-					

Table 33: Resulting equipment list, part 2.

3. Industry 4.0 equipment	Length (mm)	Width (mm)	Height (mm)	Cost	To Buy?	Yes/No		Amount	Total cost	Total Area (m)
FDM printer					-					
Hobby desktop 220x220x250 work volume — 260 °C	440	420	465	€ 220,00	To Buy?	No				
3D printer enclosure	480	600	720	€ 80,00	To Buy?	No				
Automatic bed leveling sensor			-	€ 55,00	To Buy?	No				
Professional small 330x240x300 work volume — 280 °C	495	457	520	€ 6.410,00	To Buy?	Yes		4	€ 25.640,00	0,90
Professional medium 305x305x600 — 300 °C	616	590	760	€ 6.050,00	To Buy?	No				
Professional large 914x609x914 — 450 °C	2772	1683	2027	€ 200.000,00	To Buy?	No				
AGV					-					
Cobot					-					
Single-arm 0.5 kg load — 1.5 m/s — 559 mm reach	160	160		€ 31.100,00	To Buy?	No				
Dual-arm 0.5 kg load — 1.5 m/s — 559 mm reach	399	497		€ 51.300,00	To Buy?	No				
Single-arm 5 kg load — 2.2 m/s — 950 mm	165	165		€ 32.400,00	To Buy?	No				
Single arm 4 kg load — 5.05 m/s — 475 and 580 mm reach	160	172		€ 32.200,00	To Buy?	No				
Single arm 5kg load — 1 m/s — 700 mm reach	126	126		€ 8.400,00	To Buy?	No				
Single arm 1 kg load — 0.5 m/s — 440 mm reach	126	126		€ 3.000,00	To Buy?	No				
Conveyor belts					-					
AR glasses					-					
Hobby			-	€ 550,00	To Buy?	No				
Cheap Professional			-	€ 1.030,00	To Buy?	Yes		4	€ 4.120,00	
Expensive Professional			-	€ 4.900,00	To Buy?	No				
Industrial cameras					-					
Cheap industrial	29	29	29	€ 180,00	To Buy?	Yes		1	€ 180,00	0,00
Expensive industrial	80	175	40	€ 3.450,00	To Buy?	No		1		
Industrial sensors					-					
Industrial temperature sensor -50 till 200 °C				€ 150,00	To Buy?	Yes		1	€ 150,00	
Thermal camera				€ 300,00	To Buy?	Yes		1	€ 300,00	
Gas detection sensor				€ 420,00	To Buy?	Yes		1	€ 420,00	
Torque sensor				€ 270,00	To Buy?	No				
Pick-to-light system					-					

Table 34: Resulting equipment list, part 3.

4. Software	Length (mm)	Width (mm)	Height (mm)	Cost	To Buy?	Yes/No		Amount	Total cost	Total Area (m)
Machine performance data				Free	To Buy?	Yes		1	Free	
Production performance data				Free	To Buy?	Yes		1	Free	
3D object recognition software				Free	To Buy?	Yes		1	Free	
AI software to process virtual object into picking instruction				Free	To Buy?	No				
3D print slicer software				Free	To Buy?	Yes		1	Free	
3D object design software				Free	To Buy?	Yes		1	Free	
AR software				Free	To Buy?	Yes		1	Free	
5. Project-specific equipment					-					

5 Simulation

As shown in the last section, the LFCT gives an overview of the required equipment, amount of space taken and the cost of procurement. It does not give any information on the production time and the layout of the factory, and therefore in this section a Learning Factory simulation is setup. It will help to show the feasibility of different manufacturing lines according to the base equipment list, presented in Section 4.3.7, that was suggested by the LFCT. It also helps to explore how the LFCT may be integrated with a simulation program. Having a simulation of the factory provides insight into the future operation and enables the user to see possible failures before anything has been procured and setup in reality. As such, it helps in better financial decision making. Next to that, it gives the user the possibility to try different Learning Factory configurations and see how different input parameters, influence the types and amount of equipment and ultimately the floor plan. First it is important to understand what knowledge is required to set up the simulation. Then, the simulation will be explained and the output of the LFCT will be put to practise. After the simulation an evaluation will be performed. The simulated LF will be compared to existing LFs and the EP objectives. Also, other findings are discussed and improvements will be recommended.

5.1 Value Stream Mapping

A Value Stream Map (VSM) of the project is made as a starting point for simulation. A value stream is all the actions (both value added and non-value added) currently required to route a product through the factory [128]. The ultimate goal of using a value stream map, is to get an overview of what processes within the company are of added value and which processes are not. This way it is easier to see where the most useful improvements can be made. The tool is useful to look at the big picture, instead of the individual processes. For this process only the Learning Factory phase is considered. But it is possible to include the supplier-phase and end-use-phase of the process, see Figure 31.

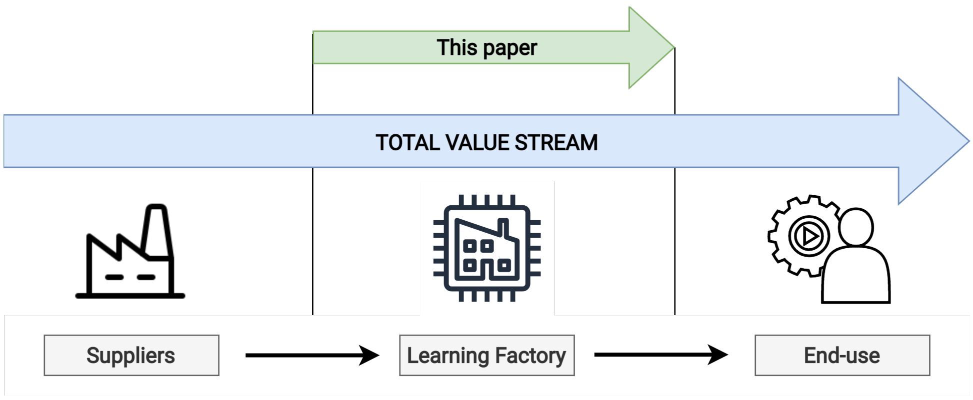


Figure 31: Only an overview of the value stream through the LF is considered.

In preparation of the simulation, only the value stream within the learning factory is important, so from material storage to final assembly. The VSM is made because it gives a clear overview of the required equipment types, amount of equipment and process times. These are based on the manufacturing plans presented in Section 4.1.3. On page 69, an example of such a VSM is shown in Tables 35 and 36. The first table shows a VSM that is made for having one piece of equipment for each task. The second table shows a VSM that is made for having multiple pieces of equipment for each task. This lowers the process times significantly and is more representative to a real situation, where you have multiple units of the same equipment-model too. It also enables the instructor to, for example, divide the assembly steps over multiple assembly stations. The VSM of other projects can be found in Appendix B.2. Note that the VSMs presented here, are an assumption of a student without prior experience. It is made for demonstration purposes only. In reality, a comprehensive time study is required to identify the times spent on various tasks and see where improvements can be made.

Table 35: VSM of Drone, part 1.

Drone, single tool for each step									
Property		1. Frame design	Equipment	2. Print the parts	Equipment	3. Assemble the Drone	Equipment	4. Calibrate control system	Equipment
C/O	(h)		Simulation software	0,25		0,25	Assembly station	0,25	Quality station (the new drone)
CT	(h)			48	3D Printer	4		16	
PT	(h)	8		48,25		4,25		16,25	
Cumulative	(h)	8		56,25		60,5		76,75	
Property		1. Selection of required equipment	Equipment	2. Order picking Equipment	Equipment				
C/O	(h)				Transport cart Warehouse				
CT	(h)								
PT	(h)	0.5		0.5					
Cumulative	(h)	1		1.5					

Table 36: VSM of Drone, part 2.

Drone, multiple tools for each step									
Property		1. Frame design	Equipment	2. Print the parts	Equipment	3. Assemble the Drone	Equipment	4. Calibrate control system	Equipment
C/O	(h)		Simulation software	0,25	Warehouse picking cart	0,25	4 Assembly station	0,25	2 Quality stations (the new drone)
CT	(h)		4 Computers	12	4 3D Printers	1		8	
PT	(h)	8		12,25		1,25		8,25	
Cumulative	(h)	8		20,25		21,5		29,75	
Property		1. Selection of required equipment	Equipment	2. Order picking Equipment	Equipment				
C/O	(h)				Transport cart Warehouse				
CT	(h)								
PT	(h)	0.5		0.5					
Cumulative	(h)	1		1.5					

5.2 Simulation explanation

Visual Components (VC) [129] is used to program the simulation. This application is designed to be user friendly. Especially for understanding the pros and cons of the 3D layout. It also contains an extensive library of the components which we may need in the factory. Another program that is currently utilized on the UT is *Tecnomatix Plant Simulation*[130], however this program is not considering the reality of the layout. AI path planning of humans factory workers is not included for example.

A simulation is made of manufacturing and assembly of a drone, see Figure 32. Just like in the Manufacturing Plan in Section 4.1.3, it consists of a 3D printed frame, 4 propellers, 4 motors, a battery, a camera, a control board and the camera housing, see Figure 33. For simplicity, the screw and cable placement were left out of the simulation. If necessary, it is still possible to add those as hidden processes with the correct assembly times.

The factory equipment selection is based on the given output in the LF configuration tool, presented in Section 4.3.7. Each piece of equipment, if possible, has been given the same dimensions as the equipment list. If the 3D model was not available within VC, it was retrieved from the internet. Examples of this are the 3D printer[131] and the inventory rack with bins[132].

Figure 32: 3D view of the drone learning factory.

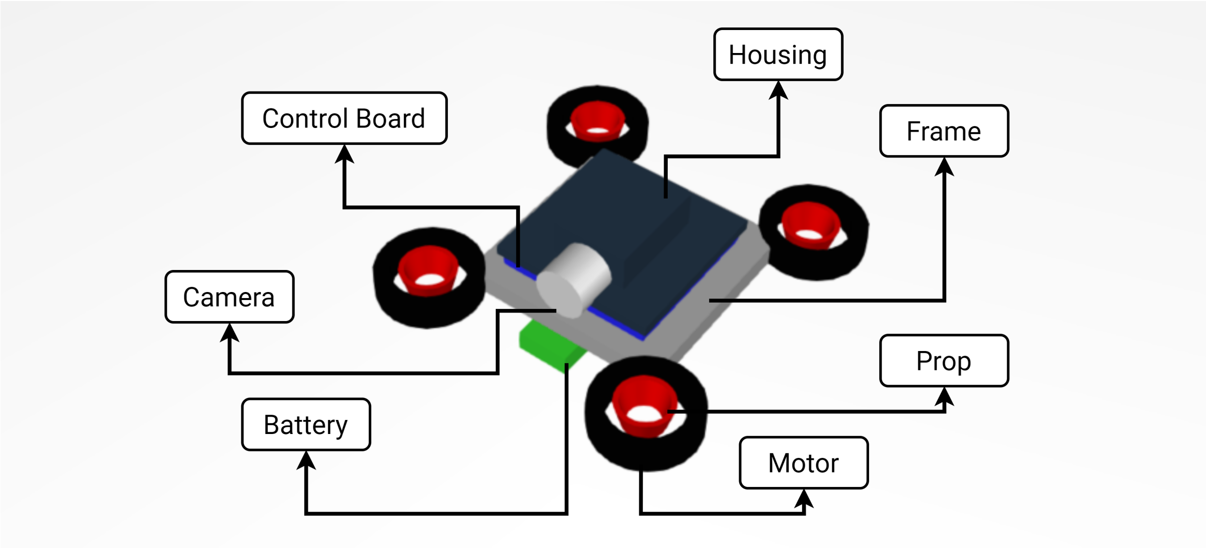


Figure 33: Drone parts overview.

Factory Assembly Route
The assembly steps of the drone were obtained from the information stated in the MP and VSM. The steps are indicated by the numbers located on the red dotted line from Figure 34. In total there are four persons in the factory and each person performs the same steps simultaneously.

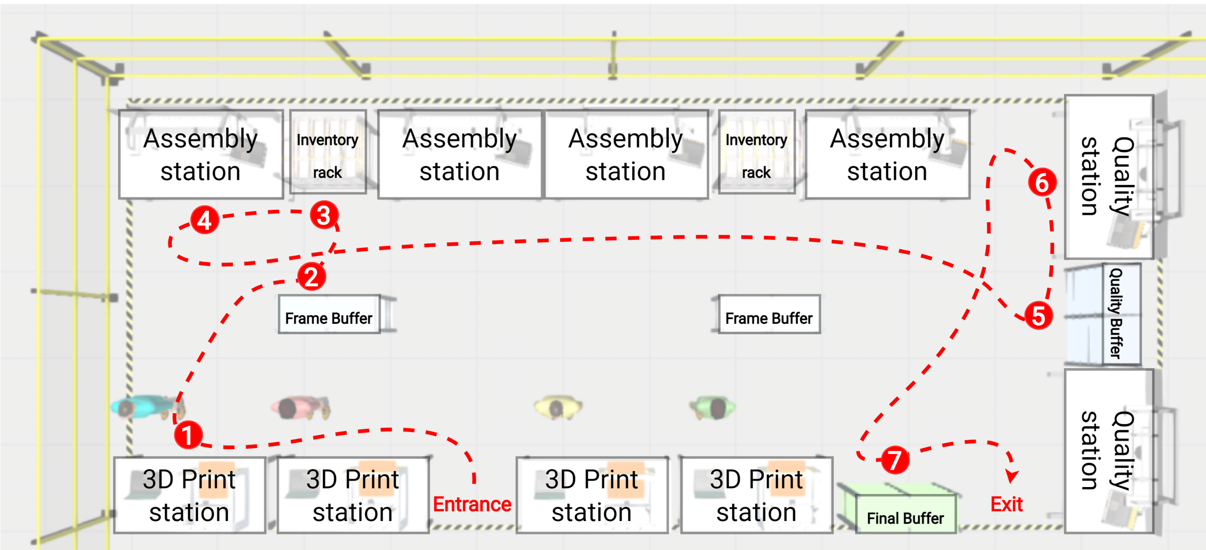


Figure 34: Top view of the drone learning factory. The red dotted line indicates the walk path of the (light blue) user.

Step 1: The user prepares the frame design for 3D printing by using 3D slicing software. After successful printing, the part is picked up by the user, see Figure 35.

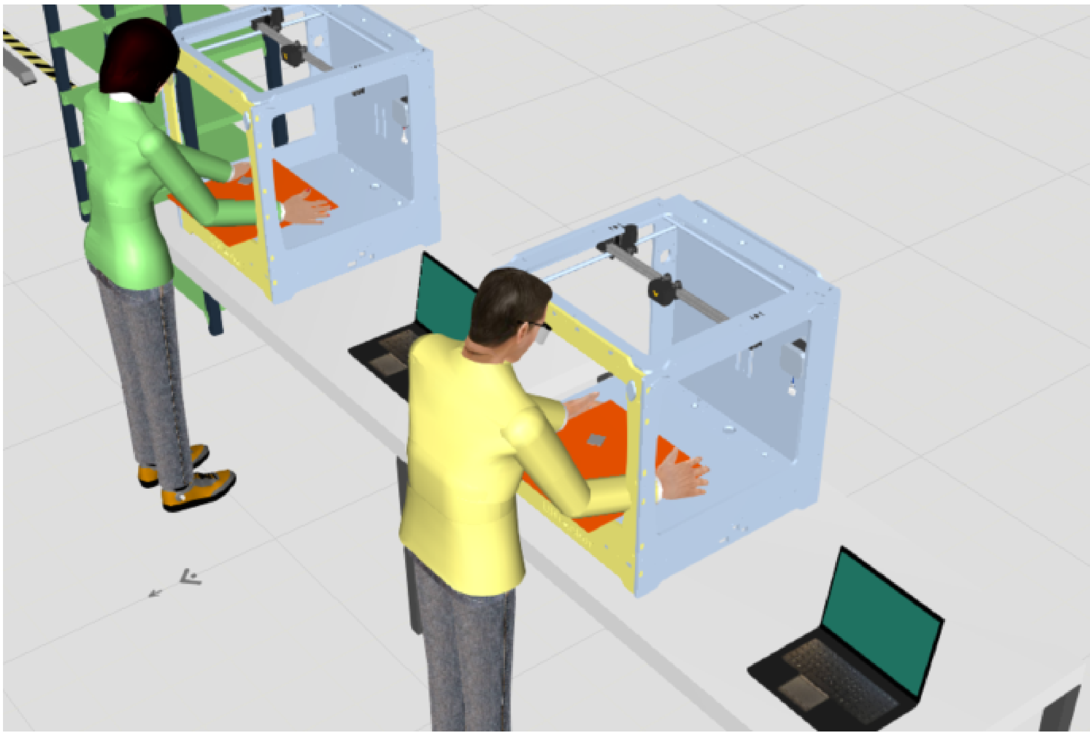


Figure 35: The printed frame is picked up and removed from the 3D printer.

Step 2: The printed part can be stored temporarily before assembly, see Figure 36. In the simulation, the persons pick it up directly after storage to continue with step 3.

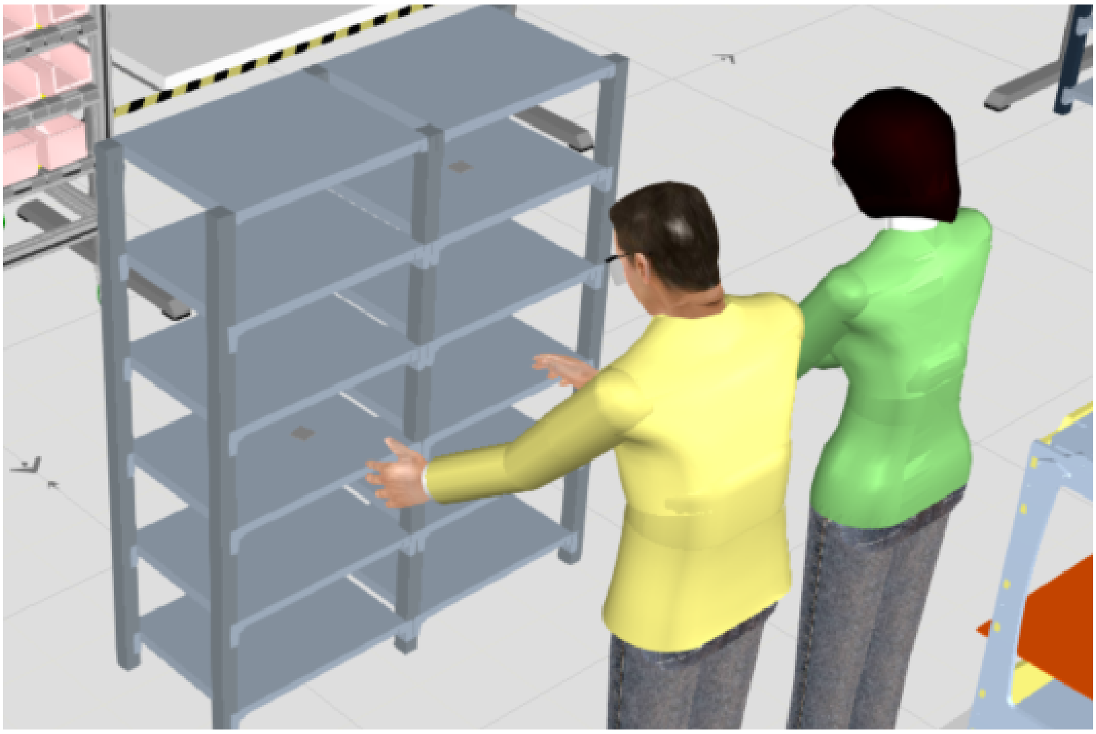


Figure 36: The users place the printed frame in the temporary buffer.

Step 3: Next in between the assembly stations, an inventory rack with bins is located which contains all the necessary parts for assembly, see Figure 37. The user picks the necessary parts for assembly. If a bin is empty, it can be restocked, while the next box slides to the front. Prior to assembly, the parts are laid out on the table in an organized manner, see Figure 38.

Figure 37: Inventory rack with bins, in between two assembly stations.

Figure 38: The user picks all the parts and arranges them neatly before assembly.

Step 4: The drone is assembled, see Figure 39. Before each assembly step, the necessary parts are moved from the side towards the assembly area. As recommended by the LFCT in Table 33, the student wears AR glasses that gives assembly instructions. The next assembly step is adding the motors, which are already spaced out around the drone.

Figure 39: The drone gets assembled.

Step 5 and 6: The drone is moved to the calibration table. Here, the drone receives a quality check and the control system is calibrated. In case these are already in use, the drone can be stored temporarily in the inventory rack in the middle, see Figure 40.

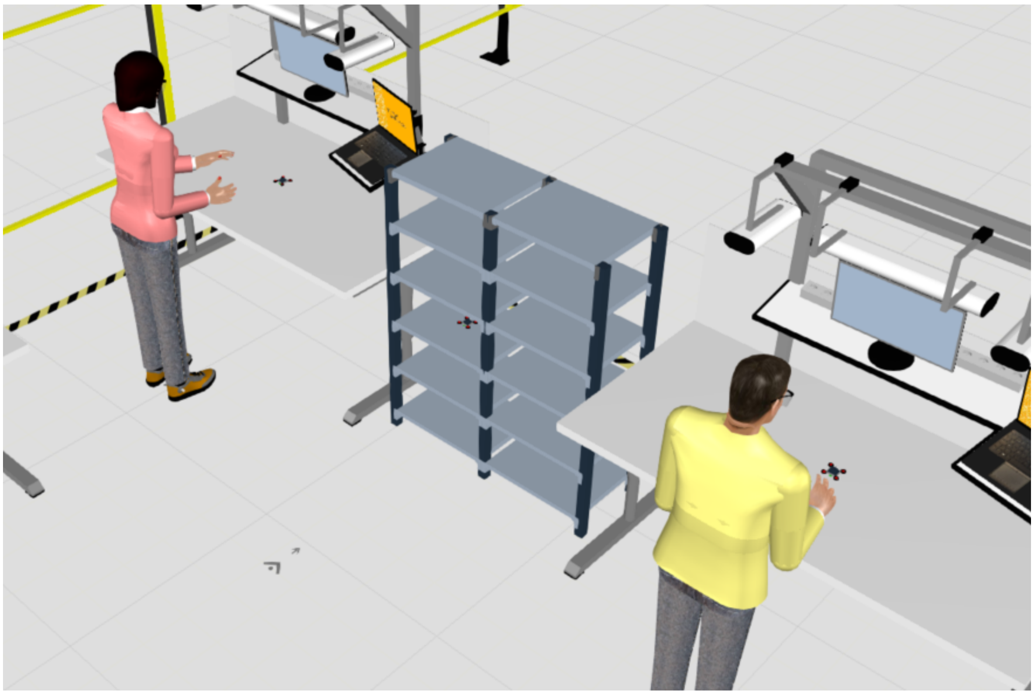


Figure 40: The users perform a quality check on the assembled drone.

Step 7: After successful calibration, the drones are stored in the, green coloured, inventory rack next to the exit of the manufacturing area, see Figure 41. As indicated in Figure 31, the testing phase is not included (in the simulation). After the project is completed, the drone is disassembled and all equipment is sorted and stored for future usage.

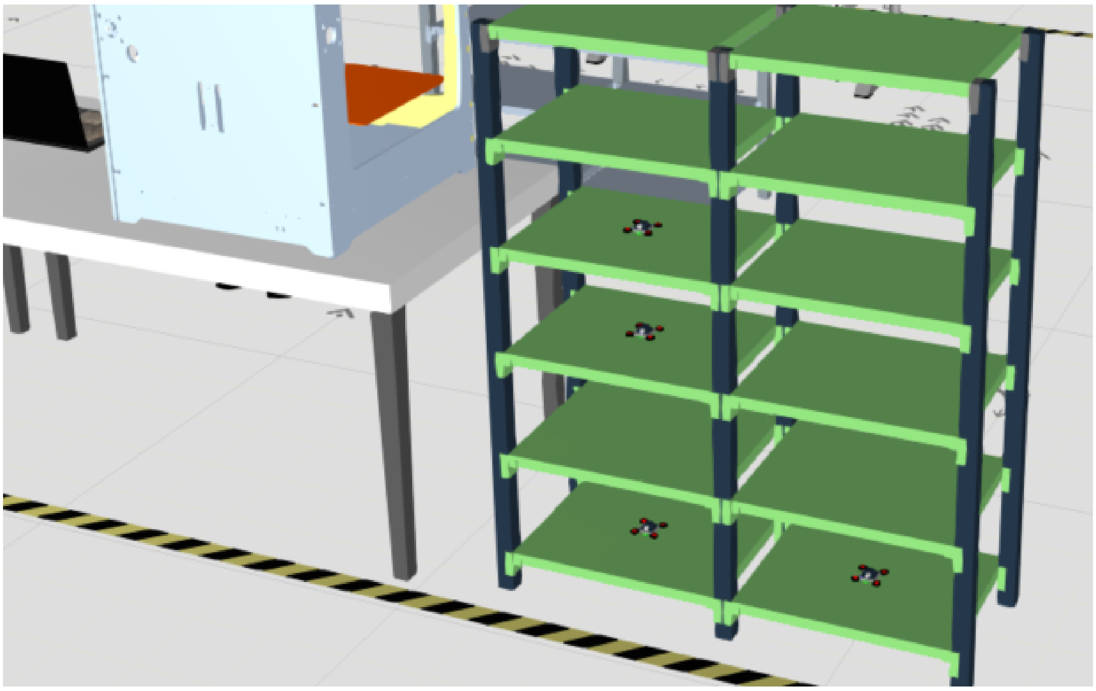


Figure 41: The drone can be stored temporarily before moving on to test-environment.

5.3 Evaluation

In this section, the simulated drone factory from Section 5.2 will be evaluated to understand what the practical implications of the tool are. In Section 5.3.1, the drone factory is compared to existing Learning Factories. Section 5.3.2 discusses the achievement of EP requirements and at last in Section 5.3.3, Section 5.3 is closed off with a general discussion about other findings and practical implications.

5.3.1 Learning Factory comparison

To validate the approach up till now, it is possible to compare my results to a real life project on the University of Twente. Fortunately while writing this thesis, the UT already has taken steps for a test Learning Factory. The layout of the UT test factory is not fixed, as each workstation contains wheels. There is the possibility to include the dual- or single-armed Cobots in the manufacturing process. The use and configuration of equipment is depending on the LSs. For the UT test factory, an EP is planned for which students have to assemble and disassemble a commercial drone [133], see Figure 42. The EP described in Section 4.1.2 is different, as there is a frame design part. The students should design a frame that can hold all necessary sensors, control plates, motors, propellers, battery. Then the frame must be 3D printed. For the EP, the drone is assembled at one workstation, while the drone at the UT is assembled over multiple workstations. The control and calibration part is the same. While making the EP simulation, inspiration was taken from the existing drone bought by the UT, see Figure 33.

Figure 42: The *HappyModel Mobula6 HDZero* used for the UT test factory [133].

Besides the project at the UT, the drone project has many similarities with the smaller factories presented in Table 13 on page 39. For example the *Lernfabrik für vernetzte produktion*[134] in Augsburg, which is about the manual assembly of a modular remote control car or the *AutFab*[135] in Darmstadt which automatically assembles relais. The second LF does not involve any human for assembly and quality control, but instead operates fully automatic. The simulated drone LF can be reconfigured to fully automatic production by adding a 6 axis robot, RFID tracking[21] and optical/weight sensors.

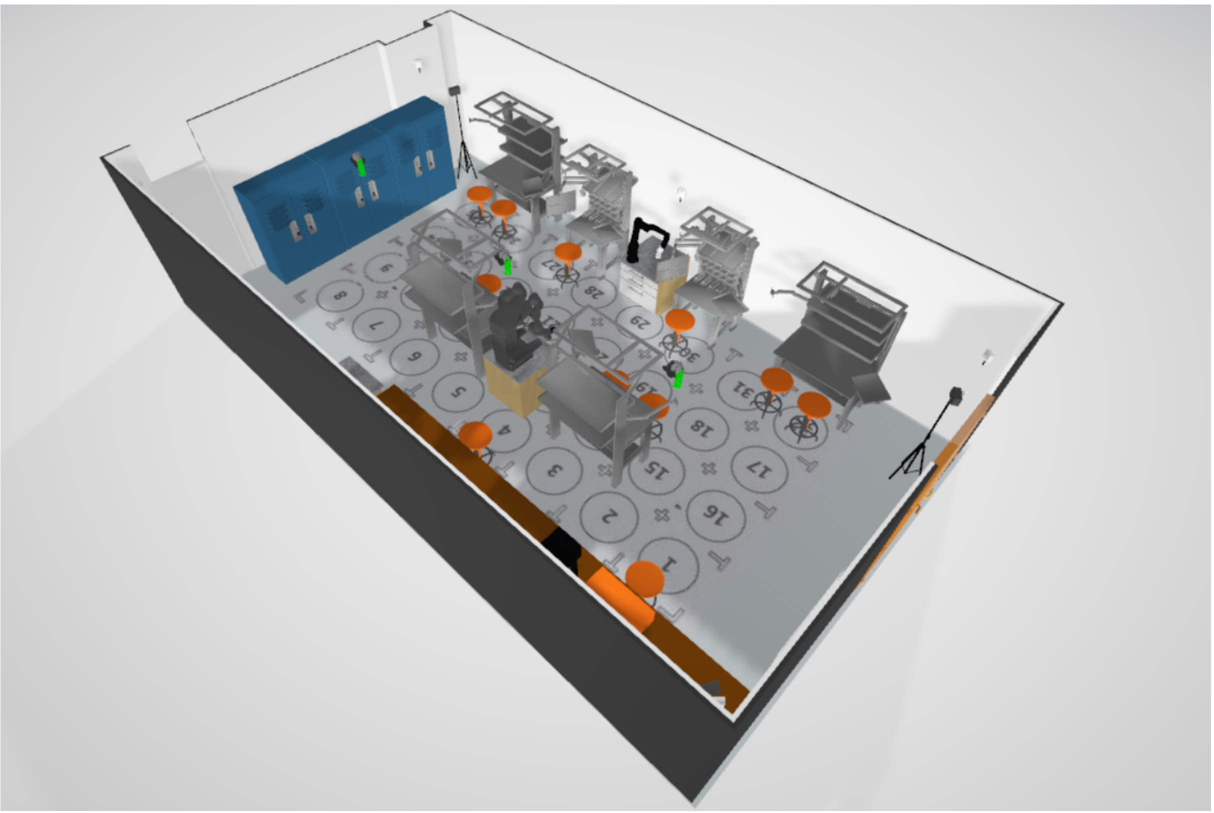


Figure 43: The 3D model of the drone assembly learning factory currently at the UT.

5.3.2 Objective validation

Looking back at the taken approach, it is logical that this small factory of Figure 32 results as configuration. Because of the criteria listed in, Table 14 on page 40. projects like the drone were selected for manufacturing. So to check if the taken approach is correct, the factory will be evaluated on each of the EP requirements, from Section 4.1.1, listed below:

1) **Value adding:** The objective is that the LF adds as much value to the world as possible, both in knowledge and materialistically.
2) **Broad LS coverage:** The objective is to be able to teach as many LSs as possible.
3) **Manufacturing facility size:** The objective is to be able to perform the project in the smallest area possible or a fixed amount of square meters.
4) **Manufacturable:** The part must be manufacturable with the available equipment.

1. Value adding
The product made is a drone. The added value in this case is a functioning drone that can do real tasks. Secondly, the gained knowledge for students about the working principle of drones, its assembly and its various functionalities. Work with drones has many benefits, as it learns the users to design and equip their drone for a given task and also enables them to put it to test. As research and regulations improve, drones are expected to be a key technology in the future. This can be approved by looking at the *Scopus*[136] results. Scopus is a search platform for scientific papers. As can be seen in Figure 44, the amount of research papers on drones increases each year (except during the COVID-19 pandemic). Recognizing this trend, it can be assumed that as time goes on, more drone applications will be devised.

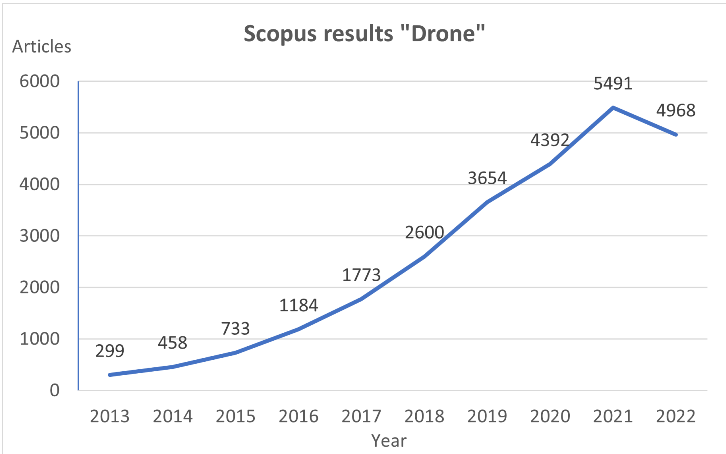


Figure 44: Scopus results when searching for "Drone"

2. Broad LS coverage
According to the Learning Subject definition described in Section 3.4, the Learning Factory facilitates that the user is able to perform multiple Learning Paths. These LPs can be part of an LS, and multiple LSs, can be part of a Learning Course. As seen in Figure 30 on page 61, the drone project should cover 4 LSs. Design of Production and Inventory Systems (DPI), Image Processing and Equipment(IPE), 3D Printing (3DP) and Machine Learning in Engineering (MLE).
DPI: In the current project setup, DPI is not used. It can be applied when for example the drone manufacturing is distributed over multiple assembly stations. Where each assembly station does part of the assembly. Then LPs about factory planning and layout would be an option, which is part of the DPI LS.
IPE: IPE is applied because the students wear AR glasses which help them to assemble the drone. As the drone is fitted with cameras, parts of IPE can be applied using the drone in the use-phase.
3DP: It is obvious that 3DP is used this project. When designing and printing the frame, many LPs of 3DP are performed.
MLE: MLE can be involved optionally. For example when designing the frame using topology optimization.
This means that 6 LSs are not covered. Concluding on this, some other projects would have been a better option for a first iteration of the LF, for example the gearbox assembly. Definitely in terms of automated production, improvements can be made. Solutions for further automation were already given in Section 5.3.1.

3. Manufacturing facility size
The drone factory scores good on this point. As shown in Figure 45 on page 45, not the entire floor space of the 200 m^2 is used. As a result of compact equipment placement, the total required area is 12 x 5 = 60 m^2. This is fine, as it gives room for additional activities as well. For example an additional automated Learning Factory. Compared to other learning factories, see Figure 13 on page 39, 60 m^2 is a very small size.

4. Manufacturable
The drone is very manufacturable, as much of the drone exists of standardized modular parts. The hard part in terms of manufacturing is designing and printing the frame directly in the good shape. However, this is part of the LSs. Disassembly is easy by unscrewing the parts. The 3D printed frame can be recycled and molten into new filament[137].

5.3.3 Other findings

Factory floor area calculation

As shown in Figure 30, even without simulation the user already receives an indication of the used equipment floor space by the LF configuration tool, which is 20.53m^2. By roughly counting the 1m x 1m squares taken by the equipment, a total floor space of 24 square meters is calculated. More correctly, by adding up the area of each equipment type, results in a total floor space 20.14 m^2, see Table 37. The difference between the simulation and the configuration tool can be explained by the four 3D printers that are stacked on top of the tables, and that area is therefore not included in the total floor area. This large area reduction is balanced by the inventory rack used in the simulation, which is larger than the one presented in the configuration tool. That is because the 3D model found online[132] is different than the inventory rack options in the database. All the other parts were already available in VC and are setup at the right size, similar to the sizes found in the database. The deviations of the printer and the inventory rack have their effect on the numbers, therefore the calculation done by the tool must be interpreted as a rough estimation, rather than a true value.

Table 37: Area calculation of the drone simulation

Equipment	**Length** (mm)	**Width** (mm)	**Area** (m^2)	**Amount**	**Total** (m^2)
Assembly table	1854	915	1,70	4	6,79
Quality table	1854	915	1,70	2	3,39
Inventory rack	1038	400	0,42	4	1,66
Inventory rack with bins	920	640	0,59	2	1,18
3D printer table	1654	1077	1,78	4	7,13
Total factory equipment area					20,14

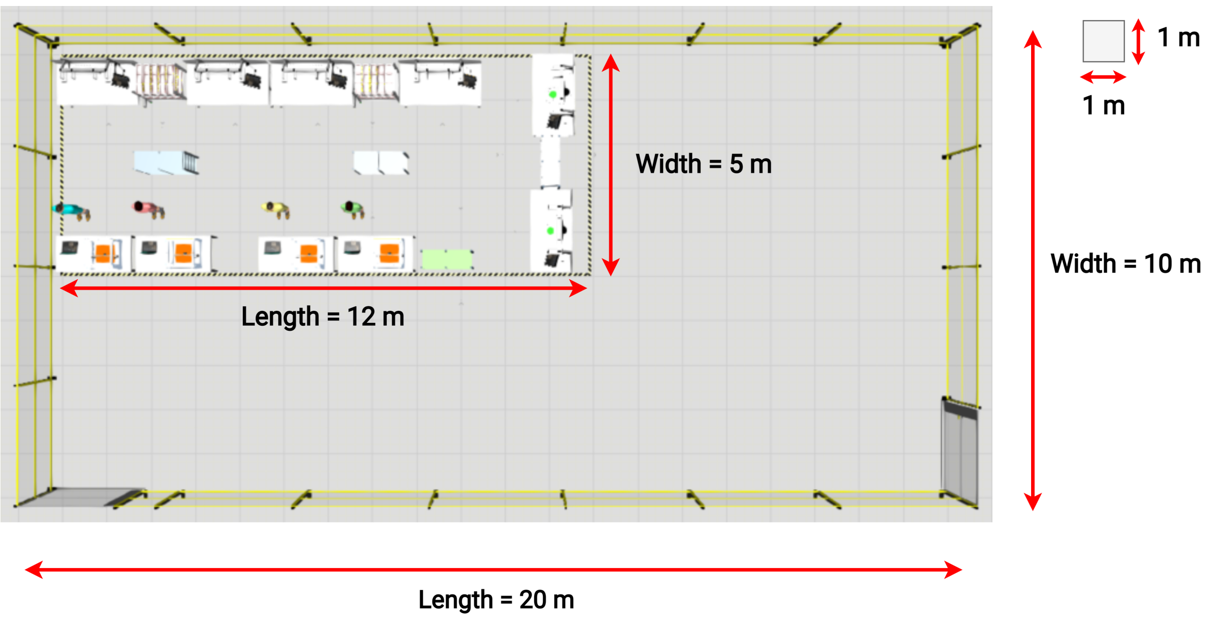


Figure 45: The Learning Factory and its dimensions.

Practical benefits

Although the simulation took long to make, a large advantage was achieved in terms of further iteration. For example, it was possible to change the layout of the factory in a very short time, while maintaining all the routing and assembly settings. The result of a first iteration can be seen in Figure 46. Compared to the factory in Figure 34, the average time spent on walking of each user is shortened by a few seconds. Considering the total processing time, the waste as a result of walking time is short. For more advanced manufacturing and production of larger volumes, the benefit will be more significant. What is useful is that the processing time per piece of equipment and per assembly step can be altered. A simulation is perfect to test and validate a change in layout or numbers.

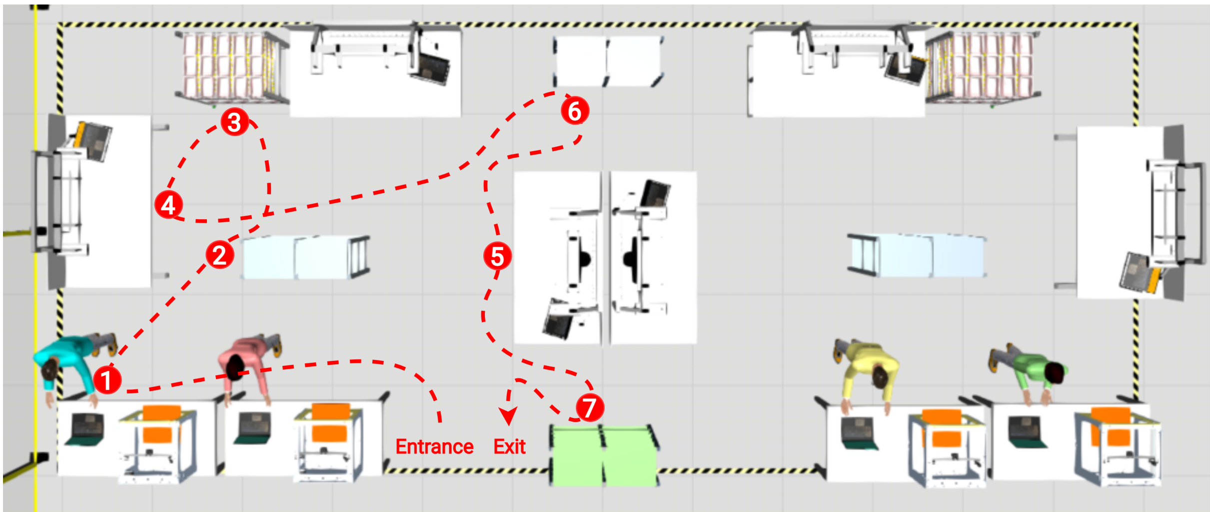


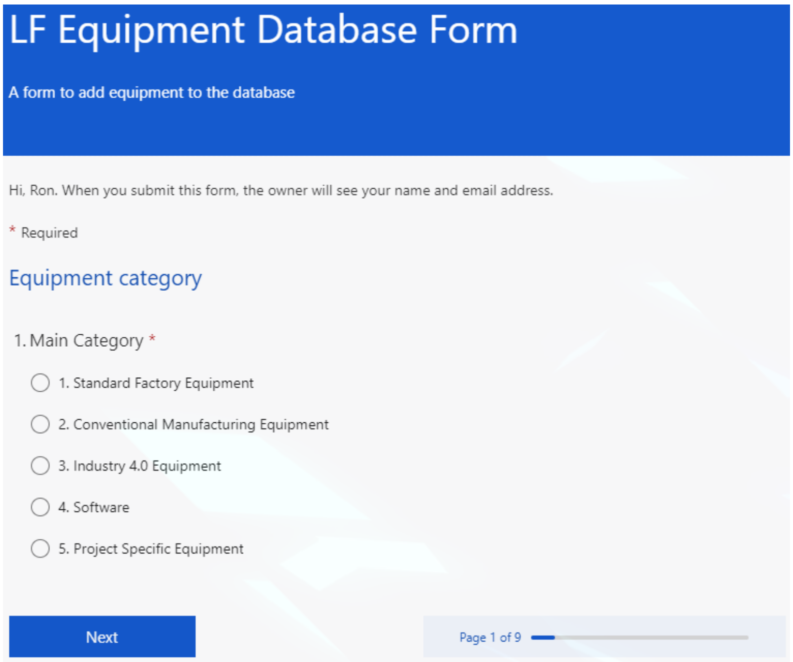
Figure 46: A changed layout of the learning factory.

6 Implementation of database input form

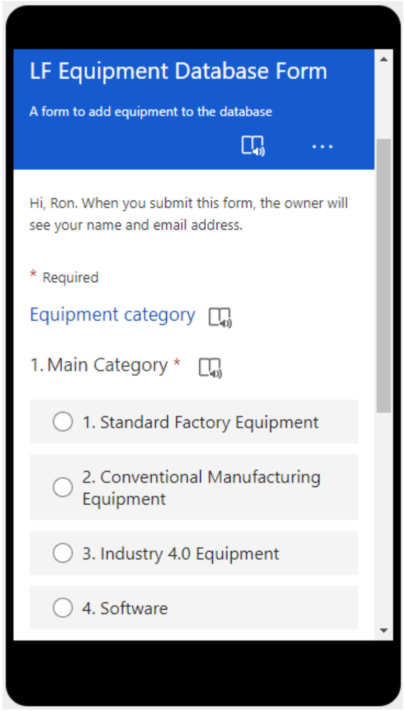
It would be desirable if users can fill the database by means of submitting an online form. This greatly improves the user experience, efficiency and above all increases the amount of equipment to choose from. The first step for this purpose has already been made.

The working principle is proven using *MS forms*[138] in combination with my personal *MS Onedrive*[139] cloud storage. Additionally the form is automatically filtered on the required information and sorted in the right order for further processing. The working principle is demonstrated in the figures below and consists of the following steps:

Step 1: Open the forms in your browser, see Figure47a. The browser asks you to log in with your UT account. As shown, the email address and name has already been taken from the UT-account. The form can also be filled using mobile phone, see Figure 47b.



(a) MS Form: PC view



(b) MS Forms: Mobile Phone view

Figure 47: The starting page of the forms. Choose an equipment-category. Name and email address are automatically recorded

Step 2: Now for the equipment that you want to add, select an e-category. As explained before in Section 4.3.1, there are 5 e-categories:

1) Standard factory equipment: generally always available in the factory.
2) Conventional factory equipment: this is equipment that you see in conventional factories like heavy machinery.
3) Industry 4.0 equipment: equipment that has affinity with industry 4.0 like a 3D printer and AR glasses.
4) Software: anything similar or related to software programs.
5) Product-specific equipment: all types of equipment that would only be useful for specific projects.

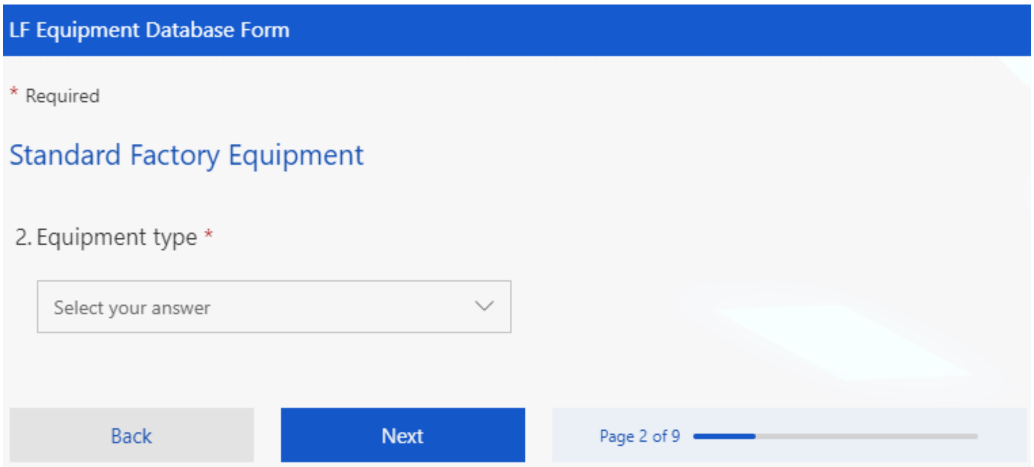


Figure 48: The user is asked to select the equipment type.

Step 3: Then select equipment-type, see Figure 49. Check if your e-type is already present or add it as 'other'.

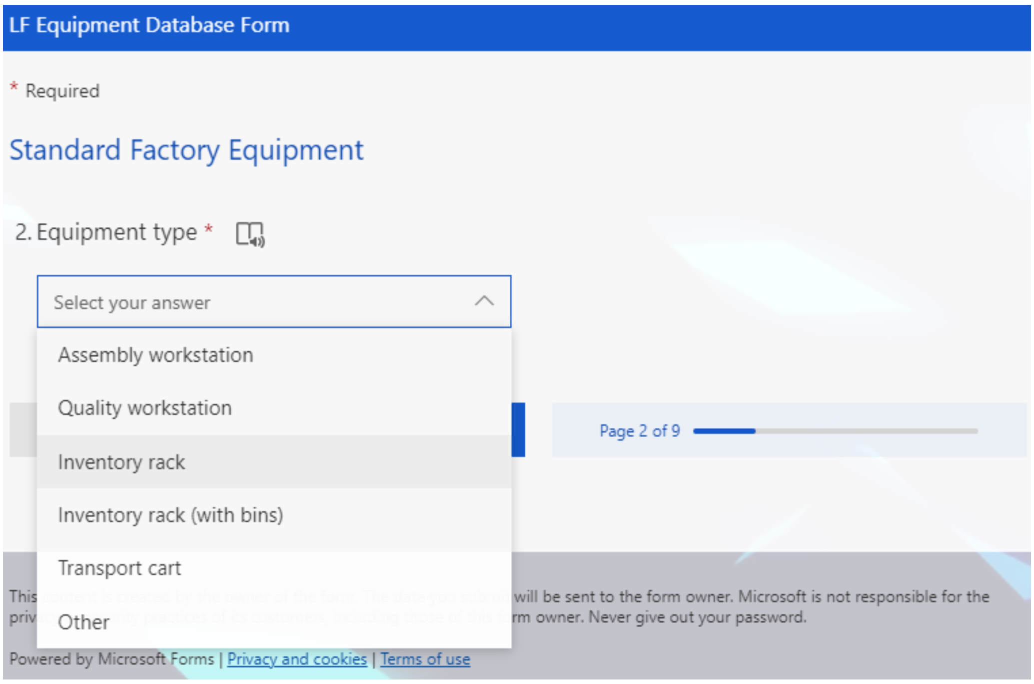


Figure 49: Equipment-type drop-down menu appears.

Step 4: Add the length, width and height dimensions for your specific equipment-model.

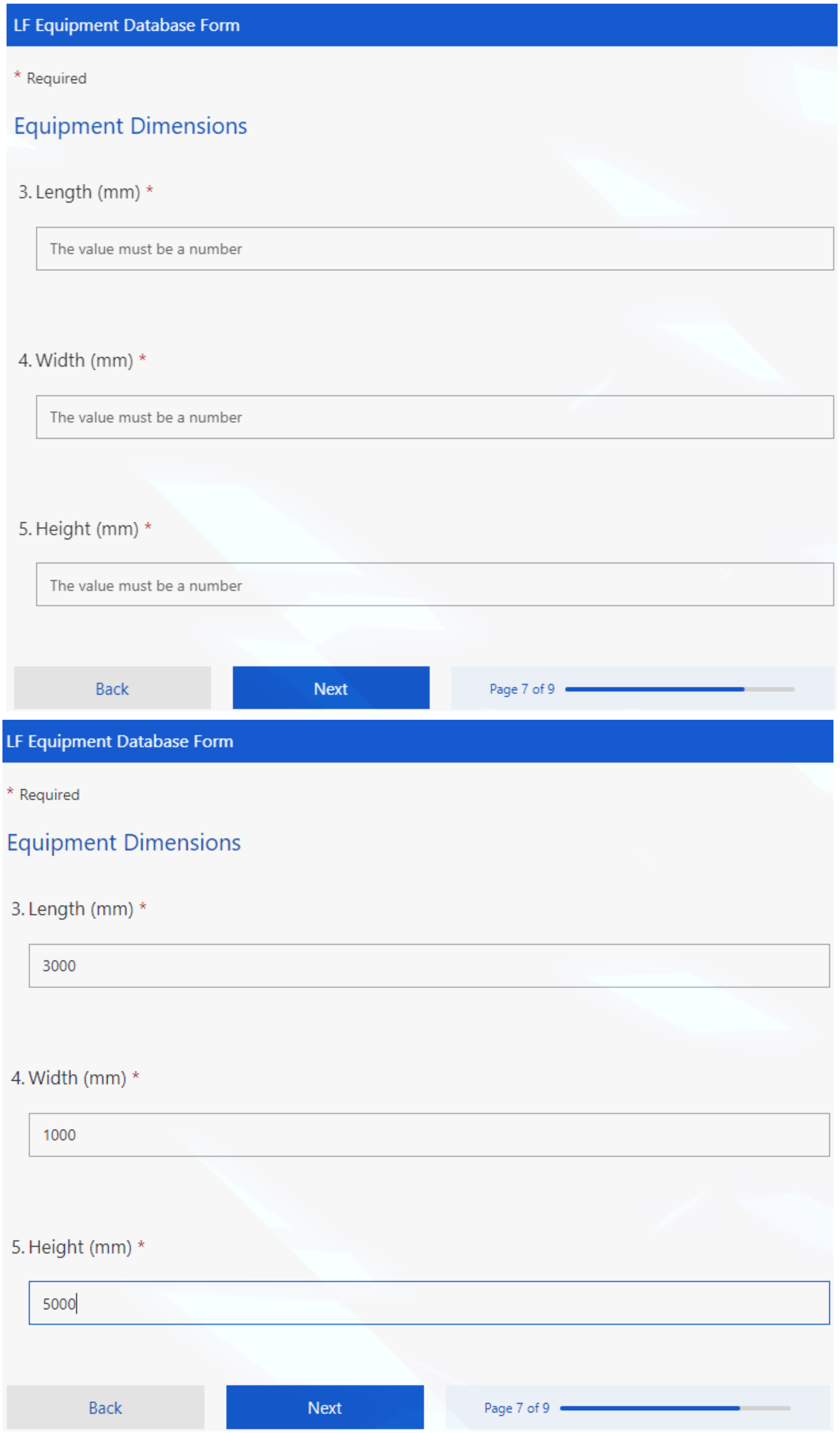


Figure 50: The user is asked to fill in the dimensions of the added equipment-model.

Step 5: As shown in Figure 51, describe briefly about special features and add the procurement price of the added e-model. Examples are given in the subtitles of the questions.

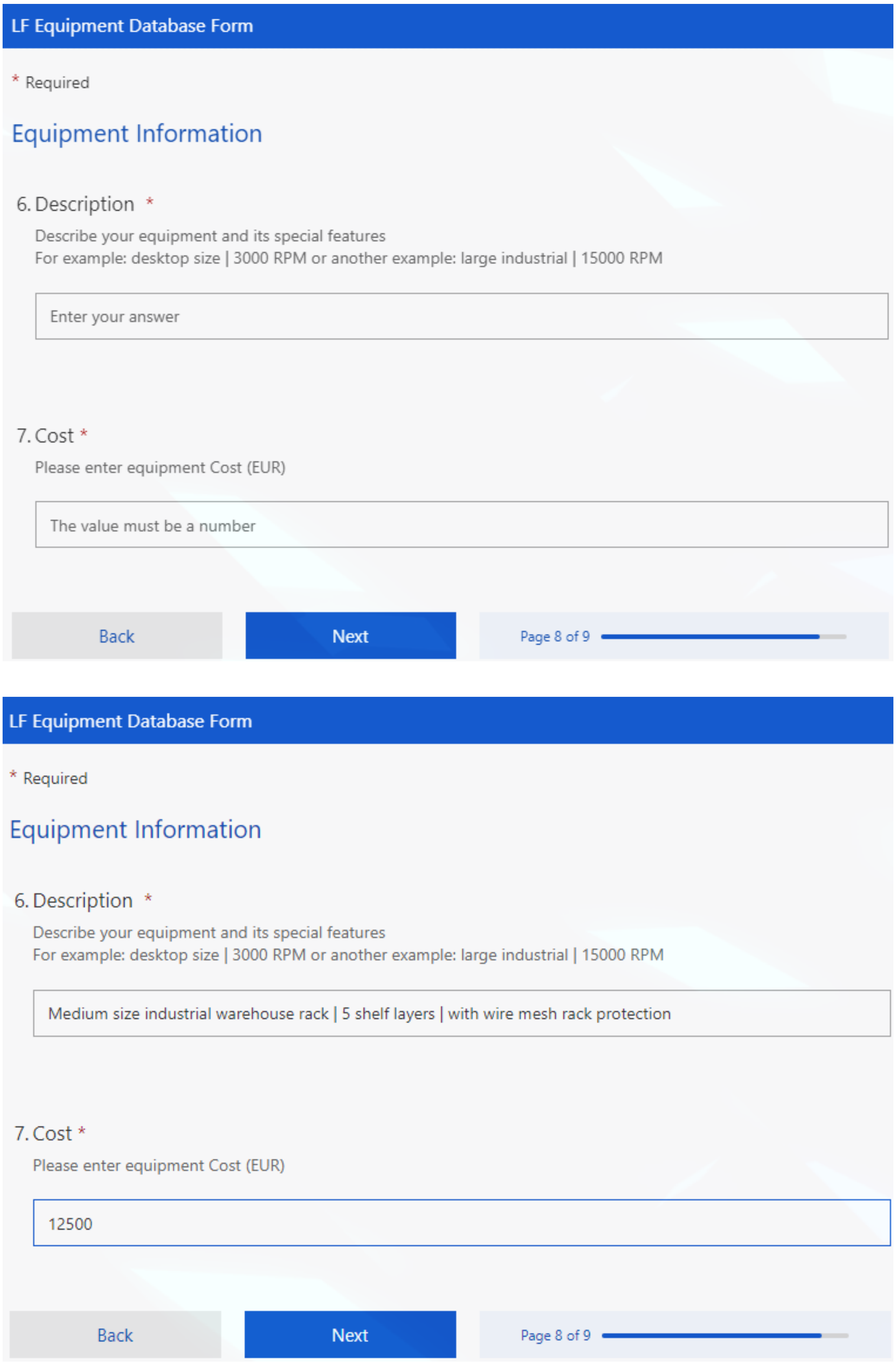
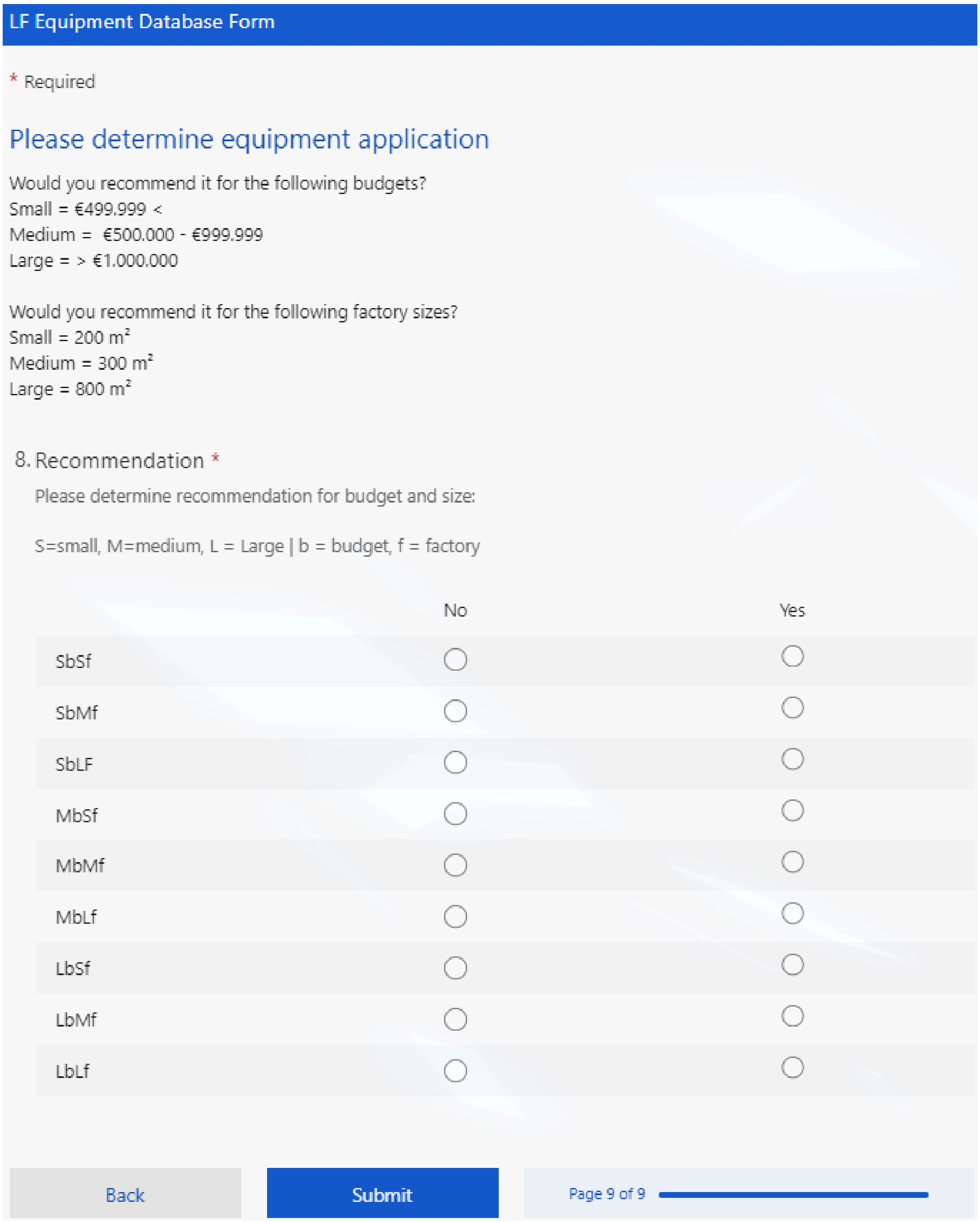


Figure 51: The user is asked to describe the equipment model and its key features

Step 6: Next, determine for what LF budget/size scenarios the e-model fits. As described in Section 4.3.2, three budget(b) and factory size(f) specifications are used. Small(S), Medium(M) and Large(L) Budget combined with a small, medium or large Factory. A combination of these, brings the total amount of budget/size scenarios to nine: SbSf, SbMf, SbLf, MbSf, MbMf, MbLf,LbSf, LbMf, LbLf. The equipment that is added by the form, has been advised to be used with a minimum budget of € 500.000 and for factories with a minimum size of 300 m^2, see Figure 53.


LF Equipment Database Form

* Required

Please determine equipment application

Would you recommend it for the following budgets?
Small = €499.999 <
Medium = €500.000 - €999.999
Large = > €1.000.000

Would you recommend it for the following factory sizes?
Small = 200 m²
Medium = 300 m²
Large = 800 m²

8. Recommendation *

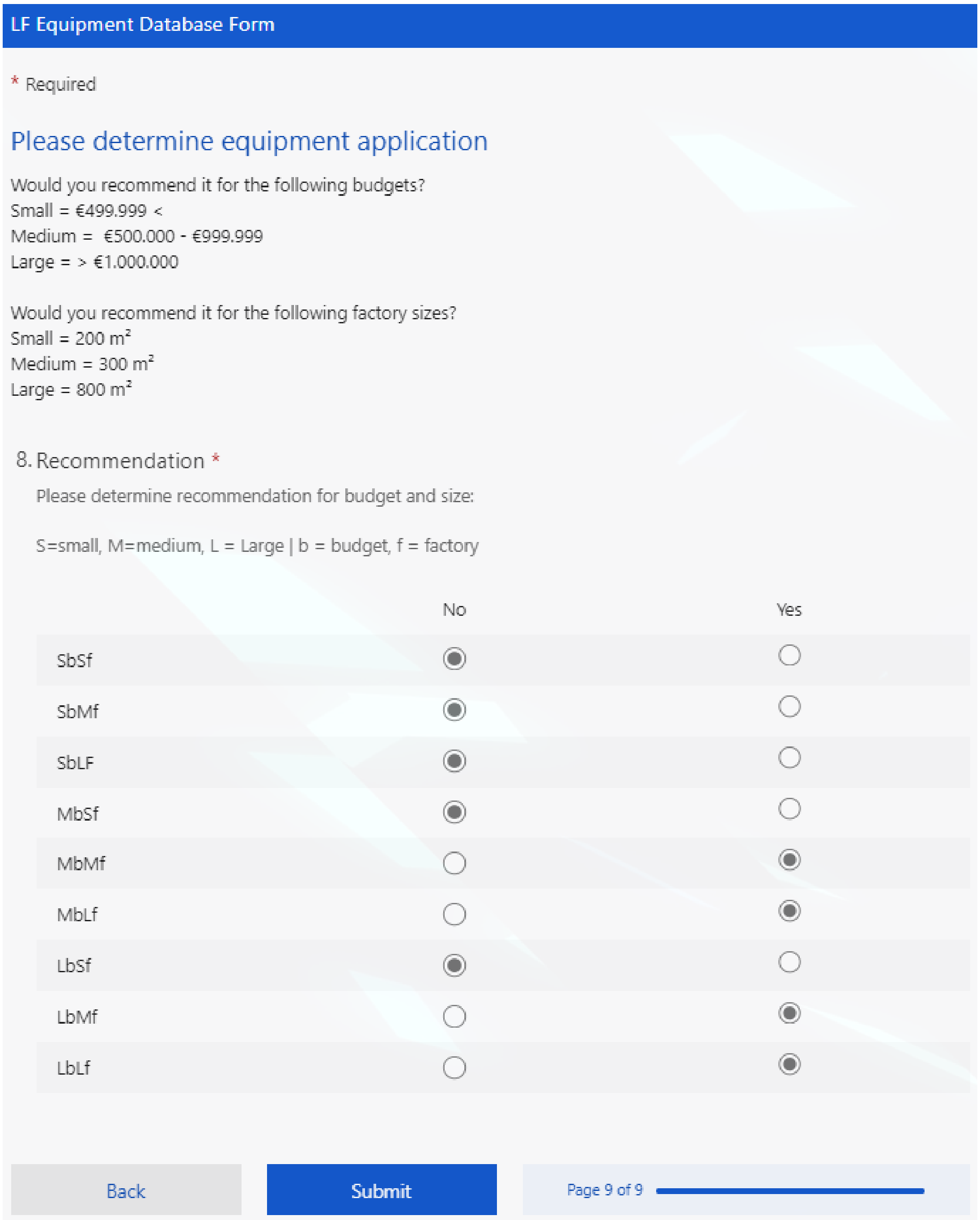
Please determine recommendation for budget and size:

S=small, M=medium, L = Large | b = budget, f = factory

	No	Yes
SbSf	○	○
SbMf	○	○
SbLF	○	○
MbSf	○	○
MbMf	○	○
MbLf	○	○
LbSf	○	○
LbMf	○	○
LbLf	○	○

Back | Submit | Page 9 of 9

Figure 52: The user is asked to give advice on the budget/size scenarios for using that model of equipment.


LF Equipment Database Form

* Required

Please determine equipment application

Would you recommend it for the following budgets?
Small = €499.999 <
Medium = €500.000 - €999.999
Large = > €1.000.000

Would you recommend it for the following factory sizes?
Small = 200 m²
Medium = 300 m²
Large = 800 m²

8. Recommendation *

Please determine recommendation for budget and size:

S=small, M=medium, L = Large | b = budget, f = factory

	No	Yes
SbSf	●	○
SbMf	●	○
SbLF	●	○
MbSf	●	○
MbMf	○	●
MbLf	○	●
LbSf	●	○
LbMf	○	●
LbLf	○	●

Back | Submit | Page 9 of 9

Figure 53: For each budget/size scenario it is indicated if the equipment-model is advised.

Step 7: Submit the form and a confirmation window pops up, see Figure 54.

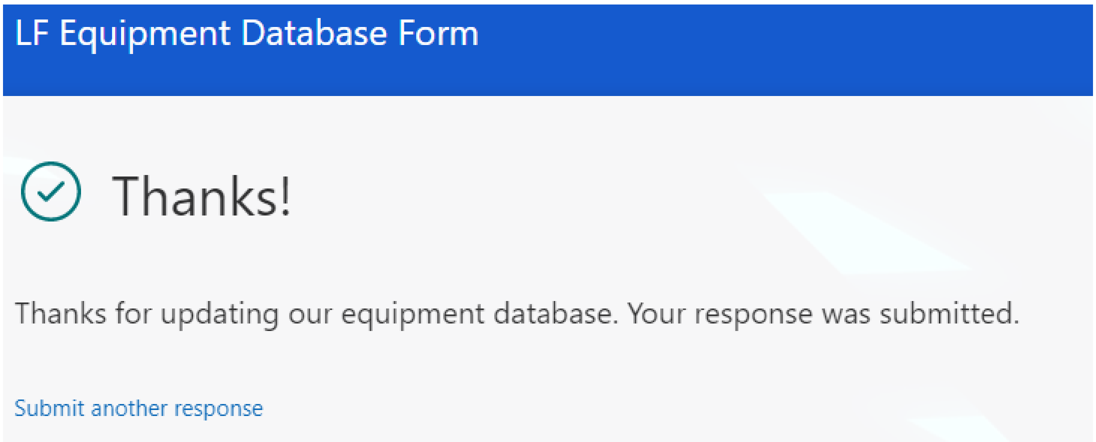


Figure 54: The user has completed the form.

Step 8: The form output is shown in Table 38. It can be seen that the form has many blank spots which are created during the first step of choosing a main category. Also, the name and email of the submitting user and the time and date of submission is recorded. An external *Excel* sheet automatically formats the cloud-data, to a condensed version using regular *Excel* commands. The condensed version shows only the necessary information and has no blank spots. The result can be seen in Table 39 on page 89. Note that it is hardly readable, but as for the important information, it will become clear in the next step.

Table 38: MS Forms output.

ID	Start time	Completion time	Email	Name	Main Category	Equipment type	Equipmen type4	Equipmen type3	Software type	Equipmen type2	Length (mm)	Width (mm)	Height (mm)	Description	Cost €	SbSf	SbMf	SbLF	MbSf	MbMf	MbLf	LbSf	LbMf	LbLf
5	11-29-22 11:48:42	11-29-22 11:49:50	rfrielinck@student.utwente.nl	Ron Frielinck	1. Standard Factory Equipment	Transport cart					2000	1000	700	large cart — electric drive support	10000	No	No	No	No	No	Yes	No	Yes	Yes
6	11-29-22 11:49:55	11-29-22 11:51:08	rfrielinck@student.utwente.nl	Ron Frielinck	1. Standard Factory Equipment	Assembly workstation					1500	700	700	regular assembly station — height adjustable	15000	No	No	No	Yes	Yes	Yes	Yes	Yes	Yes
8	11-29-22 13:15:25	11-29-22 13:17:40	rfrielinck@student.utwente.nl	Ron Frielinck	5. Project Specific Equipment					Metal SLM Printer	600	500	800	Small industrial — 0.1 m3/hour	30000	No	No	No	No	No	No	No	Yes	Yes
11	11-29-22 13:47:10	11-29-22 13:47:59	rfrielinck@student.utwente.nl	Ron Frielinck	2. Conventional Manufacturing Equipment		Injection moulding machine				400	800	400	Desktop size — 20gr shot size	5000	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
12	11-29-22 13:49:56	11-29-22 13:50:31	rfrielinck@student.utwente.nl	Ron Frielinck	3. Industry 4.0 Equipment			Industrial cameras			30	30	30	Small tracking camera	50	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
13	11-29-22 13:50:33	11-29-22 13:59:44	rfrielinck@student.utwente.nl	Ron Frielinck	4. Software				3D print slicer software					Cheap Slicer	100	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
14	11-29-22 14:00:48	11-29-22 14:01:12	rfrielinck@student.utwente.nl	Ron Frielinck	4. Software				AR software					Cheap AR software	300	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
16	12-2-22 13:45:54	12-2-22 13:47:10	rfrielinck@student.utwente.nl	Ron Frielinck	2. Conventional Manufacturing Equipment		Laser cutting machine				400	600	400	small desktop size — 20 mm/s	7500	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
17	12-2-22 15:08:54	12-2-22 15:09:52	rfrielinck@student.utwente.nl	Ron Frielinck	3. Industry 4.0 Equipment			Industrial sensors			50	50	50	Machine torque sensor	500	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
18	12-22-22 19:07:40	12-22-22 19:09:30	rfrielinck@student.utwente.nl	Ron Frielinck	1. Standard Factory Equipment	Quality workstation					1500	900	1000	Regular sized table with quality inspection tools	10000	No	No	No	Yes	Yes	Yes	Yes	Yes	Yes
19	12-22-22 19:10:11	12-22-22 19:11:47	rfrielinck@student.utwente.nl	Ron Frielinck	2. Conventional Manufacturing Equipment		Laser cutting machine				2000	800	1000	Medium sized industrial CO2 laser cutter — 20 mm/s cutting speed	15000	No	No	No	No	Yes	Yes	Yes	Yes	Yes
20	12-22-22 19:11:55	12-22-22 20:31:45	rfrielinck@student.utwente.nl	Ron Frielinck	5. Project Specific Equipment					Spot Welding Machine	700	300	1500	Desktop size — 15 mm diameter weld	1500	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
21	12-22-22 20:46:28	12-22-22 20:48:26	rfrielinck@student.utwente.nl	Ron Frielinck	5. Project Specific Equipment					Induction welding machine	800	600	1500	Small industrial — made for thermoplastic composite welding	5000	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
22	12-22-22 21:22:28	12-22-22 21:28:07	rfrielinck@student.utwente.nl	Ron Frielinck	1. Standard Factory Equipment	Inventory rack					3000	1000	5000	Medium size industrial warehouse rack — 5 shelf layers — with rack guards	12500	No	No	No	No	Yes	Yes	No	Yes	Yes
25	12-23-22 13:18:01	12-23-22 13:19:28	rfrielinck@student.utwente.nl	Ron Frielinck	3. Industry 4.0 Equipment			AGV			2000	1000	3000	Large industrial AGV — 15 km/h	100000	No	No	No	No	No	No	No	No	Yes

Table 39: MS Forms output condensed.

Main Category	Equipment type	Length (mm)	Width (mm)	Height (mm)	Description	Cost	SbSf	SbMf	SbLF	MbSf	MbMf	MbLf	LbSf	LbMf	LbLf
1. Standard Factory Equipment	Transport cart	2000	1000	700	large cart — electric drive support	10000	No	No	No	No	No	Yes	No	Yes	Yes
1. Standard Factory Equipment	Assembly workstation	1500	700	700	regular assembly station — height adjustable	15000	No	No	No	Yes	Yes	Yes	Yes	Yes	Yes
1. Standard Factory Equipment	Quality workstation	1500	900	1000	Regular sized table with quality inspection tools	10000	No	No	No	Yes	Yes	Yes	Yes	Yes	Yes
1. Standard Factory Equipment	Inventory rack	3000	1000	5000	Medium size industrial warehouse rack — 5 shelf layers — with rack guards	12500	No	No	No	No	Yes	Yes	No	Yes	Yes
2. Conventional Manufacturing Equipment	Injection moulding machine	400	800	400	Desktop size — 20gr shot size	5000	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
2. Conventional Manufacturing Equipment	Laser cutting machine	400	600	400	small desktop size — 20 mm/s	7500	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
2. Conventional Manufacturing Equipment	Laser cutting machine	2000	800	1000	Medium sized industrial CO2 laser cutter — 20 mm/s cutting speed	15000	No	No	No	No	Yes	Yes	Yes	Yes	Yes
3. Industry 4.0 Equipment	Industrial cameras	30	30	30	Small tracking camera	50	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
3. Industry 4.0 Equipment	Industrial sensors	50	50	50	Machine torque sensor	500	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
3. Industry 4.0 Equipment	AGV	2000	1000	3000	Large industrial AGV — 15 km/h	100000	No	No	No	No	No	No	No	No	Yes
4. Software	3D print slicer software	0	0	0	Cheap Slicer	100	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
4. Software	AR software	0	0	0	Cheap AR software	300	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
5. Project Specific Equipment	Metal SLM Printer	600	500	800	Small industrial — 0.1 m3/hour	30000	No	No	No	No	No	No	No	Yes	Yes
5. Project Specific Equipment	Spot Welding Machine	700	300	1500	Desktop size — 15 mm diameter weld	1500	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
5. Project Specific Equipment	Induction welding machine	800	600	1500	Small industrial — made for thermoplastic composite welding	5000	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Step 9: Finally, the form output must be sorted to represent a table that looks similar to Table 27 on page 58. This can be done using a VBA macro, of which the code is shown in Appendix C.3.2. This code removes the old list. Next it replaces it with the new equipment list and automatically sorts it to the right order, based on the equipment category. It also counts how much equipment is present within each category. Additionally some columns are swapped around, so it will fit according to Table 27. The result can be seen in Table 40. The code from this macro can be added to the 'generate equipment list' button from Section 4.3.7 and Figure 29 on page 63.

Table 40: MS Forms output sorted.

Main Category	**Equipment type**	**Description**	**Length (mm)**	**Width (mm)**	**Height (mm)**	**Cost (€)**	**SbSf**	**SbMf**	**SbLF**	**MbSf**	**MbMf**	**MbLf**	**LbSf**	**LbMf**	**LbLf**
1. Standard Factory Equipment	Transport cart	large cart — electric drive support	2000	1000	700	10000	No	No	No	No	No	Yes	No	Yes	Yes
1. Standard Factory Equipment	Assembly workstation	regular assembly station — height adjustable	1500	700	700	15000	No	No	No	Yes	Yes	Yes	Yes	Yes	Yes
1. Standard Factory Equipment	Quality workstation	Regular sized table with quality inspection tools	1500	900	1000	10000	No	No	No	Yes	Yes	Yes	Yes	Yes	Yes
1. Standard Factory Equipment	Inventory rack	Medium size industrial warehouse rack — 5 shelf layers — with rack guards	3000	1000	5000	12500	No	No	No	No	Yes	Yes	No	Yes	Yes
4															
2. Conventional Manufacturing Equipment	Injection moulding machine	Desktop size — 20gr shot size	400	800	400	5000	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
2. Conventional Manufacturing Equipment	Laser cutting machine	small desktop size — 20 mm/s	400	600	400	7500	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
2. Conventional Manufacturing Equipment	Laser cutting machine	Medium sized industrial CO2 laser cutter — 20 mm/s cutting speed	2000	800	1000	15000	No	No	No	No	Yes	Yes	Yes	Yes	Yes
3															
3. Industry 4.0 Equipment	Industrial cameras	Small tracking camera	30	30	30	50	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
3. Industry 4.0 Equipment	Industrial sensors	Machine torque sensor	50	50	50	500	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
3. Industry 4.0 Equipment	AGV	Large industrial AGV — 15 km/h	2000	1000	3000	100000	No	No	No	No	No	No	No	No	Yes
3															
4. Software	3D print slicer software	Cheap Slicer	0	0	0	100	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
4. Software	AR software	Cheap AR software	0	0	0	300	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
2															
5. Project Specific Equipment	Metal SLM Printer	Small industrial — 0.1 m3/hour	600	500	800	30000	No	No	No	No	No	No	No	Yes	Yes
5. Project Specific Equipment	Spot Welding Machine	Desktop size — 15 mm diameter weld	700	300	1500	1500	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
5. Project Specific Equipment	Induction welding machine	Small industrial — made for thermoplastic composite welding	800	600	1500	5000	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
3															

7 Conclusion

As explained in Section 2.1, a new Learning Factory (LF) will be build on the University of Twente (UT). The problem with current existing Learning Factories is that they are capital intensive and rigidly built for a few specific purposes. After completion, there is not much room for differentiating the Learning Subjects (LS), Educational Products (EP) or LF equipment. As such, the added value of the LF diminishes over time, as research and innovation within the field of manufacturing progresses.

Therefore, the goal of this paper was to develop a tool to preserve and maintain the lifespan and educational value of an LF. To answer this, a literature study has been conducted on Active Learning Methods (ALMs), Learning Factories itself, Learning Subjects and their relation to the Learning Factory. Next, methods to preserve the value of Learning Factories have been explored. All information gathered up to this point has been combined into the development of the tool to preserve the value.

Multiple Active Learning Methods (ALMs) have been identified. Although there are different approaches, they all have in common to focus on the students personal growth through collaborative group assignments. A Learning Factory is a good method to facilitate ALMs, because it provides an experiential area that allows the students to experiment with realistic problems. By doing so, thinking and doing are integrated and this gives direct feedback to the learners and their actions. Acquiring new skills can be done by following Learning Paths (LPs) that are integrated in the factory. As an actual production process is planned in the LF, multiple LPs can be featured. By performing LPs inside the LF, the learners are supported to better understand new subjects. The production process can be equipped with multiple types of equipment allowing for multiple LSs to be offered. In case multiple LSs, although in totally different fields, complement each other, it is called a Learning Course (LC). With a good mix of equipment, multiple LCs can be offered in the LF as well. An Educational Product is manufactured in the LF and has the function to bring multiple (theoretical) LSs of a LC together into a practical use-case.

To maintain and preserve the value, it is important for a learning factory to be changeable through the use of modular design that is interoperable, independent of the types of equipment. A downside of a changeable learning factory is that its hard to keep an overview of what is currently in the factory. Most importantly, what has to change to accommodate new learning subjects and educational projects.

The Learning Factory Configuration Tool (LFCT) has been developed, to solve that problem. As a starting point, a comprehensive study went into the required equipment for both the LSs and the EPs. For the LSs, it has been decided to focus on the current mechanical engineering course program of the University of Twente. 29 subjects have undergone a selection based on a set of criteria dedicated towards LF incorporation, lean and industry 4.0. In total, 10 LSs were selected for further analysis. By determining possible LF incorporation for each LS, the required equipment could be derived. This resulted in a list of equipment based on the offered Learning Subject.

For deriving Educational Products, 11 products were initially chosen by a study into existing LFs. The goal was to select 5 EPs for further treatment in the LFCT. This was done by setting up 4 requirements and 11 characteristics to accommodate these requirements as best as possible. Using a correlation matrix, the most effective characteristics were determined. Then using a second correlation matrix, the 11 products were weighed against these characteristics and eventually this resulted in 5 possible products. For each product an EP description was written. This included the knowledge gained while selecting the LSs and by going through the assembly process of the EP. This also led to writing a manufacturing plan. Using the EP description and the corresponding MP, an equipment list based on the EP could be formulated.

As introduced in Section 4, when a selection of equipment must be made, a circularity problem occurs. You either need to know what LSs are required, or you need to know what EPs will be made. On itself, each provides insight about the required equipment, but in reality you want to have both. Equipment required for manufacturing of the EP does not immediately mean that you can offer the full LS. The equipment based on the LS does not directly allow you to manufacture an EP. As such, the tool grants a list of equipment based on both inputs. This way, the user can decide on the types of equipment for the LSs and the EPs that will be running through the factory.

As described in Section 4.3.6, based on the EPs, the required (and optional) LSs, the possible LF budget and LF size, the LFCT will generate an equipment list. The equipment list, together with the project descriptions from Section 4.1.2 and Manufacturing Plans from section 4.1.3, was used for setting up a digital twin. It showed the feasibility of the suggested Learning Factory by the LFCT. The simulated EP involves the manual assembly of a drone, using a custom 3D printed frame.

When looking at the design requirements stated in Section 4.1, it can be concluded that the product adds value through knowledge and experience. It covers 4 out of 10 LSs which is bad for a first iteration, as now 6 other LSs, must be setup elsewhere. However, this can be improved by implementing automation. Besides, the used space, 60 m^2 of 200 m^2, is very minor, so there is enough room left for another EP that covers the other LSs, or for an expanded factory with a more comprehensive EP. The current drone is very manufacturable as all parts are procured and come in one assembly kit. No heavy machinery is required, but there is room for such devices.

Next to the simulation, a database input form has been successfully tested as proof of concept. It showed how a cloud-based data system can be made with easy user input. By means of filling in an online form, the database gets fed with equipment. A downside is, that over time a huge database will be created which you do not want to manually filter.

Future work on the LFCT should focus on incorporating the stakeholders into the decision making. For example a stakeholder discussion on the correlation matrices, the selection of LSs or the design of EPs would be useful. Secondly by moving the entire database, which is now saved locally, to the cloud. Next, as the database bulges out from options, an algorithm must be found that filters most results for you, such that only a few options are shown. For the factory, to accommodate more LSs, an automated production line must be setup. This could either be implemented for the drone, or with another production line, like the complex turbine gearbox assembly.

7.1 Limitations

As shortly mentioned in the conclusion, it would have been helpful to involve stakeholders, like operators, instructors and target groups, as described by Tisch et al. [30] in Section3.2.1, into decision-making procedures in Section 3.6. For example when:

* setting up educational product criteria in Section 4.1.1.
  In step 1 of this section, possible EPs to produce in the LF were investigated. In step 2, four EP requirements and eleven selection criteria were setup. In step 3, each criterion was rated on the relationship towards the EP requirements to determine its relative weight. And in step 4, each EP was given a score for each criterion, where the criteria with the highest weight had most impact on the final score of the EPs. For all of these decisions, stakeholder discussion could have been valuable to make sure all points of view were taken into account. From step one up to step four, as the outcome of each step influence affects the following steps.

* making EP descriptions and manufacturing plans in Sections 4.1.2 and 4.1.3.
  EP descriptions were written using basic knowledge of LSs and production. Instructors knowledge about LS combined with workshop staff or company knowledge about manufacturing could improve the educational value of the EPs and their respective manufacturing plans. Students could be used to test the outcome before putting it to practice in real education.

* rating and selection of learning subjects and figuring out how to implement it in the learning factory in Section 4.1.4.
  A criterion for selection of LSs was the possibility to include it in the LF and imagining how to include it in the LF. Instructor and workplace staff point of view would again be useful as they have the most knowledge about courses given on the UT and can determine best what is useful to realize.

* determining equipment selection criteria in Section 4.2 and coupling equipment to LSs and EPs in Section 4.3.5.
  Despite the performed valuation, the chosen criteria and given weights are quite arbitrary and can use a thorough discussion between workshop staff and instructors.

* coupling equipment to LSs and EPs in Section 4.3.5.
  This coupling is based on the written EP descriptions and MPs. As such, the same stakeholders could be involved in this process.

* doing an LF equipment selection in Section 4.3.7.
  Workplace staff and instructors can determine best what to procure, also in relation to the possible LSs and EPs that will be supported by the LF. Companies must be reached out to, to understand the learning factory related possibilities of complex and expensive machines.

It was sometimes difficult to decide what factors are important and how important they are. Therefore, it was inevitable that some personal preferences have poured into the result. In the end, the method itself is repeatable and still useful. The current results are as good as possible, based on well-founded decisions despite the described shortcomings.

Another part that needs discussion is Section 5.1. As already mentioned there, a VSM is not used for its original purpose. Normally a VSM is a lean tool that you utilize to measure the process time of your current production line. By measuring all value and non-value adding activities, you can map where non-value adding activities should be removed from the process. In this thesis it was used to map an imaginary manufacturing process to set up the simulation. The times used are based on an assumption of a student without prior knowledge. The problem that is created here, is that result is directly used as input for selecting the amount of equipment-models. So the simulation that followed is also based on that same assumption.

As shown in Table 35 on page 69, the assembly time is 4 hours. However, there exists a recording of an experienced instructor at the UT that does the drone assembly in 20 minutes. Both of these timings are very far apart and an experience instructor is not representative for a student. Therefore a comprehensive time study[140] must be performed on an actual production process. It is suggested that this is done using a large sample size of students without prior knowledge. The result of this study can be used to determine the process times more accurately.

7.2 Future Work

As suggested by the conclusion and section about limitations, it is possible to improve the configuration tool and the learning factory. First, in Section 7.2.1, advise is given on further development of the configuration tool. Here, the focus lies in changing the database infrastructure and improving the efficiency by automatic equipment filtering. Next in Section 7.2.2, upgrades to the currently simulated learning factory are discussed. In Section 7.2.3, improvements towards realizing a digital twin are discussed.

7.2.1 Configuration Tool Recommendations:

The working principle of the configuration model has been validated positively. However, the tool is not finished at all, as a few possibilities for improving this tool have risen and of which one concept has been proven already. Firstly, a quick change would be to include the links to the procurement websites into the equipment list output of the LFCT. As a second step, it is possible to move the database from a local storage, to a central Structured Query Language (SQL) cloud. Following up on that, To prevent the configuration tool from bulging out with options to choose from, an AI machine learning filter algorithm could be placed over it. Each of these steps will be explained in more detail below.

Include links to procurement websites into the tool
The current database includes a column that contains links to procurement websites of each equipment-model. It would probably be more efficient to retrieve these links from the database and put them into an extra column in the equipment list output of the LFCT. This could enable faster procurement or finding 3d models for the simulation.

Moving the database to a central SQL cloud
Currently the database is on my personal cloud storage at the *MS Onedrive*[139] of the University of Twente. For future usage, a central accessible database could be a possibility. The most common form of database is in tabular form and has rows and columns. SQL is the most used programming language to communicate with this type of database[141][142]. It offers queries for database modification, management and input and retrieval of data. Moving the database to a cloud has more benefits[143][141] as listed below:

1) **Accessibility:** API's for accessing the database are easily build-in for applications and web interfaces, for example a database input form.
2) **Reliability:** a cloud-based database has two advantages in terms of reliability. Firstly, your data is still accessible in case of a power outage, or equipment failure. Secondly, it offers redundancies in the form of back-up systems and your data is stored and encrypted behind multiple layers of security.
3) **Scalability:** with more usage, the amount of data stored, modified and requested in a database increases. A cloud environment allows for easy up and down scaling according to dynamically changing user needs. So no additional hardware is required if the amount of stored data increases in the future or traffic increases during peak usage.
4) **Cost savings:** having your data stored in an online cloud environment reduces the required amount resources to keep up your own database server. For example IT staff, facilities, maintenance and operation costs.

Database selection filter

The LFCT currently completely operates manually. So both the database input, the coupling of e-types to LSs and EPs and the selection of e-models from the equipment list. Because the database is expected to expand greatly in the future, the next step could be to filter the database before a user is able to select which e-model is required or not. This could be done by implementing a machine learning filter algorithm. One way of doing that is as follows:

1) First the system makes a shortlist of most selected types of equipment.
2) Then, for each newly generated equipment list, the same shortlist is used, plus a few extra options from the database. This could be done on both secondary or tertiary levels of equipment(explained in Section 4.3.1).
3) If users select some options more than others, the less selected options get a lower priority for the options-list and the more selected options get a higher priority on the options-list. This way, more usage leads to a better shortlist for everyone. For very specific equipment, a manual way of searching and adding equipment must also be included. Additionally, the AI could provide the user with an equipment selection score on, criteria determined by stakeholders, like performed in Table 26.

7.2.2 Current learning factory recommendations:

By taking into considerations the points above, a few recommendations can be given on the currently designed learning factory. Now that 60 m^2 is taken, 140 m^2 is left. The drone project covers four LSs, therefore I would recommend to fill the rest of the factory with the automated assembly of the complex wind turbine gearbox. This has the benefit that the other 6 LSs are covered and therefore all 10 LSs. It is expected that a lot of room is required for conveyor belts, cobots and AGVs, as these are key for automated factories. Independent of the LSs, I would recommend to have at least an extra injection moulding and laser cutting machine, which opens up many possibilities in terms of manufacturing and customized products. Conventional machines are currently planned for another floor in the new *CUBE* building [127], but if a selection is still required, it would be a small industrial milling machine. This type of machine is the most flexible in terms of material and shape processing. Second, a small industrial turning machine is recommended for similar reasons. The other conventional machines can become very expensive quickly while the added value is much less.

To give an impression of how that would look like, Figure 55 is made. For each type of machine the added floor area is shown, scaled down to the data from Table 41:

Table 41: The chosen equipment for the extra space in the learning factory.

Equipment Type	Name	Description	Length	Width	Cost
Injection moulder	MicroMolder[115]	Desktop 310 °C heating temperature 222x222x223 work area 59.15 cm3 shot size	1092	305	€ 10.000
Laser cutter	XM1490[112]	Small industrial 1400 x 900 work area 500 mm/s cutting speed	1980	1270	€ 7.320
Turning machine	CC-D6000HS-5M[122]	Medium industrial 600 mm between centers 270 mm turning diameter	2100	900	€ 29.920
Milling machine	SYIL X5[105]	Small industrial 300x280x300 work volume 20 kRPM	2100	1000	€ 24.990

Considerations

For the selection of equipment, only the database from Table 75 in Appendix C.1 is considered. The desktop sized *MicroMolder*[115] injection moulding machine was chosen because it can handle 3D printed moulds and is therefore is very cheap to operate throughout its lifetime. A lot of variability for parts can be achieved, a limiting factor could be the size of the parts. Also it is questionable how a 3D printed mould performs versus a metal mould.

The small industrial *XM 1490*[112] laser cutting machine is chosen because of its large work area, and at the same time staying compact at about the size of a work station table. It offers the most variability in terms of cutting functionalities compared to the other laser cutters in the database. The cheaper and smaller option is more used for engraving instead of cutting.

For the turning and milling machines, the cheaper small industrial *CC-D6000HS-5M*[122] and *SYIL X5*[105] options were selected. Small because the EPs made in the factory, will small and affordable. Industrial because you want it to be possible to configure it into a process together with a cobot for example or to read out data. Then, a smart industrial machine is more competent than a hobby desktop machine. Cheap because the parts are not made for industries like semicon where for example precision needs to be extremely high or a full-time serial production is required. And at last students need to operate with it. In the database there is for example some OKUMA[144] options as well, but those are very expensive and more cost-efficient in other types of factories. Like described above, when you want a high precision or a large series production where the quality of the output must remain the same.

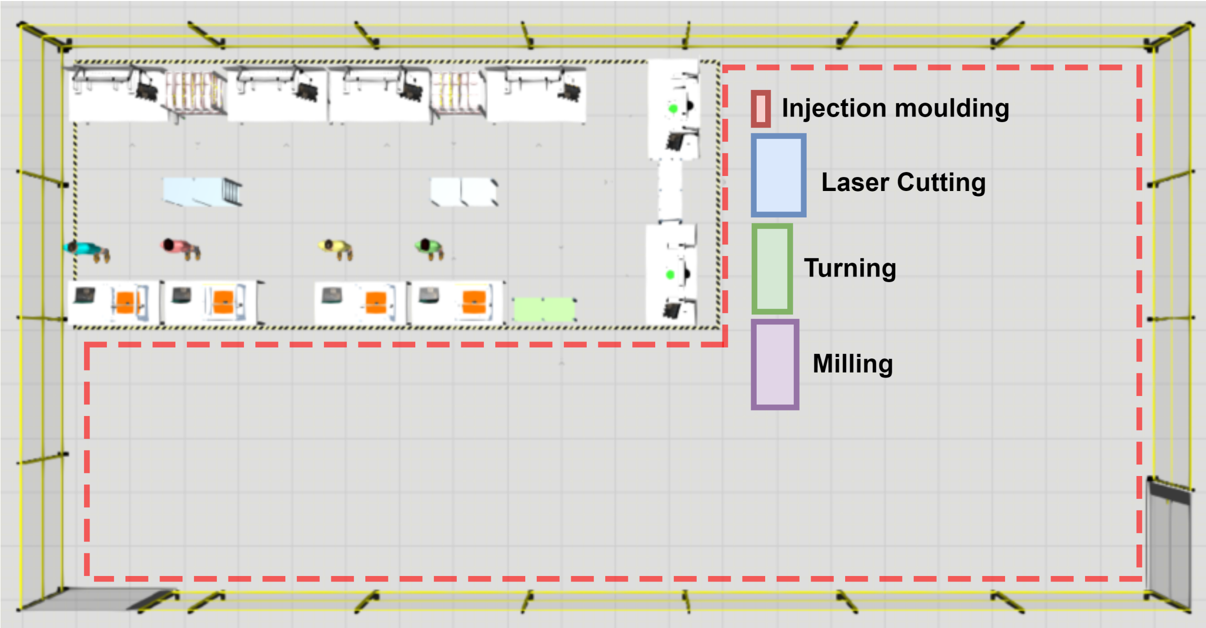


Figure 55: The top view of the learning factory, where the dashed line indicates the extra space and the coloured rectangles indicate the taken floor space from the different added machines.

7.2.3 Future learning factory recommendations:

The current Learning Factory is very dependent on manual input. The ultimate goal and also as part of the I4.0 maturity index presented in Section 3.4.2, it is the recommended to have an adaptable Learning Factory based on a machine learning algorithm. It could start by generating data, which can be done using strategically placed sensors, measuring factory performance and reading out machine data. The LF must be measured on things like: human, robot or product motion, machine utilization, energy consumption, maintenance statistics, production output, tool usage and much more. By integrating the real-time data into the simulation, a digital twin[23] could be established. Utilizing the digital twin and performance dashboards, it could be possible to get insight into the recorded data and key performance indexes. The digital twin can be used to simulate future scenarios. By implementing a machine learning algorithm, the factory could be able to automatically adapt itself or at least give change recommendations. Examples are how to improve on energy consumption, transport efficiency, production output or when to do maintenance.

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Appendices

A Literature Research

A.1 LF Morphology dimensions

<table>
<tr><td>1.1</td><td>operator</td><td colspan="2">academic institution (university, college etc.)</td><td colspan="2">non-academic institution (vocational school, high school, chamber, union, industrial network etc.)</td><td colspan="2">profit-oriented operator (consulting business, producing company etc.)</td></tr>
<tr><td>1.2</td><td>trainer</td><td>researcher</td><td>student assistant</td><td>technical expert</td><td>manager</td><td>consultant</td><td>educationalist</td></tr>
<tr><td>1.3</td><td>develop-ment</td><td colspan="2">own development</td><td colspan="2">external assisted development</td><td colspan="2">external development</td></tr>
<tr><td>1.4</td><td>initial funding</td><td colspan="2">internal funds</td><td colspan="2">public funds</td><td colspan="2">external funds</td></tr>
<tr><td>1.5</td><td>ongoing funding</td><td colspan="2">internal funds</td><td colspan="2">public funds</td><td colspan="2">external funds</td></tr>
<tr><td>1.6</td><td>funding continuity</td><td colspan="2">short term funding (e.g. single events)</td><td colspan="2">mid term funding (projects and programs < 3 years)</td><td colspan="2">long term funding (projects and programs > 3 years)</td></tr>
<tr><td rowspan="2">1.7</td><td rowspan="2">business model for trainings</td><td colspan="3">open models</td><td colspan="3" rowspan="2">closed models
(training program only for single company)</td></tr>
<tr><td>club model</td><td colspan="2">course fees</td></tr>
</table>

Figure 56: LF morphology, dimension 1: operational model [30]

2.1	main purpose	education	vocational training	research						
2.2	secondary purpose	test environment / pilot environment	industrial production	innovation transfer	public image					
2.3	target groups for education & training	schoolchildren	students	employees	self-employed	unemployed	open public			
			bachelor	master	phd students	apprentices	skilled workers	semi-skilled worker	unskilled	managers
								lower mgmt	middle mgmt	top mgmt
2.4	group constellation	homogenous	heterogenous (Knowledge level, hierarchy, students+employees, etc.)							
2.5	targeted industries	mechanical & plant eng.	automotive	logistics	transportation	FMCG	aerospace			
		chemical industry	electronics	construction	insurance / banking	textile industry	…			
2.6	subject-rel. learning contents	product creation processes	energy & resource efficiency	global production	industrial engineering	Industrie 4.0	lean mgmt	design	…	
2.7	role of LF for research	research object	research enabler							
2.8	research topics	product creation processes	energy & resource efficiency	global production	industrial engineering	Industrie 4.0	lean mgmt	design	didactics	…

Figure 57: LF morphology, dimension 2: purpose and targets [30]

3.1	product life cycle	product planning	product development	prototyping	manufacturing	assembly	logistics	service	recycling
3.2	factory life cycle	investment planning	factory concept	process planning	ramp-up			maintenance	recycling
3.3	order life cycle	configuration & order	order sequencing	planning and scheduling				picking, packaging	shipping
3.4	technology life cycle	planning	development	virtual testing				maintenance	modernization
3.5	indirect functions	primary activities			secondary activities				
		Inbound & outbound logistics	marketing & sales	service	firm infrastructure	HR	technology development	procurement	
3.6	material flow	continuous production	discrete production						
3.7	process type	mass production	serial production	small series production	one-off production				
3.8	manufact. organization	fixed-site manufacturing	work bench manufacturing	workshop manufacturing	flow production				
3.9	degree of automation	manual	partly automated / hybrid automation	fully automated					
3.10	manufact. methods	cutting	primary shaping	forming	joining	coating	change material properties		
3.11	manufact. technology	physical	chemical	biological					

Figure 58: LF morphology, dimension 3: process [30]

4.1	**learning environment**	purely physical (planning + execution)	physical LF supported by digital factory (see line "IT-Integration")	physical value stream of LF extended virtually	purely virtual (planning + execution)		
4.2	**environment scale**	scaled down	life-size				
4.3	**work system levels**	station	cell	system	segment	factory	network
4.4	**enablers for changeability**	mobility	modularity	compability	scaleability	universality	
4.5	**changeability dimensions**	product	process	organization	building & layout		
4.6	**IT-integration**	IT before SOP (CAD, CAM, simulation)	IT after SOP (PPS, ERP, MES)	IT after production (CRM, PLM…)			

Figure 59: LF morphology, dimension 4: setting [30]

5.1	**materiality**	material (physical product)	immaterial (service)				
5.2	**form of product**	general cargo	bulk goods	flow products			
5.3	**product origin**	own development	development by participants	external development			
5.4	**marketability of product**	available on the market	available on the market but didactically simplified	not available on the market			
5.5	**functionality of product**	functional product	didactically adapted product with limited functionality	without function/ application, for demonstration only			
5.6	**no. of different products**	1 product	2 products	3-4 products	> 4 products	flexible, developed by participants	acceptance of real orders
5.7	**no. of variants**	1 variant	2-4 variants	5-20 variants	…	flexible, depending on participants	determined by real orders
5.8	**no. of components**	1 comp.	2-5 comp.	6-20 comp.	21-50 comp.	51-100 comp.	> 100 comp.
5.9	**further product use**	re-use / re-cycling	exhibition / display	give-away	sale	disposal	

Figure 60: LF morphology, dimension 5: product [30]

6.1	**competence classes**	technical and methodological compentencies	social & communication competencies	personal competencies	activity and implementation oriented competencies		
6.2	**dimensions learn. targets**	cognitive	affective	psychomotor			
6.3	**learn. sce-nario strategy**	instruction	demonstration	closed scenario	open scenario		
6.4	**type of learn. environment**	greenfield (development of factory environment)	brownfield (improvement of existing factory environment)				
6.5	**communica-tion channel**	onsite learning (in the factory environment)	remote connection (to the factory environment)				
6.6	**degree of autonomy**	instructed	self-guided/ self-regulated	self-determined/ Self-organized			
6.7	**role of the trainer**	presenter	moderator	coach	instructor		
6.8	**type of training**	tutorial	practical lab course	seminar	workshop	project work	
6.9	**standardi-zation of trainings**	standardized trainings	customized trainings				
6.10	**theoretical foundation**	prerequisite	in advance (en bloc)	alternating with practical parts	based on demand	afterwards	
6.11	**evaluation levels**	feedback of participants	learning of participants	transfer to the real factory	economic impact of trainings	return on trainings / ROI	
6.12	**learning success evaluation**	knowledge test (written)	knowledge test (oral)	written report	oral presentation	practical exam	none

Figure 61: LF morphology, dimension 6: didactics [30]

7.1	**no. of participants per training**	1-5 participants	6-10 participants	11-15 participants	16-30 participants	>30 participants	
7.2	**no. of standardized trainings**	1 training	2-4 trainings	5-10 trainings	> 10 trainings		
7.3	**aver. duration of a single training**	≤ 1 day	> 1 day until ≤ 2 days	> 2 days until ≤ 5 days	> 5 days until ≤ 10 days	> 10 days bis ≤ 20 days	> 20 days
7.4	**participants per year**	< 50 participants	50-200 participants	201-500 participants	501-1000 participants	> 1000 participants	
7.5	**capacity utilization**	< 10%	> 10 until ≤ 20%	> 20% until ≤ 50%	> 50% until ≤ 75%	> 75%	
7.6	**size of LF**	≤ 100 sqm	> 100sqm bis ≤ 300sqm	> 300sqm bis ≤ 500sqm	>500sqm bis ≤ 1000sqm	> 1000 sqm	
7.7	**FTE in LF**	< 1	2-4	5-9	10-15	> 15	

Figure 62: LF morphology, dimension 7: LF metrics [30]

A.2 Existing LFs, key topics, operators and purpose

Table 42: Existing LFs: key topics.[4]

Key subjects			
Industry 4.0	**23**	**Manufacturing**	**7**
Industry 4.0	18	Manufacturing	2
Digitalization	2	Manual assembly	1
Labor 4.0	1	Production technology	1
Human-robot collaboration	1	Smart production	1
Digital twin	1	Smart manufacturing systems	1
		World-class manufacturing	1
Lean	**24**		
Lean production	16	**Cyber-physical production systems**	**6**
Lean management	3	CPPS	3
Lean manufacturing	2	Cyber-physical production	1
Lean philosophy	2	Factory virtualization	1
Lean assembly	1	Cyber-physical assembly	1
Automation	**6**	**Other:**	**23**
Automation	6	Sustainability	2
		Quality management	2
Logistics	**12**	Business improvement	1
Logistics	3	Additive manufacturing	1
Process and product planning	3	Sustainable production	1
Factory planning and operation	2	Urban production	1
Production planning and control	2	Electronics production	1
Intralogistics	1	Workplace oriented trainings	1
Scheduling and execution	1	Integrated products-systems learning	1
		Optimization	1
Energy and resource efficiency	**8**	Workers' participation	1
Energy efficiency	3	Paperless production	1
Resource efficiency	3	Assembly and maintenance of compressors	1
Energy flexibility	1	Service operations	1
Energy productivity	1	Adaptive manufacturing	1
		Railway operation	1
Engineering	**13**	Mechatronics	1
Engineering design	4	Industrial problems	1
Industrial engineering	2	R&D outputs	1
Product development and production	2	Textile industry	1
Prototypes and industrialization	1	Production research	1
Design of work systems	1		
Holistic product creation	1		
Rapid prototyping	1		
real-life engineering practices	1		

Table 43: Existing LFs: operators and purpose.

Operators	**64**	**Purpose**	
University	54	Research	37
Company	12	Education	46
		Training	47
		Transfer of knowledge	27

A.3 LF types overview

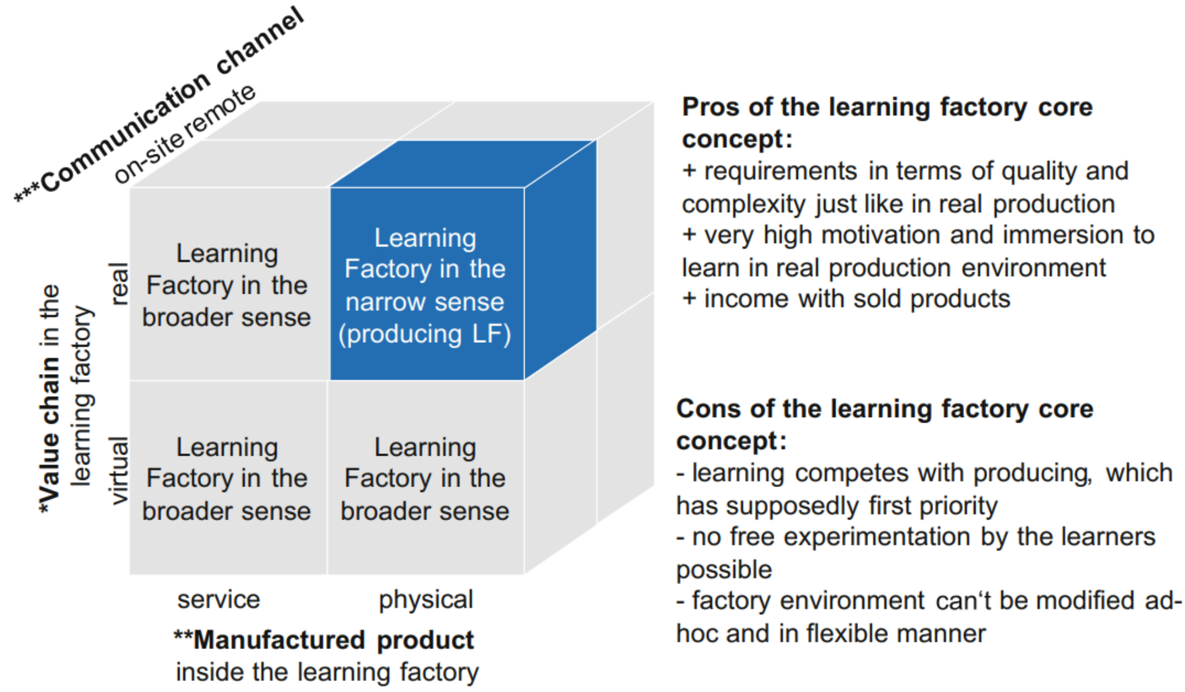

Figure 63: Pros and cons of the LF Core concept with a fixed production process. [4].

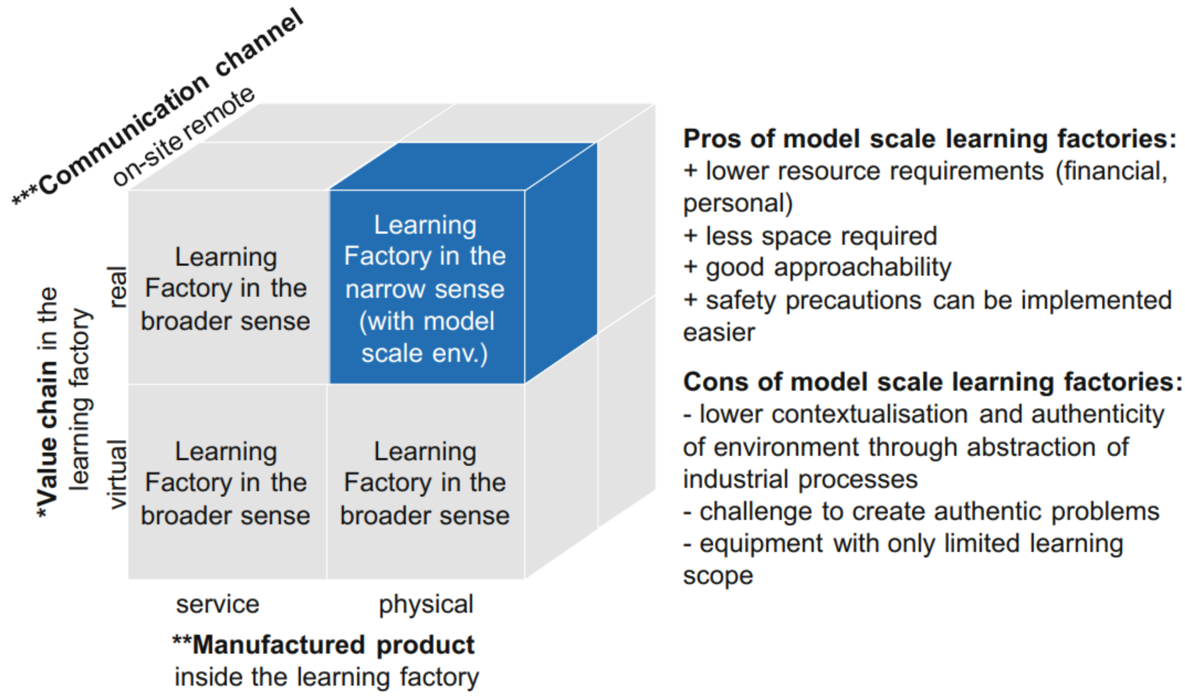

Figure 64: Pros and cons of the LF Model Scale concept [4].

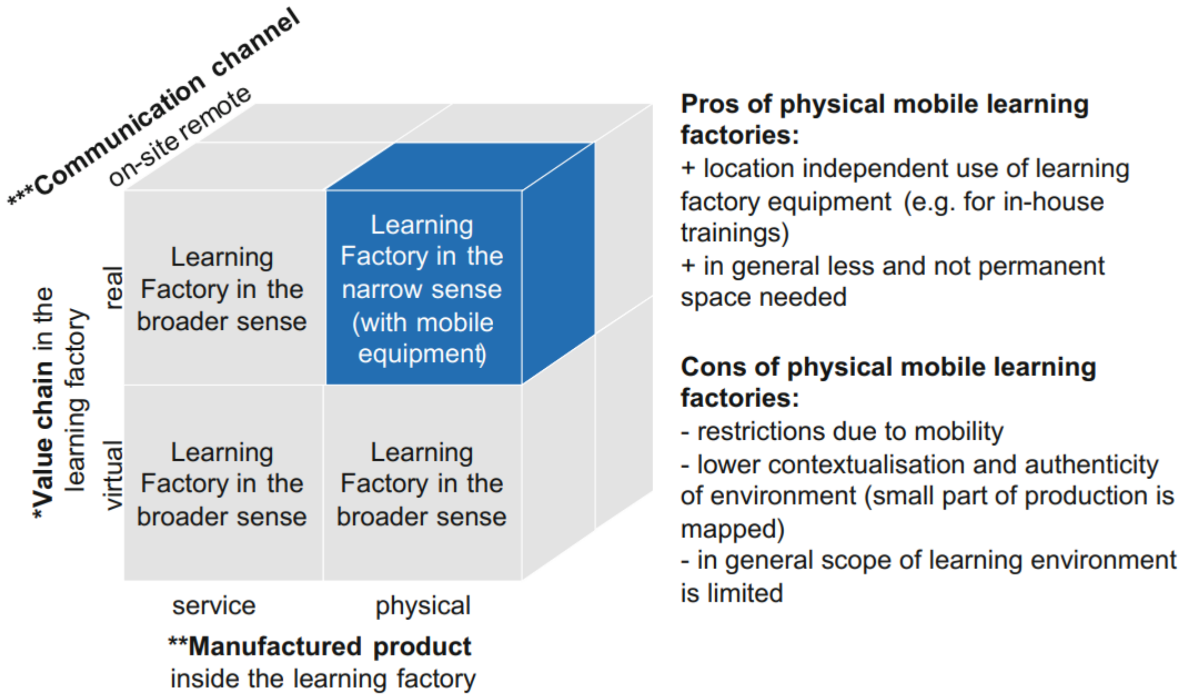

Figure 65: Pros and cons of the LF Physiscal Mobile concept [4].

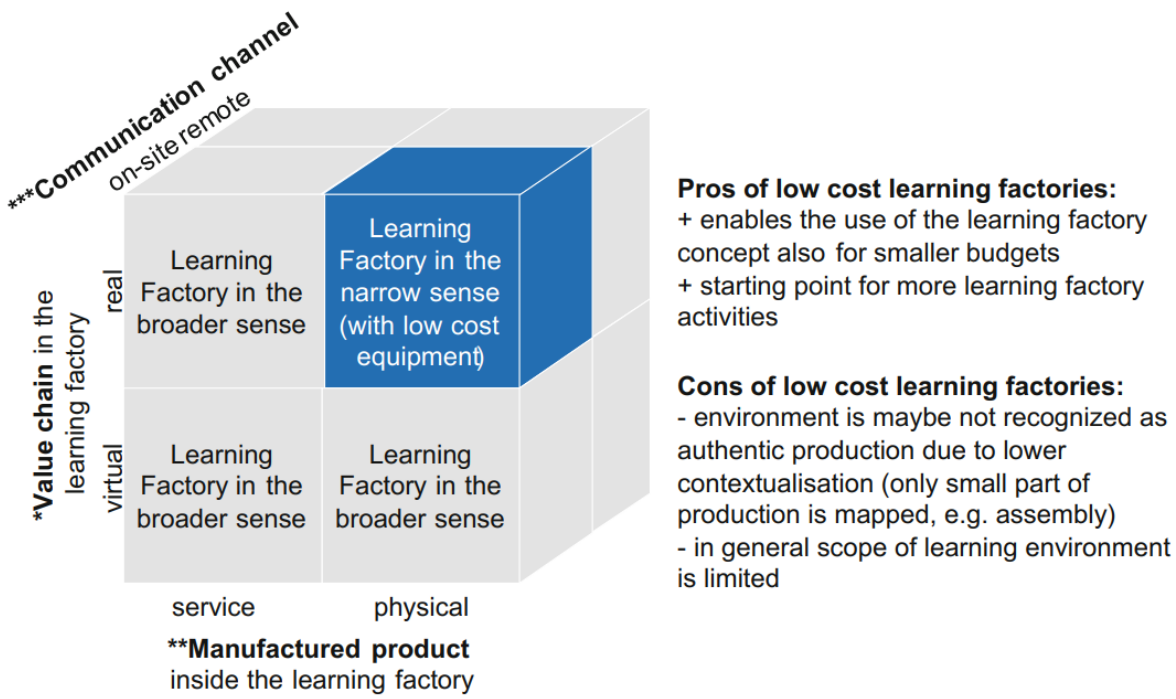

Figure 66: Pros and cons of the LF Low Cost concept [4].

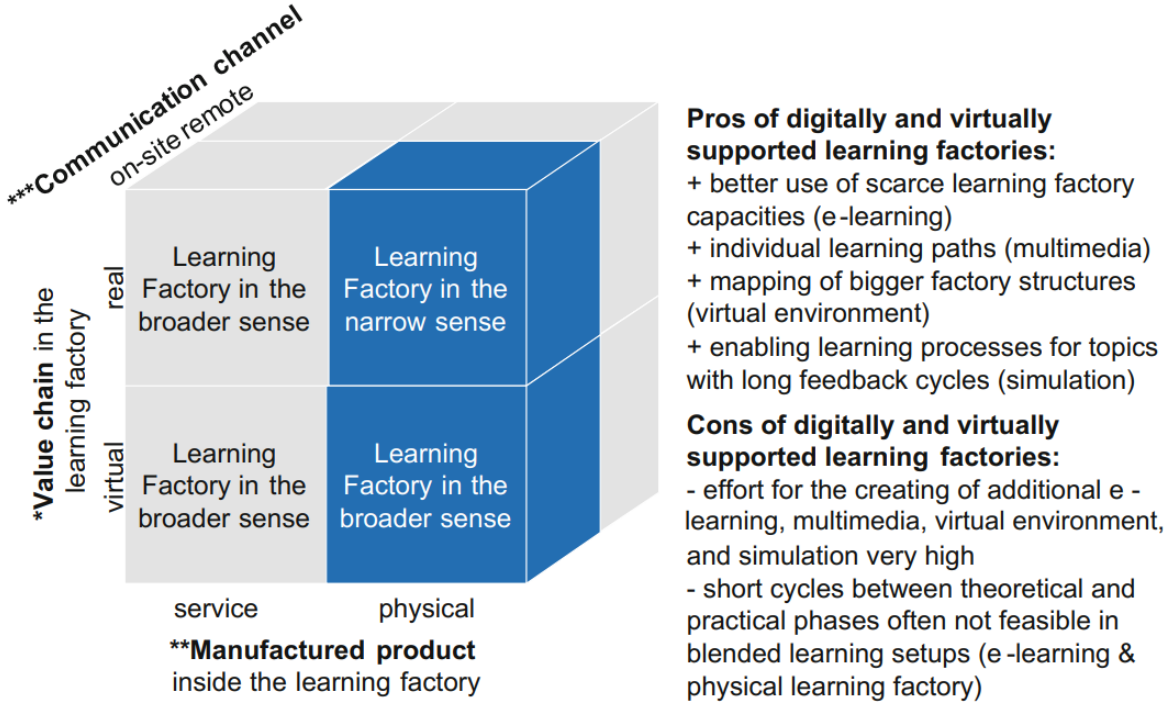

Figure 67: Pros and cons of the LF Digital and Virtual concept [4].

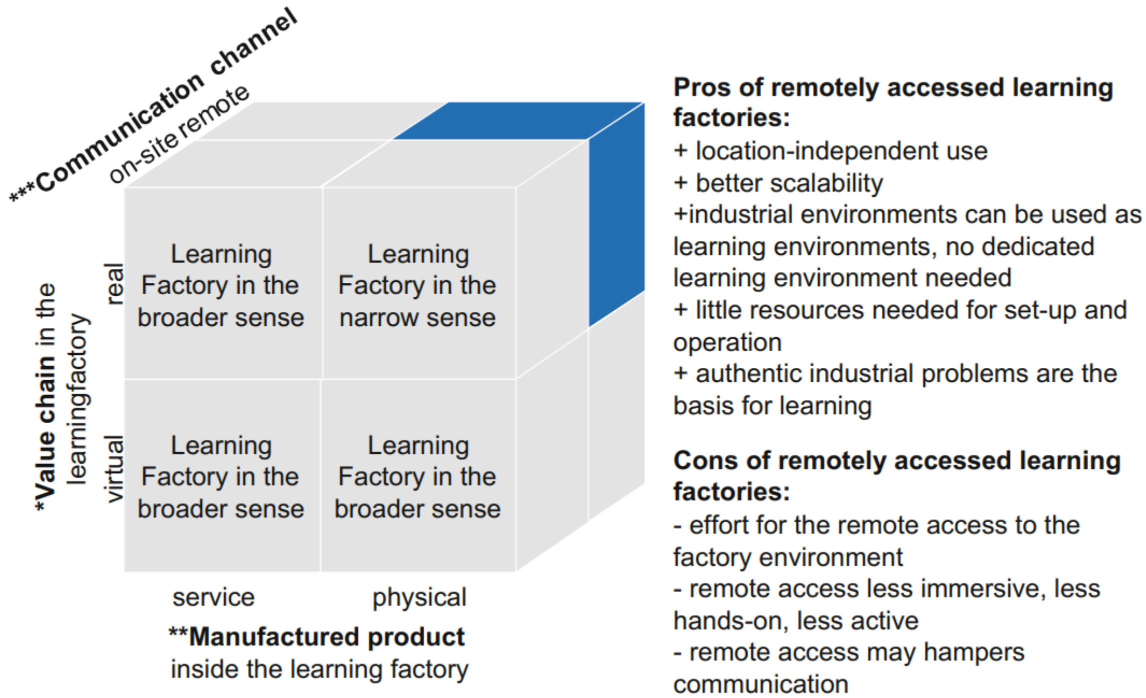

Figure 68: Pros and cons of the LF Remote concept [4].

B Research in preparation of LFCT

B.1 Manufacturing Plans

Table 44: Manufacturing Plan: Card holder assembly

	Production steps:	Required equipment:
1.	Select aluminium case	Inventory space
2.	Select leather	Inventory space
3.	Engrave leather	Laser cutter
4.	Cut leather	Laser cutter
5.	Assemble case	Assembly station
6.	Knit button or elastic band to leather	Knitting machine
7.	Adhere leather to case	Glue
8.	Perform quality check	Quality station
	Parts	
	Procured:	**Self made:**
	Anodized aluminium case	Leather engraving
	Leather covers	
	Inner fabric that prevent cards falling out	
	Card push plastic	
	Card push spring	
	Elastic bands	

Table 45: Manufacturing Plan: Topology optimized 3D Printer

	Production steps:	Required equipment:
1.	Recieve and read project description	
2.	Improve structural parts using topology optimization	Simulation software
3.	Save topology optimized parts as STL	Simulation software
4.	Send to 3D printer	Simulation software
5.	Print parts using existing 3D printer	3D printer
6.	Assemble the optimized 3D printer	Assembly station
7.	Test the printer on performance	Quality station
	Parts	
	Procured:	**Self made:**
	Stepper motors	Connection parts
	Filament tubes	Gears
	Filament feeder	Beams
	Extruder	
	Print bed	
	Cooling fan	
	Metal beams	
	Display	
	Threaded rods	
	Translation rods	
	Bearings	
	Screws	
	Bolts and nuts	

Table 46: Manufacturing Plan: Gearbox Assembly

	Production steps:	**Required equipment:**
1.	Pick all the required parts	Storage area
2.	Assemble the parts according to given order	Assembly station
3.	Transport the parts from one workstation other	Conveyor belt, warehouse trolley
4.	Let cobot do basic assembly	Cobot
5.	Use AGV to transfer to next workstation	AGV, automatic coneyor belt
6.	Perform complex assembly steps manually using instructions from AR glasses	Assembly station, AR glasses
7.	Transport the parts to quality inspection	Warehouse trolley, forklift truck
8.	Quality inspection	CMM and Quality inspection station
	Parts	
	Procured:	**Self made:**
	Gears	-
	Shafts	
	Bearings	
	Housings	
	Screws	
	Bolts and nuts	

Table 47: Manufacturing Plan: Gearbox Design

	Production steps:	**Required equipment:**
1.	Recieve and read project description	
2.	Design the gears and shafts	Simulation software
3.	Manufacture the gears	Hobbing machine
4.	Manufacture the shafts	Turning machine
5.	Manufacture the housing	Milling and grinding machine
6.	Assemble the whole	Assembly staion
7.	Install housing	Assembly station
8.	Perform quality inspection	CMM and Quality inspection station
9.	Test the whole	
	Parts	
	Procured:	**Self made:**
	Bearings	Gears
	Screws	Shafts
	Bolts and nuts	Housing

Table 48: Manufacturing Plan: Drone Assembly

	Production steps:	**Required equipment:**
1.	Selection of required equipment	Inventory space
2.	Picking the equipment	Inventory space
3.	Frame design and production or select standard frame options	3D printer or laser cutter
4.	Assemble the whole	Assembly station
5.	Calibrate the control system	Programming software
6.	Test the drone	Test environment
7.	Apply drone for the right project requirements	Test environment
	Parts	
	Procured:	**Self made:**
	Propellers	Drone frame / equipment housing
	Motors	
	Vision cameras/sensors	
	Thermal cameras/sensors	
	Leakage cameras/sensors	
	Control Board	
	Battery	

B.2 Value Stream Maps

Table 49: VSM of Card Holder.

Card holder, single tool for each step													
Property		1. Order picking (leather)	Equipment	2. Laser engraving	Equipment	3. Laser cutting	Equipment	4. Knitting	Equipment	5. Adhesion	Equipment	6. Quality check	Equipment
C/O	(s)		Warehouse picking cart	120 (B)	Operator	60 (B)	Operator	30	Warehouse picking cart	30	2 Conveyor belts	30 (B)	Conveyor belt
CT	(s)		Inventory space	30	Laser cutter	30	Laser cutter	180	Knitting machine	30	YuMi Cobot	60	Quality station
PT	(s)	60 (B)		420		360		2100		600		630	
Cumulative	(s)	60		480		840		2940		3540		4170	
Property		1. Order picking (casing)	Equipment					2. Case assembly	Equipment				
C/O	(s)	60 (B)	Inventory space					15					
CT	(s)	120 (B)	Warehouse picking cart					120	Assembly station				
PT	(s)	180						1350					
Cumulative	(s)	180						1530					
Card holder, multiple tools for each step													
Property		1. Order picking (leather)	Equipment	2. Laser engraving	Equipment	3. Laser cutting	Equipment	4. Knitting	Equipment	5. Adhesion	Equipment	6. Quality check	Equipment
C/O	(s)		Warehouse picking cart	120 (B)	Operator	60 (B)	Operator	30	Warehouse picking cart	30	4 Conveyor belts	30 (B)	2 Conveyor belts
CT	(s)		Inventory space	30	Laser cutter	30	Laser cutter	180	5 Knitting machine	30	2 YuMi Cobots	60	2 Quality stations
PT	(s)	60 (B)		420		360		390	5 Assembly stations	180		330	
Cumulative	(s)	60		480		840		1230		1410		1710	
Property		1. Order picking (casing)	Equipment					2. Case assembly	Equipment				
C/O	(s)	60 (B)	Inventory space (with bins)					15					
CT	(s)	120 (B)	Warehouse picking cart					120	2 Assembly stations				
PT	(s)	180						750					
Cumulative	(s)	180						930					

Table 50: VSM of Topology optimized 3D Printer.

Topology optimized 3D Printer, single tool for each step													
Property		1. Topology optimization	Equipment	2. Save as STL	Equipment	3. Setup 3D printer	Equipment	4. Print the parts	Equipment	5. Assemble the 3D printer	Equipment	6. Printer performance test	Equipment
C/O	(h)	1	Simulation software		Simulation software	0.25	Simulation software	0.25	Warehouse picking cart	2	Assembly station	0.25	Quality station (the new 3D printer)
CT	(h)	24				0.25	3D Printer	48	3D Printer	3		24	
PT	(h)	25		0.25		0.5		48.25		5		24.25	
Cumulative	(h)	25		25.25		26.25		74.5		79.5		93.75	
Property		1. Order picking (non 3D print)	Equipment	2. Assemble electronics	Equipment								
C/O	(h)	0.25	Inventory space	0.25									
CT	(h)	0.25	Warehouse picking cart	2	Assembly station								
PT	(h)	0.5		2.25									
Cumulative	(h)	1		4.5									
Topology optimized 3D Printer, multiple tools for each step													
Property		1. Topology optimization	Equipment	2. Save as STL	Equipment	3. Setup 3D printer	Equipment	4. Print the parts	Equipment	5. Assemble the 3D printer	Equipment	6. Printer performance test	Equipment
C/O	(h)	1	Simulation software		Simulation software	0.25	Simulation software	0.25	Warehouse picking cart	2	Assembly station	0.25	Quality station (the new 3D printer)
CT	(h)	24				0.25	3D Printer	12	4 3D Printers	3		24	
PT	(h)	25		0.25		0.5		12.25		5		24.25	
Cumulative	(h)	25		25.25		26.25		38.50		43.50		67.75	
Property		1. Order picking (non 3D print)	Equipment	2. Assemble electronics	Equipment								
C/O	(h)	0.25	Inventory space	0.25									
CT	(h)	0.25	Warehouse picking cart	2	Assembly station								
PT	(h)	0.5		2.25									
Cumulative	(h)	1		4.5									

Table 51: VSM of Gearbox Assembly.

Gearbox assembly, single tool for each step													
Property		1. Order picking	Equipment	2. Basic cobot assembly	Equipment	3. Complex manual assembly	Equipment	4. Quality inspection	Equipment	5. Testing	Equipment	6. Disassemble	Equipment
C/O	(min)	5	Warehouse picking cart	10	Cobot	5	AGV AR glasses	5	Warehouse picking cart	30	Warehouse picking cart	5	Warehouse picking cart
CT	(min)	5	AGV	30	Vision sensors	30	Assembly Station	20	Quality station	10	Test setup	50	Disassembly station
PT	(min)			40		35		25		40		55	
Cumulative	(min)	10		50		85		110		150		205	
Gearbox assembly, single tool for each step													
Property		1. Order picking	Equipment	2. Basic cobot assembly	Equipment	3. Complex manual assembly	Equipment	4. Quality inspection	Equipment	5. Testing	Equipment	6. Disassemble	Equipment
C/O	(min)	5	Warehouse picking cart	10	Cobot	5	AGV AR glasses	5	Warehouse picking cart	30	Warehouse picking cart	5	Warehouse picking cart
CT	(min)	5	AGV	30	Vision sensors	30	Assembly Station	20	Quality station	10	Test setup	50	Disassembly station
PT	(min)			40		35		25		40		55	
Cumulative	(min)	10		50		85		110		150		205	

Table 52: VSM of Gearbox Design.

Gearbox design, single tool for each step

Property		1. Topology optimization	Equipment	2. Save as STL	Equipment	3. Setup 3D printer	Equipment	4. Print the parts	Equipment	5. Assemble the 3D printer	Equipment	6. Printer performance test	Equipment
C/O	(h)	1	Simulation software		Simulation software	0.25	Simulation software	0.25	Warehouse picking cart	2	Assembly station	0.25	Quality station (the new 3D printer)
CT	(h)	24	Inventory space			0.25	3D Printer	48	3D Printer	3		24	
PT	(h)	25		0.25		0.5		48.25		5		24.25	
Cumulative	(h)	25		25.25		26.25		74.5		79.5		93.75	

Property		1. Order picking (non 3D print)	Equipment	2. Assemble electronics	Equipment
C/O	(h)	0.25	Inventory space	0.25	
CT	(h)	0.25	Warehouse picking cart	2	Assembly station
PT	(h)	0.5		2.25	
Cumulative	(h)	1		4.5	

Gearbox design, multiple tools for each step

Property		1. Topology optimization	Equipment	2. Save as STL	Equipment	3. Setup 3D printer	Equipment	4. Print the parts	Equipment	5. Assemble the 3D printer	Equipment	6. Printer performance test	Equipment
C/O	(h)	1	Simulation software		Simulation software	0.25	Simulation software	0.25	Warehouse picking cart	2	Assembly station	0.25	Quality station (the new 3D printer)
CT	(h)	24	Inventory space			0.25	3D Printer	12	4 3D Printers	3		24	
PT	(h)	25		0.25		0.5		12.25		5		24.25	
Cumulative	(h)	25		25.25		26.25		38.50		43.50		67.75	

Property		1. Order picking (non 3D print)	Equipment	2. Assemble electronics	Equipment
C/O	(h)	0.25	Inventory space	0.25	
CT	(h)	0.25	Warehouse picking cart	2	Assembly station
PT	(h)	0.5		2.25	
Cumulative	(h)	1		4.5	

Table 53: VSM of Drone, part 1.

Drone, single tool for each step									
Property		1. Frame design	Equipment	2. Print the parts	Equipment	3. Assemble the Drone	Equipment	4. Calibrate control system	Equipment
C/O	(h)		Simulation software	0,25		0,25	Assembly station	0,25	Quality station
CT	(h)			48	3D Printer	4		16	(the new drone)
PT	(h)	8		48,25		4,25		16,25	
Cumulative	(h)	8		56,25		60,5		76,75	
Property		1. Selection of required equipment	Equipment	2. Order picking Equipment	Equipment				
C/O	(h)				Transport cart				
CT	(h)				Warehouse				
PT	(h)	0.5		0.5					
Cumulative	(h)	1		1.5					

Table 54: VSM of Drone, part 2.

Drone, multiple tools for each step									
Property		1. Frame design	Equipment	2. Print the parts	Equipment	3. Assemble the Drone	Equipment	4. Calibrate control system	Equipment
C/O	(h)		Simulation software	0,25	Warehouse picking cart	0,25	4 Assembly station	0,25	2 Quality stations
CT	(h)		4 Computers	12	4 3D Printers	1		8	(the new drone)
PT	(h)	8		12,25		1,25		8,25	
Cumulative	(h)	8		20,25		21,5		29,75	
Property		1. Selection of required equipment	Equipment	2. Order picking Equipment	Equipment				
C/O	(h)				Transport cart				
CT	(h)				Warehouse				
PT	(h)	0.5		0.5					
Cumulative	(h)	1		1.5					

B.3 UT Course, Learning Subject and Path description

Table 55: Learning Course, Subject and Path description, part 1

Courses Core:	LSs	LP's	Short LP's
3D printing	3D printing, theory, application and state of the art 1 Basic Additive Manufacturing theory 2 AM economical aspects 3 Research on state of the art in AM	1. Know, Explain and compare individual AM processes from the range of additive manufacturing processes available. 2. Understanding the basic working principles, benefits and drawbacks, that apply to individual groups of AM processes. 3. Understand and explain what processing alternatives there are for certain material groups. 4. Understand, explain and use design rules for additive manufacturing. 5. Understand the economical aspects related to Additive manufacturing. 6. Explore the current state of the art related to Additive manufacturing.	1. Basic 7 Additive Manufacturing processes theory. 2. AM process distinction 3. AM materials understanding 4. AM design rules 5. AM economical Aspects 6. Research on state of the art in AM
Design Production and Materials	Composites, basic theory, design and manufacturing. 1. Basic continuous fibre-reinforced composite ply theory and calculations. 2. Laminate loading, deformation and failure analysis. 3. Design an object that is able to perform according to the requirements. 4. Choose manufacturing technology and strategy.	1. Derive the properties of a continuous fibre reinforced composite ply as a function of its constituents and their fractions. 2. Determine and analyse the stress – deformation relation of a continuous fibre reinforced composite ply for varying fibre orientation. 3. Derive and analyse the loading – deformation relation of a laminated plate. 4. Classify the way composite materials fail and quantify first-ply failure in a laminate. 5. Choose and advise on manufacturing technologies (for a given set of requirements on the part to be made). 6. Design a lay-up for plate- or cylinder-like composite structures given the loading requirements.	1. Basic theory continuous fibre reinforced composite plies. 2. Stress - deformation under varying fibre orientation. 3. Loading - deformation derivation and analysis. 4. Composite material failure classification. 5. Composite manufacturing technologies. 6. Design laminate according to the given load.
Design of Production and Inventory systems	1. Understand the basics of production system design, control and modelling, containing the topics: 2. Apply methods ,(mathematical) models and techniques with respect to the afore mentioned topics, to make design decisions concerning production and inventory systems.	1. The structure of production systems. 2. The behaviour of production systems. 3. The standard production system decision hierarchy. 4. Forecasting of market demands. 5. Long-range, medium-term and operational planning. 6. Production and inventory control systems. 7. Shop-floor design and operation. 8. Mathematical models and techniques that enable decision making on the LA's 1-7 above.	1. The structure of production systems. 2. The behaviour of production systems. 3. The standard production system decision hierarchy. 4. Forecasting of market demands. 5. Long-range, medium-term and operational planning. 6. Production and inventory control systems. 7. Shop-floor design and operation. 8. Mathematical models and techniques that enable decision making on the LA's 1-7 above.

Table 56: Learning Course, Subject and Path description, part 2

Frontiers in Design and Manufacturing	1. Info on state of the art in Design and Manufacturing	1. Gathering info on the state of the art in a topic of choice. 2. Transforming the information into a research paper.	1. State of the art on topic of choice. 2. Write research paper on topic of choice.
Maintenance Engineering and Management	1. Maintenance Engineering and Asset Management performance indicators, application and analysis tools.	1. Describe ME&AM in practice: the approaches and performance indicators used for ME&AM: -Asset Management -Total Productive Maintenance (TPM) -Overall Equipment Effectiveness (OEE) 2. Describe the goals, inputs and outputs of various analyses to be performed in Maintenance Engineering and Asset Management (ME&AM). 3. Explain the relations between various analyses in ME&AM and what this means for decisions resulting from these analyses and the final maintenance plan. 4. Use models and solution approaches for various analyses to be performed, e.g.: -Failure modes, effects(, and criticality) analysis (FME(C)A) -Reliability centred maintenance (RCM) -Maintenance Feedback Analysis (MFA)-Mechanism Based Failure Analysis (MBFA) -Spare part optimization (LORA)	1. ME&AM Performance indicators. 2. Define, goals, inputs and outputs of analysis. 3. Analysis explanation and discussion. 4. Use FMEA, RCM, MFA or LORA to analyse the performance indicators
Manufacturing Facility Design	1. Manufacturing Facility Design methods and application.	1. Manufacturing facility design. 2. Product, process and schedule design. 3. Production capacity. 4. Layout planning models and design algorithms. 5. Material handling/warehousing. 6. Manufacturing systems.	1. Manufacturing facility design. 2. Product, process and schedule design. 3. Production capacity. 4. Layout planning models and design algorithms. 5. Material handling/warehousing. 6. Manufacturing systems.
Modelling of Technical Design Process	1. Define a tailored product design and development process (PDDP) for a specific situation.	1. Summarize the main challenges for a successful PDDP. 2. Determine the appropriate PDDP model (waterfall, iterative, spiral or agile) considering the products technical and requirements uncertainty. 3. Determine the appropriate design and development tools and techniques for each PDDP phase, considering the disciplines needed during the process (mechanical, electronic, software, etc.) 4. Integrate into the PDDP the best practices for organizational process definition, engineering, and engineering support according to the CMMI-Dev 1.3. 5. Integrate creative design techniques into the PDDP. 6. Determine how to take advantage from the Industry 4.0 capabilities to improve the design process. 7. Reflect on how to use the learnings from LO1 to 5 during a tailored PDDP definition.	1. Theory PDDP models (waterfall, iterative, spiral or agile). 2. Determine the right model for the right application. 3. Add creative design techniques to PDDP. 4. Add Industry 4.0 possibilities to PDDP. 5. Reflect on learnings from earlier steps to tailor PDDP.

Table 57: Learning Course, Subject and Path description, part 3

Elective:			
Adhesion and bonding technology	Adhesion and Bonding Technology.	1. Recognize the common adhesion theories and principles. 2. Relate between properties of constituent materials and bond performance. 3. Classify and analyze the mechanical tests for adhesive bonds. 4. Determine the relation among intermolecular forces, surface science and adhesion. 5. Select the relevant surface treatment for different adhesion scenarios. 6. Contrast between different structural adhesives. 7. Apply the knowledge gained to design an adhesive joint. 8. Communicate the knowledge gained both orally as well as a written report.	1. Adhesion theory. 2. Properties of constituent materials and bond performance. 3. Mechanical tests for adhesive bonds. 4. Intermolecular forces, surface science and adhesion. 5. Surface treatments for adhesion. 6. Structural adhesive distinctions. 7. Design adhesive joint. 8. Write report.
Biomechanics of human movement	Modelling and simulating musculoskeletal tissue function	1. Build subject-specific musculoskeletal models from recorded movement and imaging data. 2. Model the mechanical properties of muscle tissues, series-elastic tendons, and ligaments. 3. Perform quantitative analysis of musculoskeletal geometry, 4. Simulate transmission of muscle-tendon forces to articular joints. 5. Simulate how muscle mechanics contribute to modulation of joint stiffness and compressive loads. 6. Recording technic for human movement and data processing of bio-signal and movement data.	1. Build musculoskeletal model from movement and imaging data. 2. Mechanical properties of muscle tissues, series-elastic tendons, and ligaments. 3. Quantitative analysis of muscoleskeletal geometry. 4. Simulate transmission of muscle-tendon forces to articular joints. 5. Simulate how muscle mechanics contribute to modulation of joint stiffness and compressive loads. 6. Data processing of bio-signal and movement data.
Composites forming	Understanding of forming processes of highly anisotropic materials.	1. To translate a physical process phenomenon, which happens during manufacturing of a composite part, to the underlying elementary deformation mechanisms. Instead of a phenomenon directly encountered during processing, this may also concern an idealised situation envisaged to take place during a characterisation experiment, designed to measure an appropriate material property. 2. To quantify this in terms of the relevant balance laws. 3. To identify the appropriate material properties. 4. To provide a quantitative description of the phenomenon.	1. To translate a physical process phenomenon, which happens during manufacturing of a composite part, to the underlying elementary deformation mechanisms. 2. Quantify this in terms of the relevant balance laws. 3. Identify the appropriate material properties. 4. Provide a quantitative description of the phenomenon.

Table 58: Learning Course, Subject and Path description, part 4

Computational optimization	No info	No info	
Cost management and Engineering	Economic and financial evaluation of engineering solutions. The course objective is to provide engineering students with the theoretical understanding and practical approaches as well as the tools and techniques for the economic and financial evaluation of stand-alone but also competing design solutions for processes, products, construction projects, services and the practical application of the approaches in more complex settings.	1. Understand the basic theoretical concepts in Cost Management Engineering like cash flows, cost estimation and project input / output valuation techniques, Discounted Cash Flow analysis methods, cost of capital / choice of discount rate. 2. Understand the basic problems and modeling techniques regarding uncertainty in long-horizon investment decisions or projects, and will have a basic understanding to cope fruitfully with informational challenges connected to this uncertainty. 3. Be able to apply and integrate these concepts and techniques to perform basic economic evaluations of private sector and public sector projects. 4. Have insight in several important differences in private and public sector projects and resulting differences in approach for the economic evaluation of private and the public sector projects; 5. have insight in important differences in the quality of financial data and be able to weigh their importance critically; 6. Be aware of multi-attribute analysis as an alternative approach evaluation of projects and be able to use this method for (simplified) project evaluation; 7. Be able to comment critically on the theoretical and practical validity of recommendations by third parties regarding investment decisions and surrounding issues as discussed; 8. Be able to investigate applications of approaches taught independently and report their findings in writing.	1. Basic cost management theory. 2. Basic problems and modeling techniques and corresponding informational challenges. 3. Apply and integrate the gained knowledge to private and public sector projects. 4. Understand important differences in private and public sector projects. 5. Understand important differences in the quality of financial data. 6. Do multi-attribute analysis. 7. Comment critically on the theoretical and practical validity regarding investment decisions and surrounding issues as discussed. 8. Investigate applications of approaches taught independently and report their findings in writing.
Design for additive manufacturing	Design for Additive Manufacturing	1. Understand and explain the principal additive manufacturing processes, the fundamental mechanism of operation, and applications. 2. Identify the entire product life cycle from design conception to the final product in the additive manufacturing process. 3. Understand, explain and use design strategies and rules for metal and polymer additive manufacturing processes. 4. Identify the design constraints in additive manufacturing and post-processing consideration. 5. Apply qualitative and quantitative simulation tools in the design of additive manufactured parts. 6. Explore current and future perspective on digital design tools for additive manufacturing.	1. Principal additive manufacturing processes theory. 2. Identify the product life cycle from design conception to the final product in the AM process. 3. Metal and polymer AM process theory. 4. Identify the design constraints in additive manufacturing and post-processing consideration. 5. Apply qualitative and quantitative simulation tools in the design of additive manufactured parts. 6. Explore current and future perspective on digital design tools for additive manufacturing.

Table 59: Learning Course, Subject and Path description, part 5

Design principles for robotic and mechatronics	Design Principles for Robotic and Mechatronic Mechanisms	1. Analyse, design and evaluate precision mechanisms with respect to stiffness. 2. Analyse, design and evaluate precision mechanisms with respect to degrees of freedom and constraints. 3. Design, analyse and evaluate precision mechanisms based on flexure elements. 4. Design and analyse precision mechanisms which inherently have hysteresis and microslip. 5. Design and analyse precision mechanisms with bearings, rollers and webs. 6. Design and analyse precision mechanisms with respect to dynamics and energy management.	1. Precision mechanisms, stiffness theory. 2. PM degrees of freedom and constraints theory. 3. Design PM based on flexure elements. 4. Design PM which inherently have hysteresis and micro slip. 5. Design PM with bearings, rollers and webs. 6. Design PM with respect to dynamics and energy management.
Governing product development	Governing Product Development	1. Outline the prospective development process based on analyses of a product notion. 2. Predict and substantiate possible risks and threats that might be encountered during the development cycle. 3. Attain a structured description of the development process (in its context). 4. Abstract specific situations to a more aggregate overview of product development. 5. Critically assess product development processes.	1. Outline the prospective development process based on analyses of a product notion. 2. Predict and substantiate possible risks and threats that might be encountered during the development cycle. 3. Attain a structured description of the development process (in its context). 4. Abstract specific situations to a more aggregate overview of product development. 5. Critically assess product development processes.
Lean six sigma green belt	Lean Six Sigma Green Belt	1. Describe existing production processes (using the Lean Six Sigma method) and make a project plan. 2. Define the elements that are part of the process improvement project. 3. Measure current process performance and capabilities. 4. Analyse the results and draw conclusions about improvements to be made. 5. Select and implement improvement measurements that solve a problem. 6. Plan for sustaining achievements and quality control. 7. Explain how to produce and processes according to the Six Sigma method.	1. Describe existing production processes (using the Lean Six Sigma method) and make a project plan. 2. Define the elements that are part of the process improvement project. 3. Measure current process performance and capabilities. 4. Analyse the results and draw conclusions about improvements to be made. 5. Select and implement improvement measurements that solve a problem. 6. Plan for sustaining achievements and quality control. 7. Explain how to produce and processes according to the Six Sigma method.

Table 60: Learning Course, Subject and Path description, part 6

Life-cycle strategy	LCA Theory in Engineering	1. Assessment of product lifecycles. Creating process trees, mass and energy balances, collecting and interpreting data, simulating values, coping with uncertainties and incomplete methods and theories assessing. 2. Developing impact assessment methods for different aspects than environment. 3. Effect of (environmental) interventions on (environmental) systems 4. (Environmental) Profiles in connection with options of improvement, maintaining a balance between thoroughness and progress within certain limits 5. Consistency in overall work and subactivities. Use of LCA simulation solftware (probably Gabi).	1. Assessment of product lifecycles. 2. Developing impact assessment methods for different aspects than environment. 3. Effect of (environmental) interventions on (environmental) systems 4. (Environmental) Profiles in connection with options of improvement, maintaining a balance between thoroughness and progress within certain limits 5. Consistency in overall work and sub-activities. Use of LCA simulation solftware (probably Gabi).
Multiscale functional materials for engineering application	Understand, adapt, and improve multiscale materials.	1. Optimize the functionality of materials by selecting the right length scale from nanoscale to part size. 2. Predict and modify material properties, especially thermal transport, based on material engineering and/or size reduction. 3. Design multi-scale functional materials for thermal management and energy harvesting applications. 4. Apply multiscale functional materials to achieve optimized energy dissipation in electronics, thermal insulation and waste heat conversion to electricity. 5. Suggest material modifications that can improve the efficiency of solid-state energy harvesting or improve thermal management capabilities.	1. Optimize the functionality of materials by selecting the right length scale from nanoscale to part size. 2. Predict and modify material properties. 3. Design for thermal management and energy harvesting applications. 4. Apply multiscale functional materials to achieve optimized energy dissipation in electronics, thermal insulation and waste heat conversion to electricity. 5. Suggest material improvement modifications.
Multiscale mechanics		1. Describe / give an overview of research possibilities in the field of multiscale materials. 2. Face Multi Scale Mechanics problems with a research approach. 3. Name and revise arguments from mechanics from solids and fluids from a micromechanical point of view. 4. Relate micromechanical approach and classical continuum mechanics to fully describe the behaviour of materials with internal structure. 5. Analyse material behaviour at particle level using the Discrete Element Method simulations and compare this to theoretical models. 6. Perform small scale experiments on discrete materials.	1. Give an overview of research possibilities in the field of multiscale materials. 2. Face Multi Scale Mechanics problems with a research approach. 3. Name and revise arguments from mechanics from solids and fluids from a micromechanical point of view. 4. Relate micromechanical approach and classical continuum mechanics to fully describe the behaviour of materials with internal structure. 5. Analyse material behaviour at particle level using the Discrete Element Method simulations and compare this to theoretical models. 6. Perform small scale experiments on discrete materials.

Table 61: Learning Course, Subject and Path description, part 7

Simulation	Simulation	1. Explain the principles of discrete event simulation. 2. Describe the steps to be taken when conducting a simulation study focused on improvement of operations systems (logistics systems and business processes). 3. Judge whether simulation can be a useful technique to analyse certain operations systems (when to use and when not to use). 4. Design a simulation model for a given operations system. 5. Implement this model in an advanced simulation tool (currently Plant Simulation). 6. Verify the model and examine its validity. 7. Define input and analyse output of a simulation model. 8. Design and conduct a structured set of simulation experiments. 9. Combine simulation with optimization. 10. Write a well-structured project report on a simulation study.	1. Discrete event simulation theory. 2. Plan of action for a simulation study focused on improvement of operations systems. 3. Judge whether simulation can be a useful technique to analyse certain operations systems. 4. Design a simulation model for a given operations system. 5. Implement this model in an advanced simulation tool (currently Plant Simulation). 6. Verify the model and examine its validity. 7. Define input and analyse output of a simulation model. 8. Design and conduct a structured set of simulation experiments. 9. Combine simulation with optimization. 10. Write a well-structured project report on a simulation study.
Stochastic models in operations management	Stochastic models in operations management	1. Queueing theory: exponential single and many server queues; M—G—1 model; open and closed exponential queueing networks, mean value analysis. 2. Stochastic dynamic programming: problems with finite and infinite horizon; value and policy iteration methods; linear programming formulation.	1. Queueing theory: exponential single and many server queues; M—G—1 model; open and closed exponential queueing networks, mean value analysis. 2. Stochastic dynamic programming: problems with finite and infinite horizon; value and policy iteration methods; linear programming formulation.
Stochastic models in production and logistics	Stochastic models in production and logistics	1. Apply analytic results for open and closed queueing models with exponentially distributed inter-arrival and service times and about approximations for systems with generally distributed service times, especially for non-product form networks. 2. Apply (generalized) Mean-value techniques. 3. Apply general manufacturing systems with set-ups and break-downs and about workload control. 4. Model a(n idealized) practical situation as a network of queues. 5. Numerically find and evaluate (approximations for) performance measures. 6. To critically interpret numerical results for approximated performance measures.	1. Apply analytic results for open and closed queueing models. 2. Apply (generalized) Mean-value techniques. 3. Apply general manufacturing systems with set-ups and breakdowns and about workload control. 4. Model a(n idealized) practical situation as a network of queues. 5. Numerically find and evaluate performance measures. 6. Critically interpret numerical results.

Table 62: Learning Course, Subject and Path description, part 8

Other:			
Machine learning in engineering	Machine Learning in Engineering	1. To sum up different approximations and forms of learning from data. 2. To classify data into a priori specified classes, or by constructing/clustering classes a posteriori by using the concept of similarity of data sets. 3. To construct predictive models given data sets by using analytical functions or complex predictive models based on the deep learning concept. 4. To optimize the learning machine given data sets by using both deterministic and probabilistic approaches. 5. To analyze and validate machine learning models. 6. To synthesize results of the analysis into a meaningful conclusion and to evaluate the quality of data.	1. Sum up different approximations and forms of learning from data. 2. Classify data into a priori specified classes, or by constructing/-clustering classes a posteriori by using the concept of similarity of data sets. 3. Construct predictive models given data sets by using analytical functions or complex predictive models based on the deep learning concept. 4. Optimize the learning machine given data sets by using both deterministic and probabilistic approaches. 5. Analyze and validate machine learning models. 6. Conclude and evaluate the quality of data.
System life cycle management	No info	No info	
Automated production systems	Technical and engineering aspects of automated production systems.	1. Define manufacturing metrics for different automated systems, including material handling, storage, transportation and manufacturing. 2. Recognize state-of-the-art automated systems for material handling, transportation, storage and manufacturing. 3. Understand design principles of different automated systems discussed in the course. 4. Analyze automated systems related to material handling, storage, transportation and manufacturing. 5. Apply knowledge learned during the course to design a real-world automated production system.	1. Define manufacturing metrics for Automated Systems. 2. State of the art of Automated Systems. 3. Design principles of Automated Systems. 4. Logistics handling of Automated Systems. 5. Design real-world Automated System.
Industrial robotic systems	Design automation by using industrial robot cells.	1. Define, describe and compare components of industrial robots in manufacturing environment (e.g. robot configuration · end-effectors · actuators & drive). 2. Define, describe and compare sensing perceptions that enable robots to analyze the environment, reason, and take actions towards given tasks in manufacturing environment. 3. Select configurations, actuators, and sensors for industrial robots to implement given tasks in manufacturing environment & justify the choices. 4. Use industrial robots to implement given tasks in manufacturing environment, and assess performance in terms of accuracy & precision. 5. Formulate supervisors for perceiving situations, reasoning, and taking actions for automation of given tasks in manufacturing environment and assess the formulated supervisors.	1. Industrial robot components. 2. Industrial robot sensors. 3. Configure robots for given tasks. 4. Implement given tasks. 5. Assign industrial robot supervisors.

Table 63: Learning Course, Subject and Path description, part 9

Image processing and computer vision	Image processing and computer vision	1. Apply fundamental signal processing techniques on 2D images. 2. Identify and apply image restoration methods to filter image artefacts such as image noise, distortion and blurring. 3. Recognize and apply advanced image processing techniques including geometrical transforms, edge and line detection and morphological operations. 4. Describe image formation models such as geometric camera models and perspective projection. 5. Implementation of computer vision techniques such as camera calibration and rectification, and structure image analysis. 6. Describe and apply computer vision and image processing algorithms to solve a practical problem in Matlab and evaluate the performance of the proposed implementation.	1. 2D signal processing techniques. 2. Image restoration methods. 3. Advanced image processing techniques. 4. Image formation models. 5. Computer vision techniques. 6. Apply gained knowledge to solve practical problems in Matlab.
Basics for process simulation	Basics for Process Simulation	1. Insight in the thermodynamics of flow systems with mechanically and thermally active components. 2. Ability to apply mass, energy and species balances over compressors, pumps, turbines, mixers and several types of reactors. 3. Ability to handle systems of homogeneous chemical reactions in gases and liquids. 4. Insight into the working mode of several chemical reactor systems. 5. Insight in and ability to the use of programming methods with Matlab. 6. Sufficient background to follow the course Thermodynamics and Flow Sheeting. 7. Sufficient back ground in programming for courses where the use of programming methods is required. 8. Basic programming skills to solve engineering equations with the use of Matlab.	1. Thermodynamics in flow systems (mechanical/thermal components). 2. Calculate thermodynamics in flow systems. 3. Homogeneous chemical reactions. 4. Chemical reactor systems. 5. Programming methods (Matlab). 6. Thermodynamics and Flow Sheeting. 7. Solve engineering equations (Matlab).
Process equipment design	The transfer of insight, knowledge and experience for the technological design of (chemical) process equipment.	1. Apply a design methodology. 2. Select the proper types of equipment for the duty asked. 3. Design, understand, analyze and optimize process equipment for an existing industrial process on large scale (able to as well as skilled in). 4. Redesign the concepts to a final design after reviewing the results of a competitive group of experts and a final discussion with them. 5. Point out the bottleneck parameters in the design. 6. Work together in a team to handle and solve challenging technical designs for process equipment, present the results in a report, specification sheets and in a presentation to a group of experts in this field.	1. Apply design methodology. 2. Equipment selection. 3. Design, understand, analyze and optimize process equipment. 4. Redesign concepts towards a final design. 5. Bottleneck parameters in the design. 6. Solve challenging technical designs for process equipment.

B.4 LS rating

Table 64: LS rating, part 1.

	Criteria			
Core DPM master courses	1: Does it already require a lab?	2: Are practical excercises used?	3: Is it part of Lean or Industry 4.0?	4: Are there lab possibilities?
3D printing	No	No, only a research assignment	Yes, industry 4.0	Yes. By actually having a part produced with a 3D printer and see how that affects the process.
Design Production and Materials	No	No, only conceptual	No	Yes, by being able to design an object and actually produce it.
Design of Production and Inventory systems (Lean)	No	Calculation excercises	Yes, lean production	Yes, by designing or analyzing the LF on the logistics.
Frontiers in Design and Manufacturing	No	No, only a research assignment	Yes, industry 4.0	Yes, by exploring how new technologies could improve the LF
Maintenance Engineering and Management	No	Yes, an assignment to perform various maintanence analysises. And guest lectures where analysises are applied.	Yes, Lean production	Yes, by practically doing analysis on the existing LF.
Manufacturing Facility Design	No	?	?	Yes
Modelling of Technical Design Process	No	Yes, a group assignment to analyze a production design and development process (DPPD).	Yes, both lean and industry 4.0	Yes, by including the LF constraints in the design process.
Elective DPM master subjects:	1: Does it already require a lab?	2: Are practical excercises used?	3: Is it part of Lean or Industry 4.0?	4: Are there lab possibilities?
Adhesion and bonding technology	No	No, only conceptual	No	Yes, by applying various adhesion and bonding techniques in the assembly phase and see how that affects the production process
Biomechanics of human movement	Yes, a movement analysis lab	Yes, simulations of muscle mechanics on joints and gathering dynamic formulations from actual human movement data.	Yes, industry 4.0	Maybe testing human movement in an assembly process and see how a supporting robot can be designed based on the required mechanics of the human.

Table 65: LS rating, part 2.

Composites forming	No	No, only a research assignment	Yes, industry 4.0	Yes, by applying various composite forming techniques and see how that affects a production process.
Computational optimization	***No information***	***No information***	***No information***	***No information***
Cost management and Engineering	No	A research paper must be written on the financial viability of an investment in a random engineering field	No	The shop floor could be used to show what types of investments must be done, for example in machinery, and how to rate the creditworthiness of such investments.
Design for additive manufacturing	No	Simulation excercices are used	Yes, industry 4.0	Yes, seeing the practical side of having a 3d printer on your shop floor and how that affects the production line
Design principles for robotic and mechatronics	No	Simulation excercices are used	No	No, it is about the design of flexures but has not a lot to do with a production shop floor.
Governing product development	No	A project about the (consumer) product development process	No	Yes, for example the practical reality of a production process.
Lean six sigma green belt	No	A project about the analysis and improvement of a production process	Yes, Lean	Yes, by using an actual production process that purposely has errors that can be improved.
Life-cycle strategy	No	A project to assess a product lifecycle.	No	Maybe, by doing a production process-oriented lifecycle assessment.
Multiscale functional materials for engineering application	Yes, "Laboratory tour: Material fabrication and measuring techniques from the Thermal and Fluid Engineering Department and MESA+ Institute"	Yes, "design multi-scale functional materials for thermal management and energy harvesting applications"	Yes, industry 4.0	Yes, as it already does

Table 66: LS rating, part 3.

Multiscale mechanics	Yes, "Small scale experiments on glass beads, sands and powders will be performed in the lab related to the numerical and theoretical analysis."	Yes, but its all about analysing multiscale mechanics and doing small scale experiments.	Yes, Industry 4.0	No, this course has nothing to do with production processes
Simulation	No, only simulation software is used.	Yes, "For the practical part, we use advanced simulation software to implement simulation models and, as an examination, to carry out a small but realistic simulation project. Besides, the course contains three small assignments to get acquainted with the principles of simulation and to learn working with the simulation software."	Yes, industry 4.0	Yes, for example comparing simulations with real life situations.
Stochastic models in operations management	No	Yes, mathematical excercices	Yes, industry 4.0	Yes, by using data from the factory to use in calculation models
Stochastic models in production and logistics	No	Yes, mathematical excercices	Yes, industry 4.0	Yes, by using data from the factory to use in calculation models
Other ME master subjects:	1: Does it already require a lab?	2: Are practical excercices used?	3: Is it part of Lean or Industry 4.0?	4: Are there lab possibilities?

Table 67: LS rating, part 4.

Machine learning in engineering	No	Yes, some practical excercises to apply machine learning methods	Yes, industry 4.0	Yes, by using data from the factory to use in machine learning models
System life cycle management	**Not existing anymore**	**Not existing anymore**	**Not existing anymore**	**Not existing anymore**
Automated production systems	No	Yes, an assignment to design a real-world automated production system	Yes, industry 4.0	Yes, an assignment to change the existing Learning Factory in an automated production factory.
Industrial robotic systems	No	Yes, an assignment to design and program an automated industrial robot and corresponding sensors	Yes industry 4.0	This could work very well with for example a cobot in the LF.
Image processing and computer vision	No	Yes, an assignment to apply image processing and computer vision skills in Matlab image processing software.	Yes, industry 4.0	Yes, a project which involves image processing and tracking of objects throughout the factory.
Basics for process simulation	No	Yes, a matlab coding practical.	No	No, This course is about thermodynamics, not very oriented towards a production process.
Process equipment design	No	Yes, a group assignment to design thermodynamic flow equipment.	No	No, This course is about designing thermodynamic process equipment like pumps, compressors etc.

B.5 Learning Subjects that were not selected

Table 68: Learning Subjects that were not selected, part 1.

Not suited for LF:					
Manufacturing Facility Design (not available)	No	?	?	Yes	No info
Computational optimization (not available)	*No information*	*No information*	*No information*	*No information*	*No info*
System life cycle management (not available)	**Not existing anymore**	**Not existing anymore**	**Not existing anymore**	**Not existing anymore**	**No info**
Design principles for robotic and mechatronics	No	Simulation excercices are used	No	No, it is about the design of flexures but has not a lot to do with a production shop floor.	Nothing to do with LF
Basics for process simulation	No	Yes, a matlab coding practical.	No	No, This course is about thermodynamics, not very oriented towards a production process.	Nothing to do with LF
Process equipment design	No	Yes, a group assignment to design thermodynamic flow equipment.	No	No, This course is about designing thermodynamic process equipment like pumps, compressors etc.	Nothing to do with LF
Multiscale mechanics	Yes, "Small scale experiments on glass beads, sands and powders will be performed in the lab related to the numerical and theoretical analysis."	Yes, but its all about analysing multiscale mechanics and doing small scale experiments.	Yes, Industry 4.0	No, this course has nothing to do with production processes	Nothing to do with LF
Cost management and Engineering	No	A research paper must be written on the financial viability of an investment in a random engineering field	No	Yes, the shop floor could be used to show what types of investments must be done, for example in machinery, and how to rate the creditworthiness of such investments.	Not lean or industry 4.0
Life-cycle strategy	No	A project to assess a product lifecycle.	No	Yes, by doing a production process-oriented lifecycle assessment.	Not lean or industry 4.0
Adhesion and bonding technology	No	No, only conceptual	No	Yes, by applying various adhesion and bonding techniques in the assembly phase and see how that affects the production process	Not lean or industry 4.0

Table 69: Learning Subjects that were not selected, part 2.

Biomechanics of human movement	Yes, a movement analysis lab	Yes, simulations of muscle mechanics on joints and gathering dynamic formulations from actual human movement data.	Yes, industry 4.0	Yes, by testing human movement in an assembly process and see how a supporting robot can be designed based on the required mechanics of the human.	Already uses existing infrastructure.
Multiscale functional materials for engineering application	Yes, "Laboratory tour: Material fabrication and measuring techniques from the Thermal and Fluid Engineering Department and MESA+ Institute"	Yes, "design multi-scale functional materials for thermal management and energy harvesting applications"	Yes, industry 4.0	Yes, as it already does	Already uses existing infrastructure.
Design Production and Materials	No	No, only conceptual	No	Yes, by being able to design an object and actually produce it.	Challenging to involve
Modelling of Technical Design Process	No	Yes, a group assignment to analyze a production design and development process (DPPD).	Depending on how the assignment is done, it could be lean or industry 4.0.	Yes, by including the LF constraints in the design process.	Challenging to involve
Composites forming	No	No, only a research assignment	Yes, industry 4.0	Yes, by applying various composite forming techniques and see how that affects a production process.	Challenging to involve
Governing product development	No	A project about the (consumer) product development process	No	Yes, for example by showing the practical reality of a production process.	LF not crucial, simulation could be enough.
Simulation	No, only simulation software is used.	Yes, "For the practical part, we use advanced simulation software to implement simulation models and, as an examination, to carry out a small but realistic simulation project. Besides, the course contains three small assignments to get acquainted with the principles of simulation and to learn working with the simulation software."	Yes, industry 4.0	Yes, for example comparing simulations with real life situations.	Can be done side by side

B.6 Learning Subject Projects and corresponding Equipment

Table 70: Exploration of projects and corresponding equipment for each Learning Subject, part 1.

Learning Subject	**Projects**	**Equipment/ required data**	**Comments**
1. Lean six sigma green belt	By using an actual production process that purposely has errors that can be improved.	Existing LF	
	Or by using/making augmented reality to speed up the manual production process and remove waste from looking at instructions	AR glasses	Show standardized process instructions to operator.
	Bottleneck Analysis	Throughput time of each production step	To solve bottlenecks based on workflow optimization.
	Just-in-Time (JIT)	A pull system	Manufacture based on demand
		Kanban board	To map the workflow
	Value Stream Mapping	Time record of each production step: -Machine tasks -Manual tasks -Transport time	Not just from machines, but also manual and transport steps.
		Amount of operators per step	
		Cycle time	Time to complete one part
		Changeover time	Time to switch product type
		Uptime	The percentage that machine is up and running
		Yield	The percentage of parts that pass inspection
		Wait times	The time parts spent as inventory between production steps due to bottlenecks.
		Inventory amount	Storage amount, before and after each production step.
		Production lead time	Total non-value added time from the top of the timeline.
		Value added time	Total value-added time from the bottom of the timeline.
		Process cycle efficiency	Percentage of value-added time out of the total process time.

Table 71: Exploration of projects and corresponding equipment for each Learning Subject, part 2.

1. Lean six sigma green belt	Overall Equipment Effectiveness (OEE)	Data records of each step: -Yield -Cycle time -Planned production time OEE: Yield x CT / planned production time Availability calculation: -Planned production time -Process stop time Performance calculation: -Cycle time -Amount of products -Planned production time -Process stop time Quality calculation: -Yield -Total count OEE calculation: Availability x Performance x Quality	The percentage of parts that pass inspection Time to complete one part Total time scheduled - planned downtime (breaks) Calculation of OEE Total time scheduled - planned downtime Unplanned downtime Time to complete one part Amount of parts Total time scheduled - planned downtime Unplanned downtime The percentage of parts that pass inspection Total amount of parts produced by factory OEE = A x P x Q
	Plan-Do-Check-Act (PDCA)	/	Plan-Do-Check-Act cycle is a useful tool that can help your team solve problems much more efficiently.
	Error Proofing	/	Also called po. Any mechanism or device in a process that helps eliminate defects by preventing, correcting, or drawing attention to human error as they occur. For example, a signal to the operator when a certain production step is not properly completed.
	Root Cause Analysis (RCA)	/	Method to get the foundation of an issue.
	Digital tracking where each object is within the factory.	Industrial cameras Industrial sensors RFID tags RFID readers	Vision-based object tracking RFID tracking
	5S	Sort / Set in order Defined space for everything in the factory Shine Cleaning equipment Standardize Standard operating procedure guides Sustain /	Sort: Removing things that are not needed in the workspace. Set in order: put everything in its proper place. Easily findable = reduced waste time. Shine: Operators clean their workspace, equipment and tools regularly to remove dust an dirt. Standardize: Standard procedures for the first three 5S activities. Checklist and audits to ensure operators complete tasks. Sustain: Meet regularly to review and audit current operations.

Table 72: Exploration of projects and corresponding equipment for each Learning Subject, part 3.

2. Design of Production and Inventory systems	Yes, by analyzing and designing the LF based on the logistic numbers.	Production performance data	
3. Industrial robotic systems	Yes, for example by implementing a Yuumi in the LF.	A yuumi cobot Conveyor belts Storage space	A yuumi for picking and placing pieces. A conveyor belt to bring part to/from yuumi, or directly to/from machine.
	Pick by light	Shelf with lights for each inventory box	A shelf that has a light at each inventory box. This is coupled to an automatic program that signals the worker what pieces must be grabbed before/during the assembly of parts.
	Yes, a project which involves image processing and tracking of objects throughout the factory. See below		
4. Image processing and equipment	Automatic cutting in right shape, by object geometry and position scanning.	Industrial cameras	Industrial cameras play a significant role in this, as they offer a tireless method for auditing the color, structural and geometric properties of even large workpieces and products for correctness or deviation. 'Soft' factors such as lubrication, wear and rusting can also be taken into account, providing data for a company's enterprise resource planning systems.
	Automatic spray pattern generation, by object geometry and position scanning.	Industrial cameras	
	Quality control by auditing the color, structural and geometrical tolerances.	Industrial cameras Industrial sensors	
	Assisting human workers by giving instructions and simultaneously performing quality control.	Industrial cameras Industrial sensors Augmented reality glasses	
	Object tracking	Industrial cameras Industrial sensors	Due to 3D scanning and recognition, an objects location can be followed throughout the factory

Table 73: Exploration of projects and corresponding equipment for each Learning Subject, part 4.

5. 3D printing	1. Learning to design for 3D printing. Practically learn how various 3D print settings affect the process. (Speed, width, temperature etc.) 2. By actually having a part produced with a 3D printer and see how that affects the production process. 3. Learn how different materials affect the printing process and what is mechanically possbile for end products. 4. A project that is about improving a current part production, which is possible due to the rapid prototyping ability of a 3D printer.	Fused Deposition Modeling (FDM) printer. 3D printer enclosure Multiple nozzles with different sizes + extra nozzles and feeder tubes Automatic bed leveling sensor Filament rolls that differ in material, size and colour	Easy to use, enough possibilities and not too expensive To be able to print ABS, it keeps the hot air inside and prevents ABS from warping. Also to prevent harmful fumes to spread around the printing area. For different widths For replacements due to wear Manual bed leveling is a time-consuming process To support many applications
6. Maintenance engineering and management	1. By practically doing analysis on the existing LF using wear and performance data of machines. 2. Check machine performance and use AR to do the right maintenance.	Wear rate of used tools Wear sensors for tools Wear rate of dynamically moving parts Wear sensors for dynamically moving parts Leakage sensors Thermal sensors Performance data QR code on each machine AR vision glasses	Wear rate for performing a production step Sensors that detect wear Wear rate for performing a production step Sensors that detect wear Sensors that detect gas/fluid leakages Sensors that detect thermal leakages Amount of times used, tells when to intervene Could be used by maintenance engineers. As every machine is different, AR could be used to do the right maintenance steps or fix all kinds or defects.
7. Stochastic models in operations management	By using data from the factory to use in models to predict the probability of future scenarios.		
8. Stochastic models in production and logistics	By using data from the factory to use in models to predict the probability of future scenarios.		

Table 74: Exploration of projects and corresponding equipment for each Learning Subject, part 5.

9. Machine learning in engineering	By using machine learning to read technical drawings quickly.	AI software Image scanning software	Software that can read an image and turn it into useful data To scan the image in the first place
	Using data from the factory to predict when maintenance is required.	Amount of cycles Wear rate of used tools Wear sensors for tools Wear rate of dynamically moving parts Wear sensors for dynamically moving parts Leakage sensors Thermal sensors	N-number of times a production step is performed Wear rate for performing a production step Sensors that detect wear Wear rate for performing a production step Sensors that detect wear Sensors that detect gas/fluid leakages Sensors that detect thermal leakages
	Do quality assurance based on images.	AI software Image scanning software	Software that can read an image and turn it into useful data To scan the image in the first place
	Use self-learning principles to let robot learn itself how to handle a new part most efficient.	3D object recognition software Industrial cameras Yuumi cobot AI software to process the virtual object into picking instruction	Software that can turn multiple camera angles into a 3D object. To capture an object from multiple angles To pick and place the objects Software that, based on the virtual 3D scanned object, instructs the robot how exactly the real object can be picked up.
10. Automated production systems	Yes, an assignment to change the existing Learning Factory in an automated production factory.	Existing LF	
		AGV	Automated transport and material handling systems
		Automated conveyor belt	Another way of transporting objects
		Cobot	Another way of transporting objects
	An assignment to integrate old and new machines in terms of data and let them talk to eachother.	*Digital system that tracks system performance of each machine*	*With the data known, machines can communicate. When a flaw happens on one side of the production chain, the process can alter at the end of the production chain.*
11. Frontiers in design and manufacturing	Yes, by exploring how new technologies could improve the LF		Object tracking RFID tracking 3D printing Machine learning Automation Robotics Stochastic models

C Supporting material LFCT

C.1 Equipment database

Table 75: Equipment database, part 1.

	1. Standard factory equipment	Length (mm)	Width (mm)	Height (mm)	Cost (€)		Size
	Assembly workstation						
[95]	Mobile mechanically height-adjustable workstation	915	1849	2107	6580	€ € €	M
[96]	Mobile non-height-adjustable workstation	1077	1654	2341	2850	€ €	M
[97]	Mobile non-height-adjustable multiple bins workstation	846	1272	1820	2900	€ €	M
	Quality workstation						
[95]	Mobile mechanically height-adjustable workstation	915	1849	2107	6580	€ € €	M
[96]	Mobile non-height adjustable workstation	1077	1654	2341	2850	€ €	M
[98]	Granite table top	450	300	75	250	€	M
	Inventory rack						
[99]	Small modular inventory rack (1m)	1038	400	2000	175	€	S
[99]	Medium modular inventory rack (3m)	3042	400	2000	495	€	M
[99]	Large modular inventory rack (5m)	5046	400	2000	765	€	L
	Inventory rack with bins						
[100]	Tiny inventory rack on wheels with 36 bins (0,6 m)	660	520	1325	250	€	S
[101]	Small modular inventory rack with 42 bins (1,4 m)	1420	335	1972	460	€	S
	Transport carts						
[102]	Transport cart	1411	954	722	1050	€ €	S
[103]	Cart with 5 drawers	1483	955	1340	4215	€ € €	M
	2. Conventional manufacturing						
	Milling machine						
[104]	Desktop — 177x228x89 work volume — 10 - 28 kRPM	500	530	492	6500	€ € €	S
[105]	Small industrial — 300x280x300 work volume — 20 kRPM	2100	1000	2050	24990	€ € € €	M
[106]	Small industrial — 762x460x460 work volume — 15 kRPM	2200	2805	3000	150000	€ € € €	L
[107]	Medium industrial 5 axis — 800x550x550 work volume — 10-30 kRPM	3000	2000	2650	41990	€ € € €	L
[108]	Medium industrial — 700x700x500 work volume — 15 kRPM	3995	2750	3000	500000	€ € € €	L
[109]	Large industrial 5 axis — 3810x1016x1067 work volume — 20 kRPM	7320	3050	3450	386995	€ € € €	L
[110]	Large industrial bridge-style — 1500 x 5100 — 22 kRPM	5140	12200	5000	2000000	€ € € €	L
	Turning machine						
[121]	Small industrial — 290 mm between centers — 230 mm turning diameter	1702	1843	2200	120000	€ € € €	M
[122]	Small industrial — 600 mm between centers — 270 mm turning diameter	2100	900	600	29920	€ € € €	M
[123]	Medium industrial — 750 mm between centers — 480 mm turning diameters	3050	4175	2200	200000	€ € € €	L
[124]	Medium industrial — 850 mm between centers — 380 mm turning diameter	2500	1800	1800	45000	€ € € €	L
[125]	Large industrial — 3000 mm between centers — 750 mm turning diameter	5300	2300	2200	130000	€ € € €	L
[126]	Large inudstrial — 1500 mm between centers — 650 mm turning diameter	5530	2995	3000	600000	€ € € €	L

Table 76: Equipment database, part 2.

	Grinding machine						
[145]	Small industrial — 250 mm between centers — 150 mm grinding diameter	1550	2547	2000	350000	€€€€	M
[146]	Medium industrial —650 mm between centers — 200 mm grinding diameter	2510	2914	2000	550000	€€€€	L
[147]	Large industrial — 1000 mm between centers — 300 mm grinding diameter	3695	2565	2000	850000	€€€€	L
	Laser cutting machine						
[111]	Desktop 400x400 work area — 350 mm/s	800	500	250	1160	€€	S
[112]	Small industrial 1400 x 900 work area — 500 mm/s	1980	1270	930	7320	€€€	M
[113]	Large industrial 2500 x 1300 work area — 1200 mm/s	3000	1700	1000	17500	€€€€	L
	Injection moulding machine						
[114]	Desktop 310 °C — 146x146x150 work area — 29.57 cm3 shot size	876	254	254	5000	€€€	S
[115]	Desktop 310 °C — 222x222x223 work area — 59.15 cm3 shot size	1092	305	305	10000	€€€€	S
[116]	Desktop 500 °C — 200x125x150 work area — 29,50 cm3 shot size	1300	400	450	5400	€€€	S
[117]	Desktop vacuum moulder 160-340 °C— 200x200x130 work area	466	274	315	615	€	S
[118]	Small industrial xx°C —250x250x200 work area — 48 cm3 shot size	1500	700	2500	6000	€€€	M
[119]	Medium industrial xx°C —635x635x425 work area — 217 cm3 shot size	4000	1200	1500	20000	€€€€	L
[120]	Large industrial (Approximation)	8000	2400	2000	60000	€€€€	L
	Kanban board						
[148]	Glass kanban board	size of glass window			210	€	S
[149]	Magnetic kanban board	size of whiteboard			200	€	S
	3. Industry 4.0 equipment						
	FDM printer						
[150]	Hobby desktop 220x220x250 work volume — 260 °C	440	420	465	220	€	S
[151]	3D printer enclosure	480	600	720	80	€	S
[152]	Automatic bed leveling sensor			-	55	€	S
[153]	Professional small 330x240x300 work volume — 280 °C	495	457	520	6410	€€€	S
[154]	Professional medium 305x305x600 — 300 °C	616	590	760	6050	€€€	S
[155]	Professional large 914x609x914 — 450 °C	2772	1683	2027	200000	€€€€	L
	AGV						
[156]	Small pulling and lifting robot	700	1030	316	32500	€€€€	S
[157]	Pallet robot, 1 m lift	1840	750	1750	44500	€€€€	M
[158]	Pallet robot, 2 m lift	2605	1010	2850	64500	€€€€	M
[159]	Pallet robot, 3 m lift	1840	1010	3850	79500	€€€€	M
	Cobot						
[160]	Single-arm 0.5 kg load — 1.5 m/s — 559 mm reach	160	160		31100	€€€€	S
[161]	Dual-arm 0.5 kg load — 1.5 m/s — 559 mm reach	399	497		51300	€€€€	S
[162]	Single-arm 5 kg load — 2.2 m/s — 950 mm	165	165		32400	€€€€	S
[163]	Single arm 4 kg load — 5.05 m/s — 475 and 580 mm reach	160	172		32200	€€€€	S
[164]	Single arm 5kg load — 1 m/s — 700 mm reach	126	126		8400	€€€	S
[165]	Single arm 1 kg load — 0.5 m/s — 440 mm reach	126	126		3000	€€€	S

Table 77: Equipment database, part 3.

	Conveyor belts						
[166]	Mobile automated belt conveyor (2.5 m)	2509	711	776	8110	€ € €	M
[167]	Automated roller conveyor (1.35 m)	1358	785	1025	3405	€ € €	S
[168]	Automated belt conveyor (1.5 m)	1564	695	997	5240	€ € €	S
[169]	Modular automated roller conveyor (4 m)	4062	895	1060	17975	€ € € €	L
[170]	Automated Roller conveyors transfer module	2283	1898	1082	18040	€ € € €	L
[171]	Gravity roller conveyor plastic (3m)	3000	460	700	300	€	M
[172]	Gravity roller conveyor steel (3m)	3000	460	700	300	€	M
	AR glasses						
[173]	Hobby				550	€	S
[174]	Cheap Professional				1030	€ €	S
[175]	Expensive Professional				4900	€ € €	S
	Industrial cameras						
[176]	Cheap industrial	29	29	29	180	€	S
[177]	Expensive industrial	80	175	40	3450	€ € €	S
	Industrial sensors						
[178]	Industrial temperature sensor -50 till 200 °C				150	€	S
[179]	Thermal camera				300	€	S
[180]	Gas detection sensor				420	€	S
[181]	Torque sensor				270	€	S
	Pick-to-light system						
[182]	High initial investment costs, low cost per system module				1	€	S
	4. Software						
	Machine performance data				1	€	s
	Production performance data				1	€	s
[183]	3D object recognition software				1	€	S
[184]	AI software to process virtual object into picking instruction				1	€	S
[185]	3D print slicer software				1	€	S
[186]	3D object design software				1	€	S
[187]	Pick-to-light software				1	€	S
[188]	AR software				1	€	S
[189]	Digital kanban board software				1	€	S
	5. Project-specific equipment						
	Hobbing machine						
[190]	Small Gear Hobbing machine 60-130 mm workpiece diameter	3945	2607	3100	480000	€ € € €	L
[191]	Medium gear hobbing machine 180-280 mm workpiece diameter	4811	3400	3100	530000	€ € € €	L
[192]	Large gear hobbing machine 300-500 mm workpiece diameter	6290	3855	3110	660000	€ € € €	L
	Knitting machine						
[193]	Desktop hobby	470	370	360	250	€	S

Table 78: Equipment database, budget/size recommendation, part 1.

Budget ⩽ € 499.999			Budget € 500.000 - € 999.999			Budget ⩾ € 1.000.000		
200 m^2	300 m^2	800 m^2	200 m^2	300 m^2	800 m^2	200 m^2	300 m^2	800 m^2
1. Standard factory equipment								
Assembly station								
1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1
Quality station								
			1	1	1	1	1	1
1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1
Inventory rack								
1	1	1	1	1	1	1	1	1
	1	1		1	1		1	1
		1			1			1
Inventory rack with bins								
1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1
Transport carts								
1	1	1	1	1	1	1	1	1
	1	1	1	1	1	1	1	1
2. Conventional manufacturing								
Milling machine								
1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1
							1	1
				1	1		1	1
							1	1
								1
								1
Turning machine								
			1	1	1	1	1	1
1	1	1	1	1	1	1	1	1
							1	1
				1	1	1	1	1
						1	1	1
							1	1

Table 79: Equipment database, budget/size recommendation, part 2.

Budget ⩽ € 499.999			Budget € 500.000 - € 999.999			Budget ⩾ € 1.000.000		
200 m^2	300 m^2	800 m^2	200 m^2	300 m^2	800 m^2	200 m^2	300 m^2	800 m^2
Grinding machine								
						1	1	1
							1	1
								1
Laser cutting machine								
1	1	1	1	1	1	1	1	1
	1	1		1	1		1	1
		1			1			1
Injection moulding machine								
1	1	1	1	1	1	1	1	1
			1	1	1	1	1	1
1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1
	1	1	1	1	1	1	1	1
				1	1		1	1
					1			1
Kanban board								
1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1
3. Industry 4.0 equipment								
FDM printer								
1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1
	1	1		1	1	1	1	1
						1	1	1
AGV								
1	1	1	1	1	1	1	1	1
				1	1	1	1	1
							1	1
							1	1
Cobot								
			1	1	1	1	1	1
			1	1	1	1	1	1
			1	1	1	1	1	1
			1	1	1	1	1	1
1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1

Table 80: Equipment database, budget/size recommendation, part 1.

Budget ⩽ € 499.999			Budget € 500.000 - € 999.999			Budget ⩾ € 1.000.000		
200 m^2	300 m^2	800 m^2	200 m^2	300 m^2	800 m^2	200 m^2	300 m^2	800 m^2
Conveyor belts								
			1	1	1	1	1	1
			1	1	1	1	1	1
			1	1	1	1	1	1
				1	1		1	1
							1	1
1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1
AR glasses								
1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1
			1	1	1	1	1	1
Industrial cameras								
1	1	1	1	1	1	1	1	1
			1	1	1	1	1	1
Industrial sensors								
1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1
Shelf with lights for each inventory box								
			1	1	1	1	1	1
4. Software								
1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1
5. Project-specific equipment								
Hobbing machine								
						1	1	1
							1	1
								1
Knitting machine								
1	1	1	1	1	1	1	1	1

C.2 Background couplings made by LFCT

Step 1: Check is the equipment-type is required for either the LS or the EP.
This sheet will check if the Equipment-type is required of either the LS or the EP, based on the input of Table 31. The last column will output: "Required" if the equipment is either required for the LS or the EP.
Step 2: Check if the equipment is recommended for the chosen budget/size scenario.
If the equipment-model is required for the selected budget and size, the 6th column of Table 82 will output: "Recommended". Then if the equipment-model is recommended for the budget/size and the equipment-type is required for the right LS and/or EP, the last column will change to: "To Buy?".
Step 3: Load equipment to LFCT Dashboard.
The equipment list will first be filtered on the last column, so only the rows that contain "To Buy?" are left. Then the sheet will be copied to the LFCT Dashboard. The code, with explaining comments, is shown in Appendix C.3.1.
Step 4: Select the equipment that you want, like explained in Section 4.3.7.

Table 81: Background coupling of Equipment/LSs/EPs.

	LS related	**EP related**	**Total:**
1. Standard factory equipment			
Assembly workstation	Required	Required	Required
Quality workstation	Required	Required	Required
CMM	Required		Required
Inventory rack	Required		Required
Inventory rack with bins	Required	Required	Required
Transport carts	Required	Required	Required
2. Conventional factory equipment			
Milling machine			
Turning machine			
Grinding machine			
Laser cutting machine	Required	Required	Required
Injection moulding machine	Required	Required	Required
Kanban board			
3. Industry 4.0 equipment			
FDM printer	Required	Required	Required
AGV			
Cobot	Required		Required
Conveyor belts			
AR glasses	Required	Required	Required
Industrial cameras	Required		Required
Industrial sensors	Required		Required
Pick-to-light system			
4. Software			
Machine performance data	Required		Required
Production performance data	Required		Required
3D object recognition software	Required		Required
AI software to process virtual object into picking instruction	Required		Required
3D print slicer software	Required	Required	Required
3D object design software	Required	Required	Required
Pick-to-light software			
AR software	Required	Required	Required
Digital Kanban Boardsoftware			
5. Project-specific equipment			
Knitting machine			
Hobbing machine			

Table 82: Background coupling of Equipment/Budget/Size to coupling of Equipment/LSs/EPs.

Inventory rack with bins					-	Required	-
Tiny inventory rack on wheels with 36 bins (0,6 m)	660	520	1325	250	Recommended	Required	To Buy?
Small modular inventory rack with 42 bins (1,4 m)	1420	335	1972	460	Recommended	Required	To Buy?
Transport carts					-	Required	-
Transport cart	1411	954	722	1050	Recommended	Required	To Buy?
Cart with 5 drawers	1483	955	1340	4215	Recommended	Required	To Buy?
2. Conventional manufacturing					-		-
Milling machine					-		-
Desktop 177x228x89 work volume — 10 - 28 kRPM	500	530	492	6500	Recommended		
Small industrial 400x300x380 work volume — 12-30 kRPM	1500	1700	2300	28990	Recommended		
Small industrial — 762x460x460 work volume — 15 kRPM	2200	2805	3000	150000			
Medium industrial 5 axis — 800x550x550 work volume — 10-30 kRPM	3000	2000	2650	41990			
Medium industrial — 700x700x500 work volume — 15 kRPM	3995	2750	3000	500000			
Large industrial 5 axis — 3810x1016x1067 work volume — 20 kRPM	7320	3050	3450	386995			
Large industrial bridge-style — 1500 x 5100 — 22 kRPM	5140	####	5000	2000000			
Turning machine					-		-
Small industrial — 290 mm between centers — 230 mm turning diameter	1702	1843	2200	120000	Recommended		
Small industrial — 600 mm between centers — 270 mm turning diameter	2100	900	600	29920	Recommended		
Medium industrial — 750 mm between centers — 480 mm turning diameters	3050	4175	2200	200000			
Medium industrial — 850 mm between centers — 380 mm turning diameter	2500	1800	1800	45000	Recommended		
Large industrial — 3000 mm between centers — 750 mm turning diameter	5300	2300	2200	130000	Recommended		
Large inudstrial — 1500 mm between centers — 650 mm turning diameter	5530	2995	3000	600000			
Grinding machine					-		-
Small industrial — 250 mm between centers — 150 mm grinding diameter	1550	2547	2000	350000	Recommended		
Medium industrial —650 mm between centers — 200 mm grinding diameter	2510	2914	2000	550000			
Large industrial — 1000 mm between centers — 300 mm grinding diameter	3695	2565	2000	850000			
Laser cutting machine					-	Required	-
Desktop 400x400 work area — 350 mm/s	800	500	250	1160	Recommended	Required	To Buy?
Small industrial 1400 x 900 work area — 500 mm/s	1980	1270	930	7320		Required	
Large industrial 2500 x 1300 work area — 1200 mm/s	3000	1700	1000	17500		Required	
Injection moulding machine					-	Required	-
Desktop 310 °C — 146x146x150 work area — 29.57 cm3 shot size	876	254	254	5000	Recommended	Required	To Buy?
Desktop 310 °C — 222x222x223 work area — 59.15 cm3 shot size	1092	305	305	10000	Recommended	Required	To Buy?
Desktop 500 °C — 200x125x150 work area — 29,50 cm3 shot size	1300	400	450	5400	Recommended	Required	To Buy?
Desktop vacuum moulder 160-340 °C— 200x200x130 work area	466	274	315	615	Recommended	Required	To Buy?
Small industrial xx°C —250x250x200 work area — 48 cm3 shot size	1500	700	2500	6000	Recommended	Required	To Buy?
Medium industrial xx°C —635x635x425 work area — 217 cm3 shot size	4000	1200	1500	20000		Required	
Large industrial (Approximation)	8000	2400	2000	60000		Required	

C.3 VBA codes

C.3.1 Load Equipment List to LFCT Dashboard

```
Sub LoadEquipmentToConfig()
Application.ScreenUpdating = False 'Allows for faster processing
' Filters and copies most updated Equipment list based on budget and size

' ----------------------------------------------------------------------------

        ' SbSf to config
    If Range("G22").Value = "Small" And Range("G24").Value = "Small" Then

        Columns("Q:W").Select
        Selection.ClearContents 'Remove old equipment list
        Sheets("SbSf").Select 'Go to external equipment list due to couplings
        ActiveSheet.Range("$B$1:$J$271").AutoFilter Field:=9, Criteria1:="<>" 'Filter out equipment that is not coupled
        Range("A:A,C:C,D:D,E:E,F:F,G:G,J:J").Select
        Range("J1").Activate
        Selection.Copy 'Copy the necessary columns for the final equipment list
        Sheets("LF Configuration").Select 'Back to configuration tool screen
        Range("Q1").Select
        ActiveSheet.Paste
        Columns("Q:AB").Select 'Paste equipment list

        'For each row within Q to AB,that has a "-" in the W-column, turn the row grey:
        Selection.FormatConditions.Add Type:=xlExpression, Formula1:="=$W1=""-"""
        Selection.FormatConditions(Selection.FormatConditions.Count).SetFirstPriority
        With Selection.FormatConditions(1).Font
            .Bold = True
            .Italic = False
            .TintAndShade = 0
        End With
        With Selection.FormatConditions(1).Interior
            .PatternColorIndex = xlAutomatic
            .ThemeColor = xlThemeColorDark2
            .TintAndShade = -9.99481185338908E-02
        End With
        Selection.FormatConditions(1).StopIfTrue = False
            ' ----------------------------------------------
            ' Reloads the selection/amount/cost/area columns from external sheet to LF Config:
            Columns("X:AB").Select
            Selection.ClearContents
            Sheets("Lists").Select
            Columns("M:Q").Select
            Selection.Copy
            Sheets("LF Configuration").Select
            Range("X1").Select
```

```
            Selection.PasteSpecial Paste:=xlPasteFormulas, Operation:=
    xlNone, _
                SkipBlanks:=False, Transpose:=False
            Columns("Y:Y").Select
            Selection.EntireColumn.Hidden = True
'
    ---------------------------------------------------------------------------

        ' SbMf to config
     ElseIf Range("G22").Value = "Small" And Range("G24").Value = "Medium"
    Then

        Columns("Q:W").Select
        Selection.ClearContents
        Sheets("SbMf").Select
        ActiveSheet.Range("$B$1:$J$271").AutoFilter Field:=9, Criteria1
    :="<>"
        Range("A:A,C:C,D:D,E:E,F:F,G:G,J:J").Select
        Range("J1").Activate
        Selection.Copy
        Sheets("LF Configuration").Select
        Range("Q1").Select
        ActiveSheet.Paste
        Columns("Q:AB").Select
        Selection.FormatConditions.Add Type:=xlExpression, Formula1:="=$W1
    =""-"""
        Selection.FormatConditions(Selection.FormatConditions.Count).
    SetFirstPriority
        With Selection.FormatConditions(1).Font
            .Bold = True
            .Italic = False
            .TintAndShade = 0
        End With
        With Selection.FormatConditions(1).Interior
            .PatternColorIndex = xlAutomatic
            .ThemeColor = xlThemeColorDark2
            .TintAndShade = -9.99481185338908E-02
        End With
        Selection.FormatConditions(1).StopIfTrue = False
            ' -----------------------------------------------
            ' Reloads the selection/amount/cost/area columns op LF Config
            Columns("X:AB").Select
            Selection.ClearContents
            Sheets("Lists").Select
            Columns("M:Q").Select
            Selection.Copy
            Sheets("LF Configuration").Select
            Range("X1").Select
            Selection.PasteSpecial Paste:=xlPasteFormulas, Operation:=
    xlNone, _
                SkipBlanks:=False, Transpose:=False
            Columns("Y:Y").Select
            Selection.EntireColumn.Hidden = True
'
    ---------------------------------------------------------------------------

        ' SbLf to config
```

```
 ElseIf Range("G22").Value = "Small" And Range("G24").Value = "Large" Then

     Columns("Q:W").Select
     Selection.ClearContents
     Sheets("SbLf").Select
     ActiveSheet.Range("$B$1:$J$271").AutoFilter Field:=9, Criteria1:="<>"
     Range("A:A,C:C,D:D,E:E,F:F,G:G,J:J").Select
     Range("J1").Activate
     Selection.Copy
     Sheets("LF Configuration").Select
     Range("Q1").Select
     ActiveSheet.Paste
     Columns("Q:AB").Select
     Selection.FormatConditions.Add Type:=xlExpression, Formula1:="=$W1=""-"""
     Selection.FormatConditions(Selection.FormatConditions.Count).SetFirstPriority
     With Selection.FormatConditions(1).Font
         .Bold = True
         .Italic = False
         .TintAndShade = 0
     End With
     With Selection.FormatConditions(1).Interior
         .PatternColorIndex = xlAutomatic
         .ThemeColor = xlThemeColorDark2
         .TintAndShade = -9.99481185338908E-02
     End With
     Selection.FormatConditions(1).StopIfTrue = False
         ' -----------------------------------------------
         ' Reloads the selection/amount/cost/area columns op LF Config
         Columns("X:AB").Select
         Selection.ClearContents
         Sheets("Lists").Select
         Columns("M:Q").Select
         Selection.Copy
         Sheets("LF Configuration").Select
         Range("X1").Select
         Selection.PasteSpecial Paste:=xlPasteFormulas, Operation:=xlNone, _
             SkipBlanks:=False, Transpose:=False
         Columns("Y:Y").Select
         Selection.EntireColumn.Hidden = True
' ---------------------------------------------------------------------------

     ' MbSf to config
 ElseIf Range("G22").Value = "Medium" And Range("G24").Value = "Small" Then

     Columns("Q:W").Select
     Selection.ClearContents
     Sheets("MbSf").Select
     ActiveSheet.Range("$B$1:$J$271").AutoFilter Field:=9, Criteria1:="<>"
     Range("A:A,C:C,D:D,E:E,F:F,G:G,J:J").Select
     Range("J1").Activate
```

```
        Selection.Copy
        Sheets("LF Configuration").Select
        Range("Q1").Select
        ActiveSheet.Paste
        Columns("Q:AB").Select
        Selection.FormatConditions.Add Type:=xlExpression, Formula1:="=$W1
   =""-"""
        Selection.FormatConditions(Selection.FormatConditions.Count).
   SetFirstPriority
        With Selection.FormatConditions(1).Font
            .Bold = True
            .Italic = False
            .TintAndShade = 0
        End With
        With Selection.FormatConditions(1).Interior
            .PatternColorIndex = xlAutomatic
            .ThemeColor = xlThemeColorDark2
            .TintAndShade = -9.99481185338908E-02
        End With
        Selection.FormatConditions(1).StopIfTrue = False
            ' -----------------------------------------------
            ' Reloads the selection/amount/cost/area columns op LF Config
            Columns("X:AB").Select
            Selection.ClearContents
            Sheets("Lists").Select
            Columns("M:Q").Select
            Selection.Copy
            Sheets("LF Configuration").Select
            Range("X1").Select
            Selection.PasteSpecial Paste:=xlPasteFormulas, Operation:=
   xlNone, _
                SkipBlanks:=False, Transpose:=False
            Columns("Y:Y").Select
            Selection.EntireColumn.Hidden = True
'
   ---------------------------------------------------------------------------

      ' MbMf to config
    ElseIf Range("G22").Value = "Medium" And Range("G24").Value = "Medium"
   Then


        Columns("Q:W").Select
        Selection.ClearContents
        Sheets("MbMf").Select
        ActiveSheet.Range("$B$1:$J$271").AutoFilter Field:=9, Criteria1
   :="<>"
        Range("A:A,C:C,D:D,E:E,F:F,G:G,J:J").Select
        Range("J1").Activate
        Selection.Copy
        Sheets("LF Configuration").Select
        Range("Q1").Select
        ActiveSheet.Paste
        Columns("Q:AB").Select
        Selection.FormatConditions.Add Type:=xlExpression, Formula1:="=$W1
   =""-"""
        Selection.FormatConditions(Selection.FormatConditions.Count).
   SetFirstPriority
```

```
        With Selection.FormatConditions(1).Font
            .Bold = True
            .Italic = False
            .TintAndShade = 0
        End With
        With Selection.FormatConditions(1).Interior
            .PatternColorIndex = xlAutomatic
            .ThemeColor = xlThemeColorDark2
            .TintAndShade = -9.99481185338908E-02
        End With
        Selection.FormatConditions(1).StopIfTrue = False
            ' -----------------------------------------------
            ' Reloads the selection/amount/cost/area columns op LF Config
            Columns("X:AB").Select
            Selection.ClearContents
            Sheets("Lists").Select
            Columns("M:Q").Select
            Selection.Copy
            Sheets("LF Configuration").Select
            Range("X1").Select
            Selection.PasteSpecial Paste:=xlPasteFormulas, Operation:=xlNone, _
                SkipBlanks:=False, Transpose:=False
            Columns("Y:Y").Select
            Selection.EntireColumn.Hidden = True
'----------------------------------------------------------------------------

      ' MbLf to config
    ElseIf Range("G22").Value = "Medium" And Range("G24").Value = "Large" Then


        Columns("Q:W").Select
        Selection.ClearContents
        Sheets("MbLf").Select
        ActiveSheet.Range("$B$1:$J$271").AutoFilter Field:=9, Criteria1:="<>"
        Range("A:A,C:C,D:D,E:E,F:F,G:G,J:J").Select
        Range("J1").Activate
        Selection.Copy
        Sheets("LF Configuration").Select
        Range("Q1").Select
        ActiveSheet.Paste
        Columns("Q:AB").Select
        Selection.FormatConditions.Add Type:=xlExpression, Formula1:="=$W1=""-"""
        Selection.FormatConditions(Selection.FormatConditions.Count).SetFirstPriority
        With Selection.FormatConditions(1).Font
            .Bold = True
            .Italic = False
            .TintAndShade = 0
        End With
        With Selection.FormatConditions(1).Interior
            .PatternColorIndex = xlAutomatic
            .ThemeColor = xlThemeColorDark2
            .TintAndShade = -9.99481185338908E-02
```

```
        End With
        Selection.FormatConditions(1).StopIfTrue = False
            ' -----------------------------------------------
            ' Reloads the selection/amount/cost/area columns op LF Config
            Columns("X:AB").Select
            Selection.ClearContents
            Sheets("Lists").Select
            Columns("M:Q").Select
            Selection.Copy
            Sheets("LF Configuration").Select
            Range("X1").Select
            Selection.PasteSpecial Paste:=xlPasteFormulas, Operation:=xlNone, _
                SkipBlanks:=False, Transpose:=False
            Columns("Y:Y").Select
            Selection.EntireColumn.Hidden = True
'---------------------------------------------------------------------------

      ' LbSf to config
    ElseIf Range("G22").Value = "Large" And Range("G24").Value = "Small" Then

        Columns("Q:W").Select
        Selection.ClearContents
        Sheets("LbSf").Select
        ActiveSheet.Range("$B$1:$J$271").AutoFilter Field:=9, Criteria1:="<>"
        Range("A:A,C:C,D:D,E:E,F:F,G:G,J:J").Select
        Range("J1").Activate
        Selection.Copy
        Sheets("LF Configuration").Select
        Range("Q1").Select
        ActiveSheet.Paste
        Columns("Q:AB").Select
        Selection.FormatConditions.Add Type:=xlExpression, Formula1:="=$W1=""-"""
        Selection.FormatConditions(Selection.FormatConditions.Count).SetFirstPriority
        With Selection.FormatConditions(1).Font
            .Bold = True
            .Italic = False
            .TintAndShade = 0
        End With
        With Selection.FormatConditions(1).Interior
            .PatternColorIndex = xlAutomatic
            .ThemeColor = xlThemeColorDark2
            .TintAndShade = -9.99481185338908E-02
        End With
        Selection.FormatConditions(1).StopIfTrue = False
            ' -----------------------------------------------
            ' Reloads the selection/amount/cost/area columns op LF Config
            Columns("X:AB").Select
            Selection.ClearContents
            Sheets("Lists").Select
            Columns("M:Q").Select
            Selection.Copy
            Sheets("LF Configuration").Select
```

```
            Range("X1").Select
            Selection.PasteSpecial Paste:=xlPasteFormulas, Operation:=xlNone, _
                SkipBlanks:=False, Transpose:=False
            Columns("Y:Y").Select
            Selection.EntireColumn.Hidden = True

'---------------------------------------------------------------------------
      ' LbMf to config
    ElseIf Range("G22").Value = "Large" And Range("G24").Value = "Medium" Then

        Columns("Q:W").Select
        Selection.ClearContents
        Sheets("LbMf").Select
        ActiveSheet.Range("$B$1:$J$271").AutoFilter Field:=9, Criteria1:="<>"
        Range("A:A,C:C,D:D,E:E,F:F,G:G,J:J").Select
        Range("J1").Activate
        Selection.Copy
        Sheets("LF Configuration").Select
        Range("Q1").Select
        ActiveSheet.Paste
        Columns("Q:AB").Select
        Selection.FormatConditions.Add Type:=xlExpression, Formula1:="=$W1=""-"""
        Selection.FormatConditions(Selection.FormatConditions.Count).SetFirstPriority
        With Selection.FormatConditions(1).Font
            .Bold = True
            .Italic = False
            .TintAndShade = 0
        End With
        With Selection.FormatConditions(1).Interior
            .PatternColorIndex = xlAutomatic
            .ThemeColor = xlThemeColorDark2
            .TintAndShade = -9.99481185338908E-02
        End With
        Selection.FormatConditions(1).StopIfTrue = False
            ' -----------------------------------------------
            ' Reloads the selection/amount/cost/area columns op LF Config
            Columns("X:AB").Select
            Selection.ClearContents
            Sheets("Lists").Select
            Columns("M:Q").Select
            Selection.Copy
            Sheets("LF Configuration").Select
            Range("X1").Select
            Selection.PasteSpecial Paste:=xlPasteFormulas, Operation:=xlNone, _
                SkipBlanks:=False, Transpose:=False
            Columns("Y:Y").Select
            Selection.EntireColumn.Hidden = True

'---------------------------------------------------------------------------
```

```
        ' LbLf to config
    ElseIf Range("G22").Value = "Large" And Range("G24").Value = "Large" Then

        Columns("Q:W").Select
        Selection.ClearContents
        Sheets("LbLf").Select
        ActiveSheet.Range("$B$1:$J$271").AutoFilter Field:=9, Criteria1:="<>"
        Range("A:A,C:C,D:D,E:E,F:F,G:G,J:J").Select
        Range("J1").Activate
        Selection.Copy
        Sheets("LF Configuration").Select
        Range("Q1").Select
        ActiveSheet.Paste
        Columns("Q:AB").Select
        Selection.FormatConditions.Add Type:=xlExpression, Formula1:="=$W1=""-"""
        Selection.FormatConditions(Selection.FormatConditions.Count).SetFirstPriority
        With Selection.FormatConditions(1).Font
            .Bold = True
            .Italic = False
            .TintAndShade = 0
        End With
        With Selection.FormatConditions(1).Interior
            .PatternColorIndex = xlAutomatic
            .ThemeColor = xlThemeColorDark2
            .TintAndShade = -9.99481185338908E-02
        End With
        Selection.FormatConditions(1).StopIfTrue = False

            ' -----------------------------------------------
            ' Reloads the selection/amount/cost/area columns op LF Config
            Columns("X:AB").Select
            Selection.ClearContents
            Sheets("Lists").Select
            Columns("M:Q").Select
            Selection.Copy
            Sheets("LF Configuration").Select
            Range("X1").Select
            Selection.PasteSpecial Paste:=xlPasteFormulas, Operation:=xlNone, _
                SkipBlanks:=False, Transpose:=False
            Columns("Y:Y").Select
            Selection.EntireColumn.Hidden = True

    Else
    MsgBox ("Please select the budget and factory size.")

End If

End Sub


    '
    Sheets("Formatted_table").Select
```

```
    Columns("A:Q").Select
    Columns("A:Q").EntireColumn.AutoFit 'Fit columnwidths better
    Columns("A:A").Select
    Selection.ColumnWidth = 14.11

    ' Add table lines
'
    Sheets("Formatted_table").Select
    Range("A1:P500").Select
    Selection.Borders(xlDiagonalDown).LineStyle = xlNone
    Selection.Borders(xlDiagonalUp).LineStyle = xlNone
    With Selection.Borders(xlEdgeLeft)
        .LineStyle = xlContinuous
        .ColorIndex = 0
        .TintAndShade = 0
        .Weight = xlThin
    End With
    With Selection.Borders(xlEdgeTop)
        .LineStyle = xlContinuous
        .ColorIndex = 0
        .TintAndShade = 0
        .Weight = xlThin
    End With
    With Selection.Borders(xlEdgeBottom)
        .LineStyle = xlContinuous
        .ColorIndex = 0
        .TintAndShade = 0
        .Weight = xlThin
    End With
    With Selection.Borders(xlEdgeRight)
        .LineStyle = xlContinuous
        .ColorIndex = 0
        .TintAndShade = 0
        .Weight = xlThin
    End With
    With Selection.Borders(xlInsideVertical)
        .LineStyle = xlContinuous
        .ColorIndex = 0
        .TintAndShade = 0
        .Weight = xlThin
    End With
    With Selection.Borders(xlInsideHorizontal)
        .LineStyle = xlContinuous
        .ColorIndex = 0
        .TintAndShade = 0
        .Weight = xlThin
    End With

    ' TitlesBold
'
    Sheets("Formatted_table").Select
    Range("A1:P1").Select
    Selection.Font.Bold = True
    Range("Q1").Select
End Sub
```

C.3.2 Load MS Forms-output to LFCT format

```
Sub SortFormOutputAndGetDatabaseTable5_1()
'
'  Sort_form_output_and_make_initial_table
'
Application.ScreenUpdating = False 'increases process speed
'
    'Sort form output  based on main category number
    Sheets("Filter-output").Select
    Columns("A:P").Select
    Selection.AutoFilter
    Application.DeleteCustomList ListNum:=6
    Application.AddCustomList ListArray:=Array("Main Category", _
        "1. Standard Factory Equipment", "2. Conventional Manufacturing Equipment", _
        "3. Industry 4.0 Equipment", "4. Software", "5. Project Specific Equipment")
    ActiveWorkbook.Worksheets("Filter-output").Sort.SortFields.Clear
    ActiveWorkbook.Worksheets("Filter-output").Sort.SortFields.Add2 Key:=Range( _
        "A1:A250"), SortOn:=xlSortOnValues, Order:=xlAscending, CustomOrder:= _
        "Main Category,1. Standard Factory Equipment,2. Conventional Manufacturing Equipment,3. Industry 4.0 Equipment,4. Software,5. Project Specific Equipment" _
        , DataOption:=xlSortNormal
    With ActiveWorkbook.Worksheets("Filter-output").Sort
        .SetRange Range("A1:P250")
        .Header = xlGuess
        .MatchCase = False
        .Orientation = xlTopToBottom
        .SortMethod = xlPinYin
        .Apply
    End With

    'Make copy of sorted table of form output
    Sheets("Filter-output").Select
    Columns("A:P").Select
    Selection.Copy
    Sheets("Sorted").Select
    Range("A1").Select
    ActiveSheet.Paste

    'Make useable table for LF configurator
    Sheets("Formatted_table").Select
    Columns("A:Q").Select
    Selection.Delete Shift:=xlToLeft 'Remove existing table
    Sheets("Sorted").Select
    Columns("A:P").Select
    Selection.Copy
    Sheets("Formatted_table").Select
    Range("A:P").Select 'Paste sorted table of form output
    Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
        :=False, Transpose:=False 'Paste arguments, just values, and also paste blanks
    Application.CutCopyMode = False 'Turn the copy mode off, to not
```

```
interfere with other operations
 Selection.Subtotal GroupBy:=1, Function:=xlCount, TotalList:=Array(1),
_
     Replace:=True, PageBreaks:=False, SummaryBelowData:=True
 Range("F3").Select
 ActiveSheet.Outline.ShowLevels RowLevels:=2
 Columns("B:C").Select
 Columns("B:C").Cut Destination:=Columns("A:B") 'Remove the first column
 and replace with main and subcategory
 Columns("G:G").Select
 Selection.Cut Destination:=Columns("C:C") 'Move description to third
column
 Columns("H:Q").Select
 Selection.Cut Destination:=Columns("G:P") 'Move the rest of the columns
 to the left
 ActiveSheet.Outline.ShowLevels RowLevels:=3
 Sheets("Formatted_table").Select
 Rows("2:2").Select
 Selection.Insert Shift:=xlDown, CopyOrigin:=xlFormatFromLeftOrAbove '
Create white line on second row

 ' Improve view
 '
 Sheets("Formatted_table").Select
 Columns("A:Q").Select
 Columns("A:Q").EntireColumn.AutoFit 'Fit columnwidths better
 Columns("A:A").Select
 Selection.ColumnWidth = 14.11

 ' Add table lines
'
 Sheets("Formatted_table").Select
 Range("A1:P500").Select
 Selection.Borders(xlDiagonalDown).LineStyle = xlNone
 Selection.Borders(xlDiagonalUp).LineStyle = xlNone
 With Selection.Borders(xlEdgeLeft)
     .LineStyle = xlContinuous
     .ColorIndex = 0
     .TintAndShade = 0
     .Weight = xlThin
 End With
 With Selection.Borders(xlEdgeTop)
     .LineStyle = xlContinuous
     .ColorIndex = 0
     .TintAndShade = 0
     .Weight = xlThin
 End With
 With Selection.Borders(xlEdgeBottom)
     .LineStyle = xlContinuous
     .ColorIndex = 0
     .TintAndShade = 0
     .Weight = xlThin
 End With
 With Selection.Borders(xlEdgeRight)
     .LineStyle = xlContinuous
     .ColorIndex = 0
     .TintAndShade = 0
     .Weight = xlThin
```

```
    End With
    With Selection.Borders(xlInsideVertical)
        .LineStyle = xlContinuous
        .ColorIndex = 0
        .TintAndShade = 0
        .Weight = xlThin
    End With
    With Selection.Borders(xlInsideHorizontal)
        .LineStyle = xlContinuous
        .ColorIndex = 0
        .TintAndShade = 0
        .Weight = xlThin
    End With

    ' TitlesBold
'
    Sheets("Formatted_table").Select
    Range("A1:P1").Select
    Selection.Font.Bold = True
    Range("Q1").Select
End Sub
```