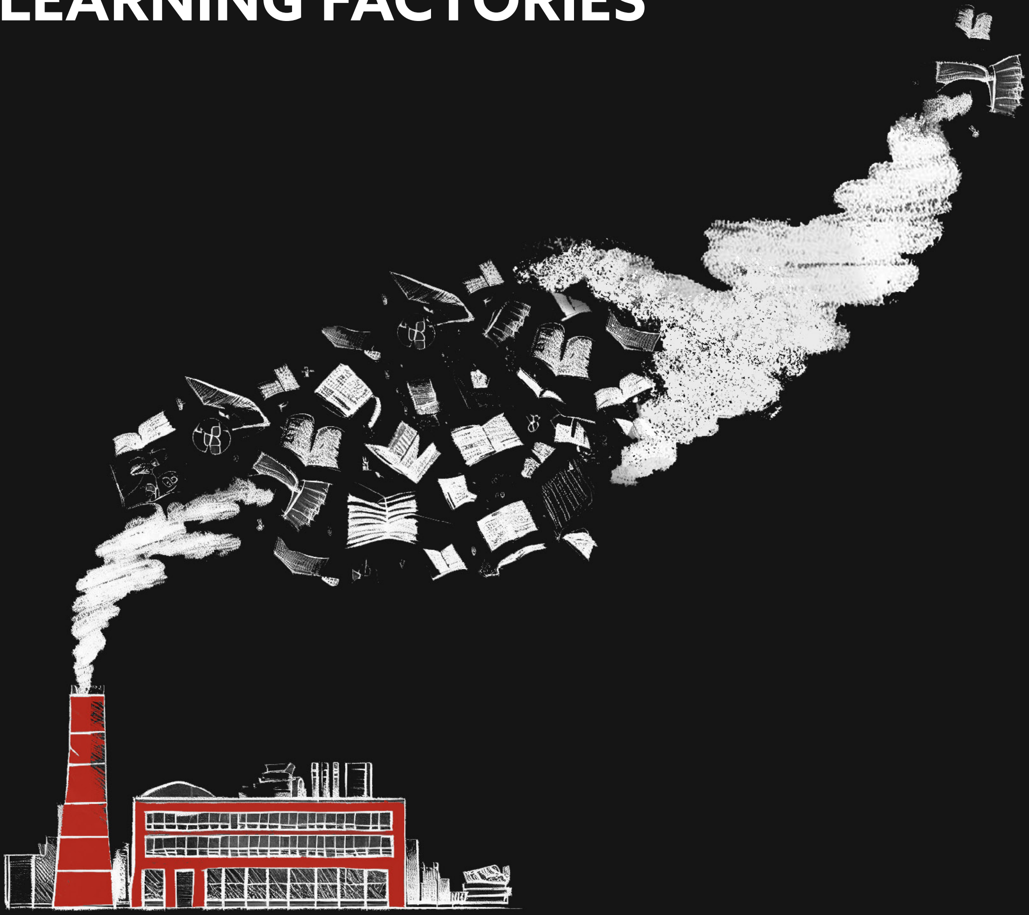
DEVELOPING A MULTI-PERSPECTIVE DESIGN GUIDE FOR EFFECTIVE LEARNING FACTORIES



JANNEKE MASSA

UNIVERSITY
OF TWENTE.

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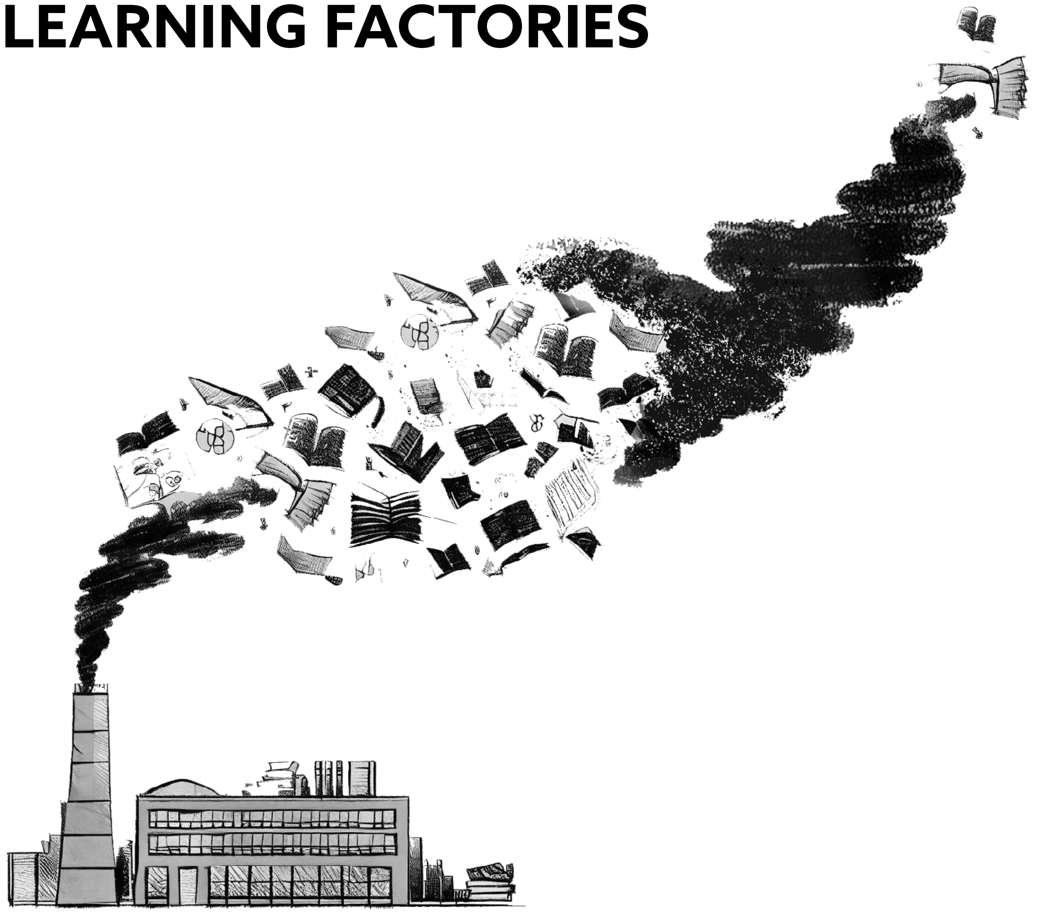

JANNEKE MASSA

Developing a Multi-Perspective Design Guide for Effective Learning Factories

Author	Janneke Massa s1959395 DPM 2047	
Educational details	Engineering Technology Industrial Design Engineering Design, Production & Management	
Educational institution	University of Twente Drienerlolaan 5 7522 NB Enschede	
Examination date	28 / 09 / 2023	
Examination committee	Prof. Dr. Ir. D. Lutters	(chair)
	Dr. Ir. R.G.J. Damgrave	(supervisor)
	Dr. Ing. S. Yang	(external member)

Preface

My journey into education is rooted in my family. With a father who is a teacher (and now a brother too), conversations about daily teaching experiences were always a staple at our dinner table. These conversations showed me the impact of education on individuals and shaped my understanding of its importance. Throughout my studies to become an Industrial Design Engineer, I made sure to keep education included in my life. During my minor, I took the opportunity to gain a diploma as a physics teacher, and throughout my studies I was involved in the educational support of young students. Through these experiences it became increasingly clear that the traditional, passive approach to education hardly works for anyone. My own experiences as an (apparently) neurodivergent individual reinforced this notion.

When Eric introduced me to learning factories two years ago, I was immediately intrigued. learning factories are a breath of fresh air in the traditional world of engineering education. When the time came to choose a topic for my Master's thesis, I quickly decided to focus on learning factories.

I would like to take this opportunity to thank all those involved in the realisation of this thesis. Their support and guidance has been invaluable and has made this research an inspiring and enjoyable journey. First and foremost, my thanks go to Eric, without whom I may never have encountered or explored the concept of learning factories. I appreciate your guidance and feedback while allowing me the freedom to pursue my research independently. In addition, I would like to thank both Eric and Roy for involving me in their own research on this topic and for giving me the opportunity to accompany them to the Conference on Learning Factories 2023. I am also grateful to all the people who have supported me in any way during my thesis journey, whether it was listening to my ramblings or sharing their own processes and experiences, especially Sanne, Carolien and Nadieh.

I would like to express my gratitude to my friends and family for their encouragement throughout this project. To my friends, your presence and support has always meant the world to me, whether it was offering assistance or providing distraction and fun through activities like climbing, swimming (or not) and more. To my parents, thank you for your support and for giving me the freedom to go in any direction I wanted. Also a special thanks to them for bringing Pixel, the best dog ever, into our lives. Lastly, I would like to thank Max for being my biggest supporter, for believing in me more than I could ever believe in myself, and for always being there, whether it be for (sometimes slightly risky) adventures, great food, or anything else.

Janneke

Abstract

This thesis starts the development of a multi-perspective, continuous and non-linear design guide to ensure that learning factories are able to fulfil their primary purpose - effective learning. The design of learning factories is complex, requiring the proper integration of different perspectives (such as education and technology) to meet unique learning objectives, while remaining adaptable to evolving technologies and emerging challenges. Despite their potential, current implementations of learning factories often face limitations that hinder their primary goal.

The research explores the fundamental concepts and principles associated with learning factories. It highlights the limitations of existing design approaches and underlines the need for a new design guide for effective learning factories that is capable of addressing the inherent complexity, adaptability requirements and limitations associated with these environments.

The development of this design guide takes into account essential requirements and characteristics, focusing on providing a comprehensive overview of the dimensions of learning factory design, continuously supporting and aligning systematic decision making, ensuring usability and visibility and transparency. The key components of the design guide are systematically structured and form the central principle of the design guide, comprising a framework, methods, requirements and specification lists that collectively facilitate learning factory development.

A small case study was used to validate the guiding principle and the initial design guide proposal, demonstrating a solid foundation for guiding the learning factory design process. This provided valuable insights for the development process of the design guide. The design guide should be adapted through practical use, possibly broadening its scope and deepening its content within different design elements. The guide should evolve continuously, taking into account different stages of the learning factory and adapting to changing needs. This thesis begins this evolutionary process by proposing a version of the design guide for early-stage learning factory development.

This thesis offers a proposal that lays the groundwork for a design guide for effective learning factories. For further development, a continuous approach with practical application should be adopted to ensure the evolution of the design guide: providing a flexible approach to creating effective learning factories that can adapt and expand in response to the ever-changing landscape of education and technology.

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Introduction

1.1 Research motive

The modern industrial landscape is characterised by its dynamic nature, constantly shaped by technological advances and the forces of globalisation. In response to this ever-changing environment, the manufacturing sector is experiencing an increasing demand for innovative approaches to education and training. It is widely recognised that employees in this sector need a wide range of knowledge and skills to cope with emerging trends, which has led to the exploration of alternative approaches to education. Among these approaches, the concept of learning factories has attracted considerable attention as a promising solution.

Learning factories are purposely designed environments that replicate real industrial settings and provide students, trainees and researchers with immersive and hands-on learning experiences. The primary objective of learning factories is to enhance the learning process by providing an interactive and dynamic environment that encourages problem solving, collaboration and critical thinking. Through active engagement in hands-on exercises, experiments, and simulations, participants gain valuable insights into different aspects of the manufacturing process (Abele et al., 2019).

Learning factories are designed to facilitate learning through education, training and/or research. These learning factories are deliberately tailored to fulfil the particular educational, training and/or research objectives of their developers. Consequently, each learning factory implementation is inherently unique. This results in a wide range of purposes, themes and target audiences across the learning factory landscape, making each one unique in its design.

Despite the potential benefits of learning factories, research has identified limitations in their current implementation (Tisch & Metternich, 2017). These limitations undermine the central purpose of learning factories, which is to facilitate effective learning. To fully realise the benefits of learning factories, it's essential to carefully consider both technical and educational aspects. In addition, these learning environments must remain adaptable to technological advances, industry changes and emerging challenges. This requires a design approach that emphasises flexibility and adaptability, allowing the structure and curriculum of the learning factory to evolve dynamically. Consequently, the process of designing learning factories becomes a multi-perspective, continuous and non-linear approach. As a result, various learning factory design approaches have emerged in recent years to support the unique development of necessary elements within learning factories.

However, a critical evaluation of published design approaches by Kreß et al. (2021) shows that these approaches have their own limitations and have not yet comprehensively addressed the identified shortcomings of learning factories. As a result, further research and refinement of learning factory design approaches is needed to bridge the gap between theoretical potential and practical implementation, and to ensure that learning factories effectively promote learning in the manufacturing domain.

1.2 Research aim

This research aims to contribute to the development of learning factories as an effective educational approach in the manufacturing sector, through further research and refinement of learning factory design approaches. The primary objective of this thesis is to develop a multi-perspective design guide for the creation of effective learning factories. The design guide should guide the creation and integration of various aspects and perspectives that are critical to the functioning of a learning factory, fostering a multidisciplinary, continuous and non-linear approach. The main focus of the design guide will be to ensure that the main purpose of a learning factory, which is effective learning, is maintained throughout the design process. By considering multiple perspectives and addressing the identified limitations in current learning factory implementations, the resulting design guide should aim to create cohesive and comprehensive learning factory designs that ensure the harmonious integration of different elements within a learning factory. So, this results in the fundamental research question of this thesis:

How can the development of effective learning factories be promoted and enhanced by a multi-perspective design guide?

It is important to emphasise that while the design guide aims to provide a solid foundation for the creation of a functioning and effective learning factory based on the needs of stakeholders, the design of a learning factory should also encourage and empower individuals to think outside the box, challenge traditional approaches and introduce new ideas and concepts. Therefore, while the design guide provides a basic foundation through prescriptive methods, the active involvement and contribution of innovative and independent thinkers is essential for the development of a truly exceptional and forward-thinking learning factory.

1.3 Scope

The scope of this thesis will be limited to establishing a basis for the design guide. It will provide a proof of principle for the methods and interdependencies between different aspects within the learning factory. In this thesis, the design guide's primary focus will be on the educational aspects of a learning factory. This emphasis on the educational elements aims to ensure that the design guide effectively promotes the core objective of a learning factory, which is to enhance the learning process. Providing a proof of principle will involve demonstrating the feasibility and effectiveness of the proposed methods, while testing the interdependencies between aspects of the learning factory.

While the developed design guide in this thesis will focus primarily on the educational aspects, it is recognised that other dimensions, such as the physical layout, play an important role in the overall effectiveness of a learning factory. Although these aspects may not be fully developed within the scope of this thesis, showing a functioning of their relationship and dependencies with the educational aspects is important in providing the proof of principle.

It is significant to note that the developed design guide and the proof of principle should act as foundational elements for further research and development in the field of learning factory design. The existing design guide offers a foundational structure for future evolvement on the content of the design guide, through case studies and additional research. This evolvement process would for instance involve integration of additional aspects and the inclusion of more details to refine the design guide's effectiveness.

1.4 Approach

The primary research question is supported by six secondary research questions, which are as follows:

1. What are the foundational concepts and principles related to learning factories?
2. What is the current state of learning factories and existing design approaches?
3. What are the essential characteristics and requirements that need to be considered in the development of the design guide?
4. How are the key components of the design guide structured?
5. How effective is the current proposal of the design guide in facilitating the design process of learning factories?
6. How can the design guide be improved to enhance its effectiveness in supporting the design process of learning factories?

Each chapter in this thesis addresses one of these secondary research questions.

This thesis divides the research process into the following main parts:

- Part I: Analysis (Chapters 2 and 3) - Comprehensive analysis of the theoretical framework and current state of learning factories. Identification of basic concepts and principles and exploration of gaps or limitations in existing approaches.
- Part II: Development and Results (Chapters 4 and 5) - Actual development and results of the design guide. Formulating requirements, providing practical solutions and explaining the framework through visualisations and detailed methodologies.
- Part III: Evaluation (Chapters 6 and 7) - Evaluation of the design guide through a case study. Assessing effectiveness, identifying strengths and limitations, and proposing the evolvement approach with a different version of the design guide for early-stage development.
- Part IV: Conclusions (Chapters 8, 9 and 10) - Summarise key findings and contributions. Integrate findings from the analysis, development and evaluation phases, to answer the main research question. Reflection on the contributions and recommendations for future work.

Part I

Analysis

2

Theoretical Framework

This chapter explores the concept of learning factories and examines their educational principles, potential and limitations. It begins by providing a clear definition of learning factories and explores the different educational concepts used in these environments. The chapter also looks at the potential benefits of learning factories, as well as the limitations they may face. By examining these aspects, the chapter aims to explore the basic concepts and principles associated with learning factories.

2.1 Definition of learning factories

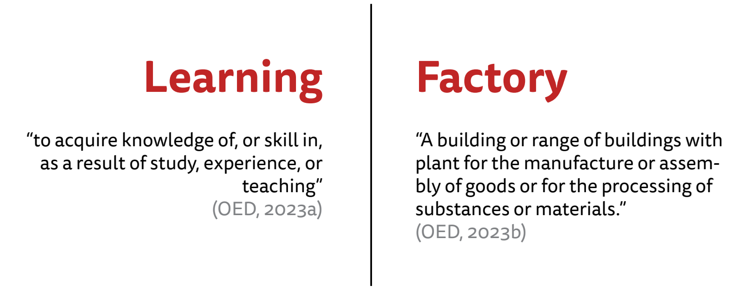
As the term “learning factory” utilizes the terms “learning” and “factory”, it implies a combination of the process of knowledge or skill acquisition, and environments for manufacturing purposes. In the case of this thesis, this idea holds true, as it is used for factory environments designed for the purpose of learning through education, training and research. However, it is important to note that in literature, the term 'learning factory' is sometimes used when describing alternative concepts, for instance as a derogatory term for educational institutions (Abele et al., 2019). In this thesis, the term 'learning factory' will only be used for describing concepts of the first definition.

Although the learning factory concept has not been around for very long, various definitions have emerged, implicitly and explicitly, over the past few decades. While the first definitions of early approaches of learning factories were limited to facilities designed for use in engineering education, more recent definitions broaden the definition to include application in education as well as training and research.

Frequently referenced and generally accepted definitions were constructed by both the IELF in 2013, and the CIRP Collaborative Working Group (CWG) on learning factories in 2016. The IELF defined a broad description of learning factories:

> *“A learning factory is a learning environment, where processes and technologies are based on a real industrial site which allows a direct approach to product creation process. Learning factories are based on a didactical concept emphasizing experiential and problem-based learning. The continuous improvement philosophy is facilitated by own actions and interactive involvement of the participants”* (IELF, 2013).

Through this definition and various other proposed descriptions, the CIRP CWG agreed on a more extensive definition, which was later published in the CIRP Ency-



Learning

“to acquire knowledge of, or skill in, as a result of study, experience, or teaching”
(OED, 2023a)

Factory

“A building or range of buildings with plant for the manufacture or assembly of goods or for the processing of substances or materials.”
(OED, 2023b)

Figure 1 Analysis of the term "learning factory".

clopedia:

> *"A learning factory in a narrow sense is a learning environment specified by*
>
> » ***processes** that are authentic, include multiple stations, and comprise technical as well as organizational aspects,*
> » *a **setting** that is changeable and resembles a real value chain,*
> » *a physical **product** being manufactured, and*
> » *a **didactical concept** that comprises formal, informal and non-formal learning, enabled by own actions of the trainees in an on-site learning approach.*
>
> *Depending on the **purpose** of the learning factory, learning takes place through teaching, training and/or research. Consequently, learning outcomes may be competency development and/or innovation. An **operating model** ensuring the sustained operation of the learning factory is desirable. In a broader sense, learning environments meeting the definition above but with a setting that resembles a virtual instead of a physical value chain, a service product instead of a physical product, or a didactical concept based on remote learning instead of on-site learning can also be considered as learning factories"* (Abele, 2016).

The different aspects of a learning factory mentioned in the definition are commonly referred to as the dimensions of a learning factory. These dimensions, illustrated in Figure 2, need to be properly integrated to create a comprehensive and unified learning environment in the learning factory. This integration involves aligning the operating model, purpose, process, setting, product and didactic dimensions. This makes designing a learning factory is inherently multidisciplinary. It involves bringing together experts from various fields, such as education, engineering, industry, and technology, to create an environment that caters to diverse learning needs. By achieving this alignment, the learning experiences within the learning factory become coherent, purposeful and effective. This leads to a wide range of unique learning factories, each deliberately tailored to fulfil their particular educational, training and/or research objectives.

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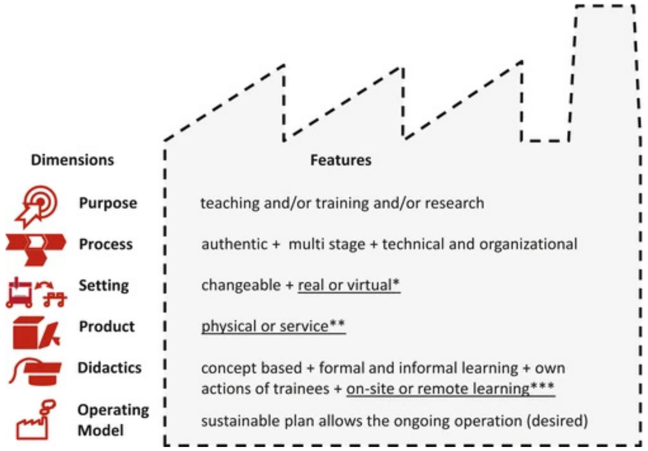
The development and evolution of learning factories began in the late 1980s. A full historical account of this development can be found in Appendix A. By the end of the 2010s, the presence of learning factories had grown significantly across Europe. In 2011, a group of European academic learning factory operators, gathered at the 1st Learning Factories Conference in Darmstadt to launch the Initiative on European Learning Factories (IELF), led by Eberhard Abele. Their main goals were to initiate collaborative research projects, to promote global awareness of the Learning Factory concept, and to jointly develop it further. Since 2012, the Conferences on Learning Factories have been organised in different locations. In 2016, the IELF changed its name to the International Association of Learning Factories (IALF). This transition to a global organisation has facilitated a stronger collaborative network. The IALF's working groups have been formed to collaborate on research proposals and publications, facilitate information exchange, support ongoing activities and projects, and foster close partnerships with industry and academia (IALF, 2021).



Dimensions	Features
Purpose	teaching and/or training and/or research
Process	authentic + multi stage + technical and organizational
Setting	changeable + real or virtual*
Product	physical or service**
Didactics	concept based + formal and informal learning + own actions of trainees + on-site or remote learning***
Operating Model	sustainable plan allows the ongoing operation (desired)

Figure 2 Key characteristics of Learning Factories. Adopted from Abele et al. (2015).

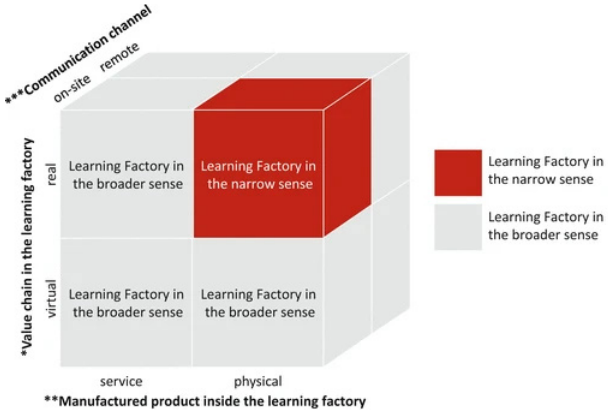


Figure 3 Learning Factories in the narrow and in the broader sense. Adopted from Abele et al. (2015).

In conclusion, a learning factory is a facility containing elements of a real manufacturing environment for the product creation process, built and used for learning purposes. The learning factory concept can support a variety of learning purposes, such as academic education, employee training and research initiatives. By representing a manufacturing workplace environment, the concept uses learning approaches (on-site and/or remote) through a strong didactical approach, such as experiential and problem-based learning to support competency development and/or innovation. Ultimately, the success of a learning factory lies in achieving the proper alignment of its different dimensions to fulfil its primary objective of learning.

2.2 Educational concepts of learning factories

The concept of a learning factory is essentially a manufacturing environment designed specifically for educational purposes. It incorporates a range of educational concepts to effectively achieve its primary objective of learning. Some of these educational concepts may naturally be part of the learning factory concept, while others may be deliberately chosen for implementation in the operation of the learning factory. Given that the aim of this thesis is to promote the development of effective learning factories, and recognising that the primary objective of learning factories is to facilitate learning, this section focuses on the concept of learning and the educational concepts that contribute to improving the overall learning experience. These concepts are crucial to consider when developing effective learning factories.

2.2.1 Learning

There is no universally accepted definition of learning among theorists, academics, and practitioners, as learning theories disagree about the origins, processes, and outcomes of learning (Shuell, 1986). Although individuals argue regarding the exact nature of learning, Schunk (1996) developed a generic definition that encompasses the criteria that most educational professionals consider to be fundamental to learning:

> *"Learning is an enduring change in behaviour, or in the capacity to behave in a given fashion, which results from practice or other forms of experience".* (Schunk, 1996)

Discussions about the exact nature of learning have led to the emergence of different learning theories. Learning theories are psychological theories about how people go through the process of learning. Well-known theories include behaviourist, constructivist, cognitivist and humanist learning theories. Learning factories can benefit from both cognitivist and constructivist perspectives on the process of learning (Abele et al., 2017).

While the term 'learning theories' is often used to describe psychological theories of the learning process, other learning theories describe different theoretical approaches to learning, such as more specific approaches to teaching-learning situations. Wu et al. (2012) refer to these approaches as learning principles. Learning factories use some of these learning principles in their didactic approach, such as non-formal learning, work-related learning and forms of active learning.

DEEP DIVE LEARNING THEORIES

Behaviourism: Behaviourism focuses on environmental factors such as rewards and punishments as the main determinants of behaviour. It suggests that learning occurs through reinforcement and conditioning, where desired behaviours are rewarded and undesired behaviours are punished. Behaviourism includes classical conditioning, associating stimuli with responses; operant conditioning, learning through rewards and punishments; and modelling, learning by observing the actions of others (Moore, 2011).

Cognitivism: Cognitivism emphasises the acquisition of new information and the transformation of existing knowledge as essential aspects of learning. Cognitivists believe that learning occurs through assimilation, the incorporation of new information into existing knowledge, and accommodation, the modification of existing knowledge to fit new information. Feedback and reflection are also seen as crucial to the learning process. Cognitivism emphasises the role of learners' mental processes in shaping their learning (Yilmaz, 2011).

Constructivism: Constructivism sees learners as active creators of knowledge and meaning from their experiences. It asserts that learning occurs when learners actively engage with their environment and construct their understanding of concepts. Prior knowledge and the social context of learning are considered important, and learning is seen as a meaning-making process in which learners construct mental models based on their experiences. These mental models are influenced by learners' prior knowledge, beliefs and experiences (Bodner, 1986).

Humanism: Humanism emphasises the individuality and agency of the learner. It suggests that learning takes place when learners have the freedom to explore and express themselves, matching personal interests and goals with their learning experiences. It recognises learners as unique individuals with their own values, beliefs and goals, and advocates tailored learning based on individual needs and interests. Humanistic learning focuses on subjective experience (Purswell, 2019)

Non-formal learning

Learning is often categorised into two distinct forms, namely formal and informal learning. While formal learning refers to the deliberately planned development of knowledge and skills in a structured learning environment, informal learning is characterised by spontaneity and autonomy through unplanned or unstructured learning

DEEP DIVE (IN)FORMAL LEARNING

Formal learning: According to Coombs & Ahmed (1974), formal education can be defined as an organised and structured system that is hierarchically graded and extends from primary school to university. This definition suggests that formal learning has several components. It involves educational institutions and the presence of designated educators, such as teachers. As a result, formal learning is often teacher-centred, with learning activities set by the teacher and guided by sequentially structured learning goals, such as specified educational objectives or a curriculum. It is also organised in a chronologically graded system (Johnson & Majewska, 2022).

Informal learning: Informal learning is characterised by its unpredictability and the fact that learning outcomes are not intentionally planned. However, this does not mean that informal learning is unintentional. Informal learning is a natural form of self-learning. It generally takes place outside formal educational institutions, does not follow a planned curriculum and is not professionally organised. It tends to be triggered by events or situations with changing practical needs that require a holistic response to a problem and is related to coping with situations and life in general (Dohmen, 2001). Dehnbostel (2009) divides the process of informal learning into 'implicit learning' and 'learning by experience' (see also Figure 5), where implicit learning refers to a learning process in which the learner is not consciously aware of the course or outcome of the learning process, and learning by experience occurs through reflection on the learning activity.

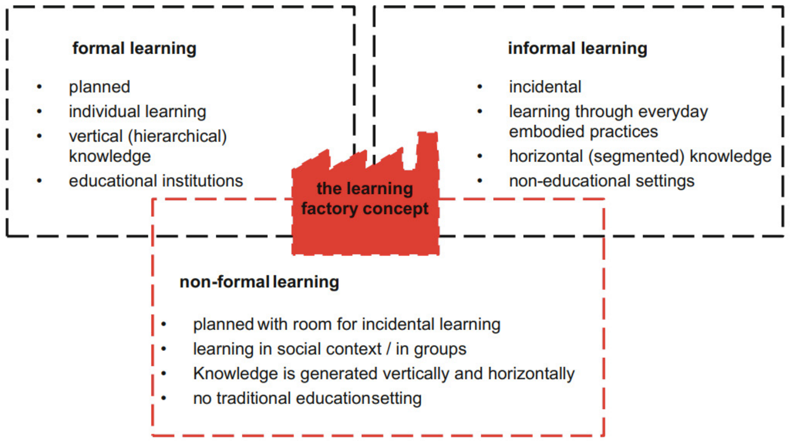


Figure 4 The relation between formal, informal, and non-formal learning. Adopted from Abele et al. (2019)

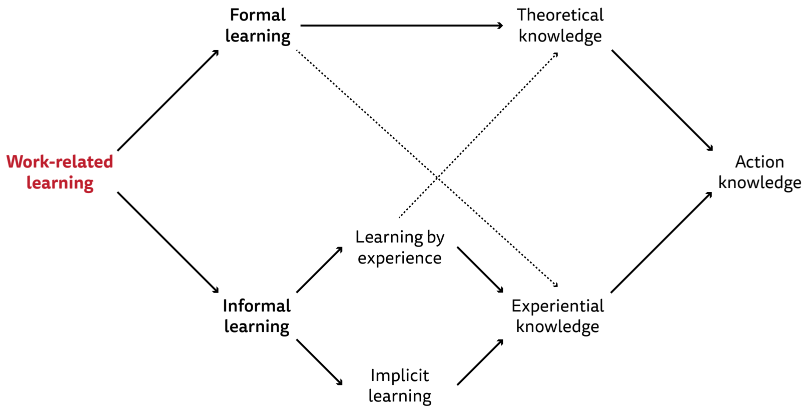


Figure 5 The learning and development process of work-related learning. Adopted from Dehnbostel (2009).

activities (Hager, 2012).

The concept of a learning factory possesses features of both formal and informal learning, it can be placed in the realm of non-formal learning theory (Abele et al., 2019). Non-formal learning is characterized by organized and purposeful learning that is less structured and systematic than formal learning, often taking place outside traditional educational settings (Coombs & Ahmed, 1974). Although non-formal learning is structured around learning objectives (Garner et al., 2015), it relies less on direct teaching and more on individualized control and self-directed learning (Colley et al., 2003).

As formal learning processes can only provide a certain amount of occupational competence (Dehnbostel, 2009), and informal learning may not be structured and effective enough to acquire necessary knowledge and skills (Johnson & Majewska, 2022), the combination of both approaches within the non-formal context of learning factories shows great promise for the development of necessary engineering competencies. This is also elaborated on in the next section.

Work-related learning

Work-related learning describes learning that takes place in businesses, training facilities, academic institutions, and schools through learning directly while working, as well as learning via work and inside work processes. As learning factories simulate a realistic work environment, tasks and processes, it employs the principle of work-related learning. Due to new necessary qualifications and educational requirements in the changing workplace, which is also extremely applicable in the engineering workplace, work-related learning has become increasingly valuable (Dehnbostel & Schröder, 2017).

Work-related learning offers great potential connecting working and learning to acquire the necessary competences, through the integration of informal and formal learning, and the use of principles of for instance self-directed and reflexive learning. Dehnbostel (2009) illustrates this through the analysis of the learning and development process of qualified workers, where both theoretical knowledge gained by formal learning, and experiential knowledge gained by informal learning, leads to action knowledge (in addition to small effects of formal learning on experiential knowledge and learning by experience on theoretical knowledge). This diagram also illustrates the promising effect of non-formal learning (combining formal and informal learning) on development of engineering competencies discussed in the previous section.

Learning factories are generally categorized as work-oriented learning, with learning in simulated work and production processes. It aims to create the most realistic learning environment possible, allowing for development and reflection on complex competencies and experiences. Additionally, it is strongly influenced by the criteria of current necessary qualifications of future employees (Dehnbostel, 2009).

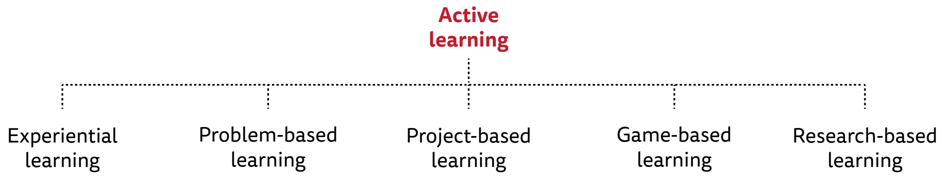


Figure 6 Diagram showing types of active learning.

Active learning

Learning factories enable learners to engage in educational activities, take ownership of learning and link concepts through analysis, synthesis and evaluation. This instructional strategy is referred to as active learning, which is focused on involving learners in learning activities to enable cognitive development, rather than acquiring data and transmitting information as a passive spectator (Gogus, 2012). Active learning uses a constructivist view by viewing learning as an active process, where learning is constructed through active involvement in activities and application of learning concepts (Mayer, 2004). This learning method focuses on thorough understanding of problems rather than reproduction of information (Crawley et al., 2007). Active learning can be subdivided into different educational concepts, some of which are commonly implemented in learning factories.

DEEP DIVE EXPERIENTIAL LEARNING

Observations and reflections are based on direct or tangible experiences (Concrete Experience). This can be seen in the four-stage learning cycle by Kolb (2000). These reflections (Reflective Observation) are then digested and condensed into abstract concepts (Active Conceptualization) from which new action implications might be derived. These consequences can be actively evaluated and used (Active Experimentation) to inform the development of new experiences (Kolb et al., 2000)

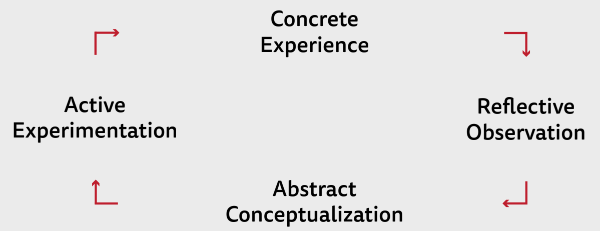


Figure 7 Kolb's Experiential Learning Cycle. Adopted from Kolb (2000).

- **Experiential learning.** According to experiential learning theory, learning is the process by which knowledge is formed via the transformation of experience. Knowledge is the product of comprehending and changing experience (Kolb, 1984). Methods that promote experiential learning, such as project-based learning and case studies, are thought to be advantageous in the development of cognitive abilities in engineering students (Crawley et al., 2007). Due to the experience-based nature of learning factories, the same conclusion can be drawn for learning factories.
- **Problem-based learning.** Problem-based learning revolves around the idea of challenging students to solve problems. Doing so, it improves learning by boosting students' skills in utilizing knowledge, solving issues, exercising higher order thinking, and independently guiding their own learning (Jonassen & Hung, 2012). Learning factories act as an ideal setting for problem-based learning for engineering education. They can be utilized to specify problem situations, while allowing for testing and revision of explanations and solutions for examined problems (E. Abele et al., 2019).
- **Project-based learning.** The approach of project-based learning revolves around learning activities incorporating a meaningful project of real-life significance. The project, often multidisciplinary in nature, motivates students to grapple the learning content while solving problems, finding solutions to questions and in the end finishing the project. Generally, the projects span over an extended pe-

riod of time, necessitating the active participation of student's efforts for weeks, or even months. In comparison to other learning activities of an inquiry-based nature, project-based learning has a focus on learner participation in group work (Lam, 2012). Project-based learning can stimulate learning outcomes for engineering education, and is thus being incorporated in many learning factory concepts (Balve & Albert, 2015).

» **Game-based learning and gamification.** The purpose of game-based learning and gamification is to harness the active and engaging nature of games for educational purposes (Connolly et al., 2012). The distinction between game-based learning (serious games) and gamification lies in the fact that gamification entails the incorporation of game-elements into non-game activities, while game-based learning involves the use of an actual game as a component of the educational experience (Al Fatta et al., 2018). Incorporating games (or game elements) into the learning process has the potential to enhance motivation, positive emotions, and deeper learning through their inherent characteristics (Jacob Habgood & Ainsworth, 2011). The integration of serious games within learning factories has been demonstrated to possess significant potential to enhance the enjoyment and efficacy of the learning experience (Teichmann et al., 2020)

» **Research-based learning.** The concept of research-based learning emerges from Humboldt's vision for higher education, which seeks to integrate research and teaching (von Humboldt, 1809), by enabling students to learn through the process of conducting research. Research based learning can be defined as a method of education in which the learners actively participate in the design, execution, and evaluation of a research project with the aim of producing new knowledge and results. The learning factory is an ideal setting for incorporating research-based learning principles, as it provides students with hands-on access to industry-standard procedures and thus real-world data (Blume et al., 2015).

2.2.2 Didactics

Didactics is the discipline of science that deals with the question of how knowledge, skills and attitudes or attitudes can be taught to students. The discipline covers both theoretical knowledge as well as practical activities about teaching, learning, and their circumstances. It drives educators to consider the teaching material (the "what"), teaching methods (the "how"), and the justification of curricular decisions (the "why") (Künzli, 2000). While didactics are highly concerned with the interrelations within elements in the educational setting, the field of didactics is often characterized by the

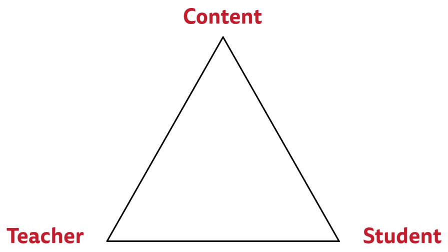


Figure 8 The 'didactic triangle'. Adopted from Künzli (1998).

basic 'Didaktik triangle' by (Künzli, 1998). This triangle illustrates three aspects present in educational settings at al times: student, teacher and content. This enables educators to conceptualize the interactions between these aspects (Ryen, 2019).

Constructive alignment

In section 2.1 it was emphasised that the integration of all dimensions is crucial to create a comprehensive and unified learning environment in the learning factory. From an educational point of view, this highlights the importance of aligning the technical and educational aspects. This requires the implementation of constructive alignment within the learning factory concept.

Constructive alignment refers to the intentional connection between pre-established learning outcomes, teaching and learning activities and the assessment process. The aim of constructive alignment is to create a cohesive and coherent learning

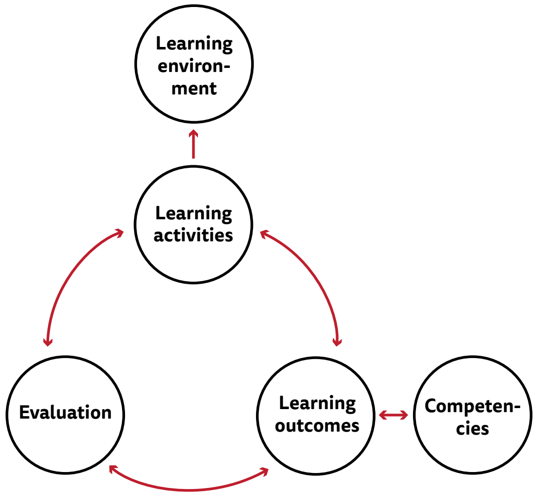


Figure 9 Diagram showing constructive alignment for learning factories

experience in which students actively engage with the content and develop the desired knowledge, skills and understanding (Biggs & Tang, 2011). In the context of the learning factory concept, constructive alignment should also consider the integration of competences and ensure that learning activities are well suited to the learning environment of the factory.

By implementing constructive alignment in the learning factory, educators should be able to create a cohesive and effective learning experience where the educational aspects are all aligned with the technical aspects. Some of these aspects of constructive alignment are discussed in more detail in the following sections.

Learning goals, objectives and outcomes

Every learning process can be described as a change process. In education and training, this usually involves consciously intended changes. Through an educational situation, a learning process is initiated that leads to (preferably the intended) changes.

DEEP DIVE LEARNING OUTCOMES

A powerful tool that can aid in the development of learning outcomes is a taxonomy created by Benjamin Bloom and other collaborators in 1956. (The revised) Bloom's Taxonomy (Anderson & Krathwol, 2001) divides learning outcomes into three domains: cognitive (intellectual skills), affective (attitudes and values) and psychomotor (physical accomplishments). The domains are each broken down into a hierarchy that correspond to different levels of learning. The cognitive domain is primarily the central focus in use cases, routinely utilized as a framework for designing curriculum in traditional education.

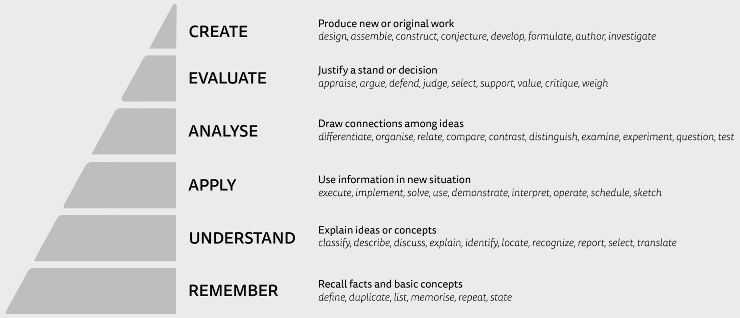


Figure 10 Bloom's revised taxonomy. Adopted from Anderson & Krathwol (2001).

The acceptance of Bloom's taxonomy for engineering education is widespread, with a consensus that engineering graduates must possess analytical, synthetic, and evaluative skills as described in Bloom's taxonomy (Williamson & Koretsky, 2007).

In order to design this correct educational setting to contribute to the changes, it is of significant value these changes are formulated into learning goals, objectives and outcomes. When clear goals are formulated, it can be verifiably argued what the most effective way is to reach these goals. Hattie, (2009) identifies the appropriate implementation of learning goals, objectives and outcomes as one of the most powerful instructional strategies for enhancing student academic achievement. The formulation of these intended changes is key in designing the didactical concept of the learning factory.

Learning goals, objectives and outcomes each differ in the scope and amount of detail they describe of a learning experience.

» **Learning goals** describe the trajectory and basic subject matter of a larger educational activity, such as a programme or a course. Goals are general achievable results but are not always observable or measurable.
  To introduce students to the topics of Lean Management
» **Learning objectives** specify learning goals in more detail, stating what the instructor needs to cover in a specific learning activity. Since they tend to be instructor-centred they are not always observable or measurable.
  To familiarize students with the most important Lean performance metrics
» **Learning outcomes** specify learning objectives by stating achievable behaviours students should be able to show at the end of a learning activity. Outcomes should be student-centred, measurable and observable.
  Students will be able to use and explain Little's Law

Competencies

While the previous section explained the importance of goals, objectives and outcomes to achieve intended changes, competencies are valuable in aligning these concepts with context-specific requirements. By setting and achieving learning goals, learners can develop the specific knowledge and skills needed to master the competencies required for their field.

Competencies refer to the integrated application of knowledge and skills in specific contexts. They involve dispositions that enable individuals to take self-organized and creative actions in complex situations. These dispositions, which involve the use of knowledge and skills, are not just limited to technical abilities but also include attitudes, values, and behaviours. Knowledge is a key component of competencies and refers to the information that an individual acquires through learning. This information may include facts, principles, theories, and practices related to a particular field of work or study (European Parliament, 2006). Knowledge can be both theoretical and practical, and it provides a foundation for the development of skills. Skills, on the other hand, are the ability to apply knowledge and use know-how to complete tasks and solve problems. Skills are acquired through practice and experience and enable individuals to find appropriate information and techniques to address new problems and situations. To do so, individuals need to analyse and understand the new situation, draw on their background knowledge or methods, and identify the appropriate relations between their previous experience and the new situation (OECD, 2005).

Overall, competencies involve the integration of both knowledge and skills, which are used to take action in specific contexts. These dispositions enable individuals to adapt to new and complex situations, solve problems, and achieve their goals (OECD, 2005). Competency development in production environments is seen as a key facilitator for continual improvement and remaining competitive (Tisch et al., 2013). Thus, it is crucial that competency development is taken into account in the education of engineers. It is widely acknowledged that effective competency development can be pursued through the learning factory approach (Cachay & Abele, 2012).

Evaluation

The assessment of whether students achieve the desired learning outcomes is a vital component of educational activities. The evaluation of learning success plays a crucial role in determining the effectiveness of the learning process and identifying any obstacles that may hinder the process (Ogunniyi, 1984). This enables control and enhancement of the quality of the learning process.

The accomplishment of desired learning outcomes and the subsequent development of intended competencies by participants are critical factors for successful learning processes within learning factories. To evaluate the learning processes, it is thus necessary to assess the learning success of the learner. Learning success evaluation determines the extent to which a learner exhibits the desired qualities, attributes, and actions. This underscores the significance of constructive alignment: formulating precise, measurable, and observable learning outcomes and utilizing these in the assessment process.

Learning success assessment can be categorized in three approaches (Gonczi, 1994; McMullan et al., 2003):

- **Behavioural:** performance-oriented approach where actions are observed and evaluated during a problem-solving scenario.
- **Generic:** knowledge-oriented approach focused on assessing knowledge and understanding of concepts and principles related to a particular subject.
- **Holistic**: combination of performance-oriented and knowledge-oriented approach

When learning outcomes are tailored to intended competency outcomes, they can often be distinguished between knowledge and skills, as competencies involve integration between the two (European Parliament, 2006). As a result, competency-oriented assessment in learning factories demands a combination of assessing knowledge and skills within the holistic assessment approach, while utilizing the formulated learning outcomes in the process.

2.2.3 Conclusion

The aim of the previous section was to identify educational concepts that are crucial to consider when developing effective learning factories.

The learning factory concept emphasises the importance of experiential and problem-based learning, incorporating different approaches such as non-formal, work-based and active learning. In the design and implementation of learning factories, educational concepts and didactics play a crucial role, since the primary objective is to promote learning. It's essential to carefully consider key factors such as competence development to ensure the best possible learning outcomes.

An integral principle that emerges from this section is constructive alignment. Constructive alignment ensures a cohesive and coherent learning experience by purposefully aligning learning outcomes, teaching and learning activities and assessment processes. When applied in the context of the learning factory, constructive alignment should also include the integration of competences and the suitability of learning activities for the unique learning environment of the factory.

2.3 Potentials and limitations of learning factories

The basic principles explored in the previous sections provide an insight into the core concepts that contribute to the effectiveness of learning factories. The following sections discuss both the potential benefits and limitations of the learning factory approach in facilitating effective learning experiences. This exploration will provide a balanced view, enabling a better understanding of the strengths and considerations associated with learning factories.

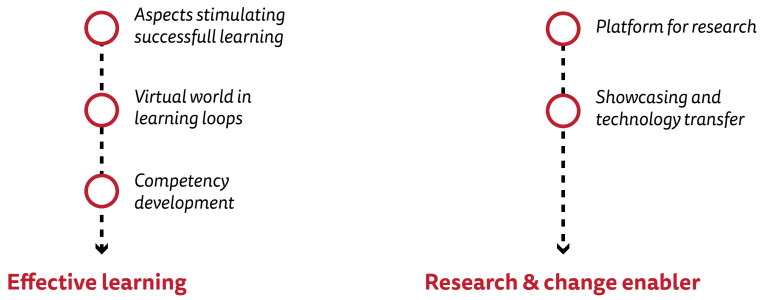


Figure 11 Schematic presentation of the potentials of learning factories

2.3.1 Potentials

Effective learning

As mentioned previously, a learning factory is built and used primarily for the purpose of learning. It is therefore crucial that a learning factory supports effective learning by incorporating effective learning methods. Section 2.2 discusses the educational concepts used by, and important for, learning factories. Together, these concepts contribute to a number of success factors for effective learning as shown in Table 1 (Tisch & Metternich, 2017).

Aspects stimulating learning success	Representation in the learning factory
Contextualization	Partial model of real factory provides a rich learning context
Activation	Generation and application of knowledge in the learning factory (learner active phases)
Problem solving	Solving of real problem situations in the learning factory
Motivation	Motivation by the reality character and the possibility to act hands-on immediately
Collectivization	Self-organized learning in groups is a suitable model in learning factories
Integration of thinking and doing	Alternation of hand-on phases in the learning factory and systematization phases
Self-regulation and self-direction	External and self-controlled learning processes are enabled – depending on the prerequisites

Table 1 Aspects stimulating learning and their representation in learning factories. Adopted from Tisch & Metternich (2017).

In addition to these aspects, learning factories are able to act as virtual worlds in learning loops (Sterman, 1994), providing high-quality feedback and stimulating learning by gaining experience with transformation processes and problem situations. In this way, learning factories are able to support 'double-loop learning'. Whereas single-loop learning occurs when decisions are made based on direct feedback from the environment, double-loop learning occurs when mental models and decision-making rules change based on feedback from the environment (Cartwright, 2002).

Through the application of effective learning methods and the function of learning factories as a virtual word, learning factories help participants to develop a deeper understanding of complex concepts and better prepare them for real-world challenges. Learning factories support the development of key competencies that are highly valued by employers (Enke et al., 2016):

» **Competency development.** It is widely acknowledged that effective competency development can be pursued through the learning factory approach (Cachay & Abele, 2012). This potential for competency development is becoming more and more significant due to the increasing demand of diverse skills in an everchanging manufacturing industry. Due to for instance globalization, new technologies and digitization, engineers must acquire proficiency in a wide range of disciplines (Abele et al., 2019). Through the hands-on approach on process-centric disciplines, Learning Factories have large potential in tackling challenges in education of future-proof engineers (Sadaj et al., 2021).

Research and change enabler

Learning factories can play a large role in the field of production-related research. Typically, the integration of research into daily industrial practice presents several challenges, such as the potential compromise of the basic stability of the factory, and the high costs and complexity associated with the direct transfer of research results into production. To mitigate these challenges, learning factories can serve as a valuable research enabler by providing a risk-free platform for the integration of practical experience. The learning factory enables the identification of research problems within a quasi-realistic environment, as well as the testing of solutions through a physical factory model, which is characterized by reduced complexity and costs as compared to testing in actual production settings.

Furthermore, learning factories are conducive to showcasing and transferring new technologies and know-how. They offer an application-oriented platform for research and development until market maturity and subsequent transmission to production processes, technologies, and products.

2.3.2 Exploiting potentials

The previous section highlighted the theoretical potential of the concept of learning factories. However, it's crucial that the practical implementation of learning factories aligns with this theoretical promise. Unfortunately, there is a lack of clear evidence or extensive studies that demonstrate the effectiveness of learning factories in realising their full theoretical potential. The available studies are often limited to specific contexts and based on short-term evaluations, making it difficult to draw definitive conclusions. Furthermore, the inherent uniqueness of each learning factory implementation adds to the complexity of assessing its impact.

As a result, there is a noticeable gap between the theoretical potential and the practical implementation of learning factories. To bridge this gap, there's an urgent need for more extensive testing and evaluation of the potential within the academic community. Equally important is the recognition that these potentials should not be seen as inherent characteristics automatically conferred by the adoption of the learning factory concept. Rather, they should be seen as goals to be maximised continuously throughout the life of the learning factory.

To be able to do so, a continuous improvement mindset needs to be fostered within these environments. This means that the design process for a learning factory should not end with its initial development. Designers should engage in ongoing evaluation of the learning environment's effectiveness, seeking feedback from participants and monitoring developments in education and technology. These findings should inform a continuous process of improvement, involving adjustments to the structure, curriculum and resources of the learning factory in order to maximise its potential. This also means that the design of a learning factory should take a non-linear approach. Flexibility and adaptability should be prioritised, allowing the structure and curriculum of the learning factory to evolve dynamically. By adopting this approach, individual, unique learning factories can progressively realise their full potential.

2.3.3 Limitations

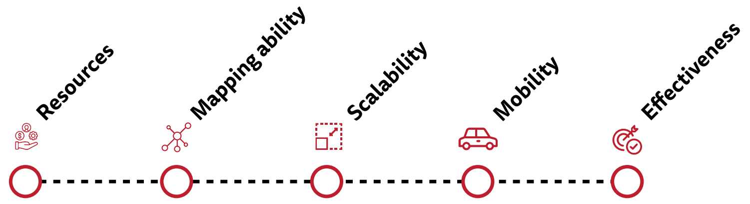


Figure 12 Schematic presentation of the limitations of learning factories

Despite the theoretical potentials of the learning factory concept, there are also some limitations in the current implementation of learning factories. Tisch & Metternich (2017) identify five categories of limitations.

While the limitations are evident in the current landscape of learning factory implementations, it's worth noting that some of these limitations may not necessarily hinder the potential of individual learning factories. Due to the unique nature of each implementation, specific limitations, such as mobility issues, may not be a limitation to meeting the particular requirements of the learning factory.

Resources

The considerable effort required to plan, develop, construct and operate learning factories is a major barrier to their establishment. This includes not only the necessary financial resources, but also the availability of qualified personnel to initiate and run the learning factory, relevant training content, access to machinery and sufficient physical space. The lack of resources can cause problems, especially in the early stages of the learning factory's life cycle, and can lead to the failure of entire projects.

Mapping ability

- **Content- and object-related.** Learning factory concepts have a limited scope of industrial production that they can address. These limitations may be due to specific industrial sectors, targeted topics, individual production processes, company departments or even demographic groups. Consequently, a single learning factory can only represent a small part of the complex industrial reality.
- **Space- and cost-related.** In theory, the learning factory concept can address challenges and problems at all levels of factory operations, from process and station to factory network. In particular, the upper levels of the factory are not represented in the learning factory concept, as the lower levels of the factory are often studied more closely because they need to be represented in the physical learning environment.
- **Time-related.** The learning factory concept is constrained by the time relationship between the feedback generated by the learning environment and the actions taken by the learners. If the feedback cycle is too long, the learning factory concept cannot be easily applied to such topics. The shorter the duration of the learning modules, the quicker these limitations are encountered.
- **Solution-related.** Limitations in the solutions created by users during learning modules can occur in learning factories. Limiting the changeability and flexibility of the learning factory can lead to ad hoc solutions by users, which can significantly hinder the learning process.

Scalability

The physical capacity of most current learning factory concepts is a significant limitation, especially when compared to other learning events such as traditional lectures. Whereas hundreds of students can attend a single lecture without significant difficulty, with only one teacher required, a maximum of 15 to 20 students can typically participate in a single learning factory course, with at least two trainers regularly assigned.

Mobility

Another limiting factor is the fixed location of learning factories with physical learning environments. As a result, learning activities are confined to this single location and access to training is limited to a specific geographical region.

Effectiveness

Although many learning factories aim to develop skills, the effectiveness of these approaches is rarely evaluated. Developing effective learning factories means not only setting clear objectives, but also building a targeted evaluation phase into the design process. In many cases, these objectives are not sufficiently integrated into the design of the learning factory and its modules, or into the evaluation of the achievement of the objectives.

2.3.4 Addressing limitations

Discussing both the potential and the limitations provides a holistic view of the educational approach, enabling stakeholders to maximise the benefits while effectively managing the challenges. In this way, limitations can be addressed to maximise the potential of the learning factory approach. Tisch & Metternich (2017) and Abele et al. (2019) propose several variations of the learning factory concept and methods to do so.

Each of these concepts and methods approaches the limitations of learning factories differently and offers a different solution. However, it's important to note that while certain approaches may effectively address certain constraints, they may inadvertently introduce or intensify other limitations. The suitability of these concepts and methods will depend on the specific context of the individual learning factory, taking into account the importance of each constraint they seek to address. In essence, the choice of concept or method should be based on the particular constraints and priorities of the individual learning factory.

Concepts

» **Model scale.** These learning factories use scaled-down equipment resembling full-size versions.

» **Physically mobile.** Learning factories with (modular) setups that can be relocated for flexible training.

» **Low cost.** Cost-effective learning factories, often focusing on simpler production processes.

» **eLearning, ICT & Multimedia.** Utilize e-learning and multimedia to complement hands-on training.

» **Producing.** Combining practical training with simultaneous real production.

» **Digital, Virtual & Hybrid.** Digital learning factories leverage IT and digital models for process, resource, and product representation. Virtual factories enhance this with visual software tools and virtual/augmented reality for tasks like process planning. Hybrid factories blend physical, digital, and virtual aspects, integrating data sources for a seamless real-virtual learning experience.

» **Remotely accessible.** Enable remote learning through ICT, no physical presence required.

Methods

» **Systematic design.** Applying systematic principles for effective learning factory design.

» **Turnkey.** Ready-to-use comprehensive learning environments.

» **Learning success measurement.** Assessing the effectiveness of learning experi-

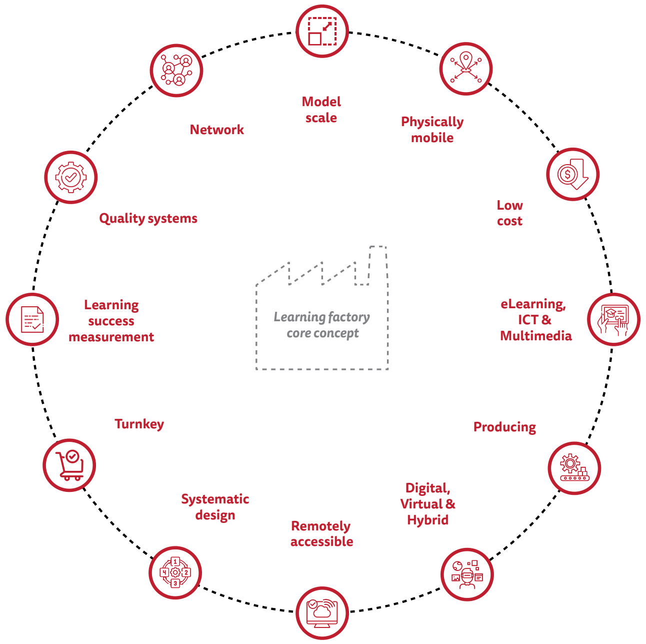


Figure 13 Schematic presentation of concepts and methods to overcome limitations

ences.

- **Quality systems.** Implementing structured frameworks for ongoing improvement.
- **Network.** Facilitate collaboration, standardization, and knowledge sharing in learning factory communities.

2.3.5 Conclusion

The previous section explored the potential and limitations of the learning factory concept. While theoretical potentials and general limitations across the learning factory landscape can be identified, this section also highlighted the influence of the individual context of learning factory implementations on both potentials and limitations. Adopting the learning factory concept does not necessarily mean adopting the potentials, while certain limitations may not necessarily hinder the operation of the individual learning factory. Furthermore, the suitability of concepts or methods to address constraints will depend on the specific context of the individual learning factory.

It's crucial to understand that the potentials, limitations and strategies to overcome limitations in learning factories should be seen as unique attributes specific to each individual learning factory, rather than applying a one-size-fits-all approach.

First and foremost, it is important to recognise that the potentials of learning factories should not be assumed as automatic outcomes resulting from the adoption of the learning factory concept. Instead, they should be seen as goals to be continuously optimised throughout the lifecycle of the learning factory. Achieving this requires a continuous and non-linear approach to learning factory development.

Furthermore, in order to deal effectively with (potential) limitations, it's necessary to identify them within each specific learning factory (taking into account the five commonly identified limitations). These limitations can potentially be addressed by applying the concepts and methods discussed earlier. The aim is to reduce these limitations and unleash the full potential of each unique learning factory by using different approaches to the learning factory concept. This underlines the importance of adopting a non-linear and continuous approach to allow for this process. By recognising and addressing these limitations, while striving to maximise potential, learning factories can become more effective. The alternative approaches to address limitations can be a good starting point in providing unique solutions for individual learning factories, effectively dealing with limitations and optimising their potential.

2.4 Chapter conclusion

Exploring the basic principles associated with learning factories provides valuable insights into the design and implementation of these educational environments. Learning factories are facilities that replicate elements of a real manufacturing environment, specifically tailored for learning purposes. The integration of technical and educational aspects is at the core of learning factories, aiming to create a comprehensive and unified learning experience. This integration involves aligning the operating model, purpose, process, setting, product and didactic dimensions. This makes designing a learning factory is inherently multi-perspective and multidisciplinary. It involves bringing together experts from various fields, such as education, engineering, industry, and technology, to create an environment that caters to diverse learning needs. By achieving this alignment, the learning experiences within the learning factory become coherent, purposeful and effective.

The concept of learning factories places a strong emphasis on experiential and problem-based learning, incorporating different approaches such as non-formal, work-based and active learning. As the main objective of learning factories is to promote learning, educational concepts and didactics play a crucial role in their design and implementation. Key aspects such as competence development should be carefully considered to ensure optimal learning outcomes. An important principle that emerges is constructive alignment. By deliberately linking learning outcomes, teaching and learning activities and assessment processes, constructive alignment ensures a cohesive and coherent learning experience. In the context of the learning factory concept, constructive alignment should consider the integration of competences and ensure that learning activities are well suited to the learning environment of the factory. Using this concept of constructive alignment in learning factory design, involves aligning all educational elements that influence learning activities, consequently shaping the learning environment within the learning factory.

Furthermore, examining the potential and limitations provides a balanced perspective on learning factories. While theoretical potentials and general limitations across the learning factory landscape can be identified, the influence of the individual context of learning factory implementations on both potentials and limitations should be considered. Learning factories should allow for a non-linear and continuous approach, which focuses on recognizing and addressing limitations, while maximising potentials. This highlights the need to foster different variations of the learning factory concepts which are able to address needs for individual learning factory concepts. The alternative approaches to address limitations can be a good starting point in providing these unique solutions for individual learning factories.

3

Current State

The purpose of this chapter is to lay the groundwork for the development of a design guide. It begins by drawing up a list of requirements for effective learning factories. These requirements are derived from both the standard prerequisites for learning factories and the need to overcome existing limitations. By considering the limitations identified in current approaches to learning factory design, the chapter formulates the requirements for the new design guide. In order to meet these requirements effectively, a process of translating them into practical solutions is undertaken.

3.1 Current landscape of learning factories

As noted previously, there has been an increase in the implementation of learning factories worldwide in recent years, particularly in Europe. These learning factories vary in size, purpose and scope, with a focus on enhancing the learning experience of participants from both academic and industrial backgrounds. Despite the popularity of learning factories, their potential is limited by certain limitations that can be identified in current implementations. In the previous section, variations of learning factories were proposed to overcome these limitations. These alternative concepts can serve as a valuable starting point for providing unique solutions for specific learning factory contexts. However, it remains unclear to what extent learning factories have adopted these variations to increase their potential. Therefore, a systematic analysis will be carried out to identify existing learning factories, examine their main themes, and assess the extent to which individual learning factories have addressed these limitations by adopting the proposed concepts.

3.1.1 Analysis method

The initial stage involved gathering data on the establishment, primary objectives, and subject areas of each individual learning factory from established networks of learning factories, including the Initiative on European Learning Factories (IELF), the Network of Innovative Learning and Research Factories (NIL), and the International Association of Learning Factories (IALF). Learning factories still under development were excluded from the list. Furthermore, prior systematic analyses of learning factories were consulted. Subsequently, an extensive collection of academic publications relating to individual learning factories was built utilizing research databases such as Scopus. Terms such as "learning factory" and "teaching factory" were used in the search process. Analysis was conducted on collected publications, whereby the articles were carefully examined to determine the presence of relevant keywords associated with the aforementioned concepts aimed at addressing limitations. The

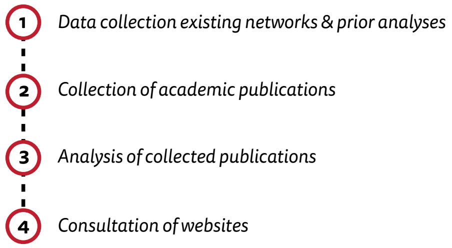


Figure 14 Schematic representation of the learning factory landscape analysis.

comprehensive lists of keywords used in this analysis can be found in the Appendix B, specifically under section B.1. Furthermore, in certain instances, websites associated with specific individual learning factories were consulted as an additional source to gather supplementary information. However, it is important to note using such a systematic analysis may impose certain constraints and rules that can influence the conclusions. To further validate the following conclusions, a more comprehensive assessment of existing learning should be carried out in the future.

3.1.2 Results

The aim of the systematic research was to identify existing learning factories, to examine their main themes, and to assess the extent to which these limitations have been addressed by individual learning factories through the adoption of the proposed approaches. In order to collect and present the findings, an extensive spreadsheet was created with specific entries for each learning factory in the study. These entries include information on the name of the learning factory, the operator and geographical location, the country of operation, the product, the primary objective, the target industry and the subjects/topics of learning. In addition, the inclusion of each concept used is indicated by the use of an 'X'. Figure 15 shows a preview of the developed spreadsheet. The full spreadsheet can be found in the Appendix B. To provide a con-

Name	Operator & location	Country	Product	Purpose	Industry	Learning subjects	Physical	Digital	Virtual	Model scale	Physically mobile	Low-cost	Use of e-learning, ICT & multimedia	Real production	Remotely accessible	Systematic design method	Turnkey LF	Learning success measurement	Quality system	TOTAL CONCEPTS	Reference
AAU Smart Production Labaratory	DMP, Aalborg University	Denmark	Electric product	Education, Training	Manufacturing Engineering	Industry 4.0, Smart production		X		X										2/12	Madsen & Moller, 2017
Additive Manufacturing Model Factory	Friedrich Alexander Universität Erlangen-Nürnberg, McKinsey	Germany	Various products	Training, Research	Manufacturing Engineering	Additive Manufacturing	X													0/12	Yoo et al., 2016
Advanced Manufacturing Technology Center (AMTC)	Tongji University	China	5G adapter	Education, Research	Manufacturing Engineering	Industry 4.0	X	X					X							2/12	Zhang et al., 2020
AllFactory	University of Alberta	Canada	Lego based 3D printing machine	Education, Training, Research	Manufacturing Engineering	Lean production, Industry 4.0	X					X								1/12	Ahmad et al., 2018
Anglo American Training Center	Anglo American, Johannesburg	South Africa	Not stated	Training	Mining Engineering	Lean production, Business improvement	X											X		1/12	Makumbe et al., 2018
Aquaponics 4.0 Learning Factory	University of Alberta	Canada	Crops	Education, Training, Research	Bio Engineering	Industry 4.0, Resource and Energy Efficiency, Digital Twin, Robotics	X	X					X							2/12	Martinez & Ahmad, 2021
AutFab	University of AS Darmstadt	Germany	Relay	Education, Training, Research	Manufacturing Engineering	Industry 4.0, IoT	X	X	X	X										3/12	Simons et al., 2017
Bernard M. Gordon Learning Factory	Penn State University	United States of America	Various products	Education	Manufacturing Engineering	Product development, Industrial Engineering	X													0/12	PSU, 2022
BERTHA	Bremen Institute for Mechanical Engineering	Germany	Bulky assembly products	Education, Training, Research	Manufacturing Engineering	Manual Assembly	X			X								X		2/12	Schreiber et al., 2016
CubeFactory	TU Berlin (no fixed location)	Germany	Various products	Training	Manufacturing Engineering	Additive Manufacturing, Resource and Energy Efficiency	X	X		X	X	X	X							5/12	Muschard & Seliger, 2015
Cyber-Physical Learning Factory	Norwegian University of Science and Technology	Norway	Roller ski, skate	Education, Research	Manufacturing Engineering	Industry 4.0, Cyber Physical Production systems	X	X		X										2/12	NTNU, n.d.
DFA Demofabrik Aachen	RWTH Aachen	Germany	E-Mobility vehicles	Training, Research	Manufacturing Engineering	Industry 4.0, Prototyping, Industrialization	X	X					X	X						3/12	Schuh et al., 2015 + Abele et al., 2018
Die Lernfabrik	TU Braunschweig	Germany	Various products	Education, Training, Research	Manufacturing Engineering	Resource and Energy Efficiency, Industry 4.0, Urban production	X	X	X	X								X		4/12	Blume et al., 2015
Digital Capability Center Aachen / Textile Model Factory 4.0	McKinsey & ITA Acedemy Aachen	Germany	Wristband	Training, Research	Textile Engineering	Lean production, Digital manufacturing, Quality management, Leadership development, Industry 4.0	X	X					X		X					3/12	Küsters et al., 2017
Digital Capability Center Atlanta	McKinsey Atlanta	United States of America	Product–refrigerator compressors	Training, Research	Manufacturing Engineering	Lean production, Digital manufacturing, Resource and Energy Efficiency	X	X					X		X					3/12	McKinsey, 2023
Digital Capability Center Beijing	McKinsey Bejing & Tsinghua University	China	Gearbox	Training, Research	Manufacturing Engineering	Lean production, Digital manufacturing	X	X					X							2/12	McKinsey, 2023

Figure 15 Preview of spreadsheet of learning factory landscape analysis.

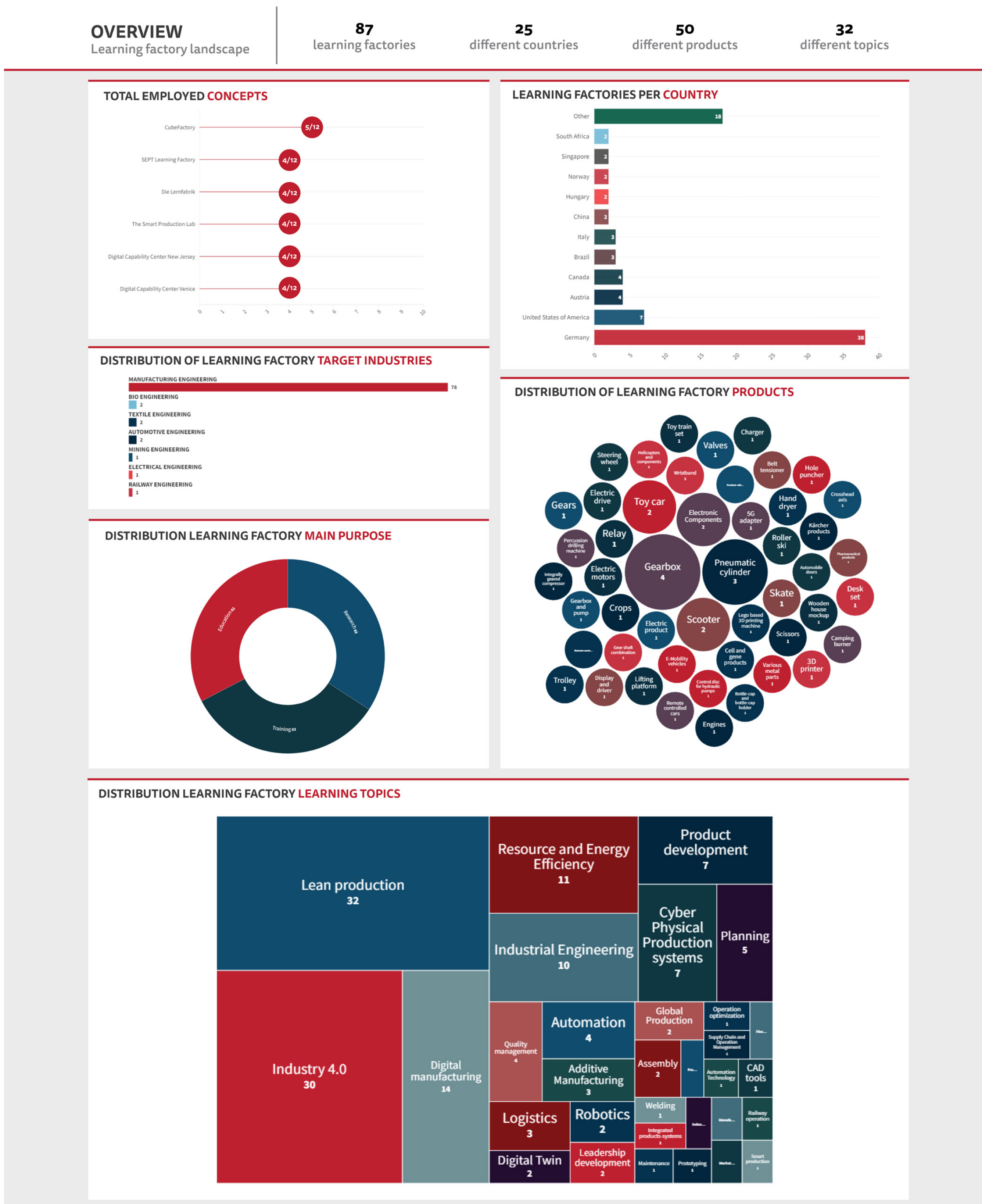


Figure 16 Graphical overview of the analysis of the current learning factory landscape.

cise summary, Figure 16 offers a visual representation depicting the analysis of the spreadsheet results.

Results learning factory

- **Numbers.** A total of 87 distinct learning factories were identified in this study. Nevertheless, it is important to acknowledge that certain learning factories are replicated across multiple locations, as exemplified by the case of 'Lernfabriken 4.0 in Baden-Württemberg', which is reported to be present in 37 vocational schools in the region of Baden-Württemberg, Germany. It should be emphasised that these replicated learning factories were not individually examined or subjected to separate analysis in this study.
- **Country.** The concept of learning factories has been developed and implemented in 25 different countries. Empirical evidence shows that Germany has the highest number (38) of registered learning factories worldwide. This can be explained by Germany's robust industrial base with a wide range of manufacturing sectors. A more thorough analysis of learning factories in Germany has previously been carried out by Sudhoff et al. (2020).
- **Products.** The results of the analysis show that the learning factories include a repertoire of 50 different products. It is noteworthy that certain learning factories show a shared use of specific products, such as the presence of the 'scooter' at both ESB Business School and TU Graz.
- **Purpose.** The primary purposes of learning (education, research and training) show a relatively balanced distribution across the different learning factories. It is worth noting that most learning factories have a wide range of purposes and usually combine several learning objectives within their operational framework.
- **Target industry.** The prominence of the manufacturing industry as the primary target sector for the vast majority of learning factories reflects the significance of hands-on training and competency development in this particular domain. It is important to note that while the manufacturing industry remains a primary target for learning factories, the learning factories in this study show that it is very possible to diversify into other target sectors.
- **Learning topics.** Although the target industries of learning factories show minimal variation, the topics covered within these facilities vary significantly. In particular, contemporary topics that are highly relevant to the present day, such as Industry 4.0 and lean management, are often addressed in learning factories. In addition, some learning factories focus on smaller topics, such as additive manufacturing.

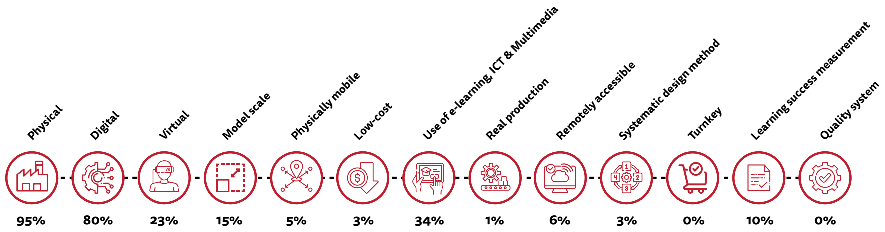


Figure 17 Percentages of employed learning factory concepts in 87 learning factories.

Results concepts

The analysis aims to assess the extent to which the proposed concepts are being implemented in order to overcome the constraints encountered within the learning factories. In addition to the aforementioned concepts, it is also noted whether the factories under study have a tangible physical infrastructure, although this aspect does not contribute to the scoring process measuring the application of concepts within the factories. In addition, in order to provide a comprehensive overview, the overarching category 'Digital, Virtual & Hybrid' has been broken down into distinct sub-categories, namely Digital and Virtual.

The results of the study reveal variations in the level of adoption of the proposed strategies aimed at overcoming limitations of learning factories. The majority of learning factories included in the study (95%) employ a physical representation of the learning factory. This physical representation is often complemented by a digital infrastructure, referred to as a digital learning factory (80%). However, despite the prevalence of digital infrastructure, only a small proportion of learning factories (23%) extend their physical (and often digital) infrastructure to include a virtual learning factory.

Concepts that offer potential for resource optimisation and increased mobility, such as model scale (15%), physically mobile (5%) and low-cost (3%) learning factories, are rarely used in learning factories. Although e-learning, multimedia and ICT are often used in conjunction with a digital learning factory (34%), the use of the learning factory for real production purposes is observed in only one learning factory, representing only 1% of the total pool of learning factories. Furthermore, a meagre 6% of learning factories are remotely accessible.

In terms of the methods proposed, the adoption rates are extremely low. Only a small fraction of learning factories use a systematic design method (3%), turnkey learning factories (0%), learning success measurement (10%) or quality systems (0%). It is possible that the low adoption rates are due to under-reporting of the use of these

Name	Operator & location	
CubeFactory	TU Berlin (no fixed location)	5/12
Digital Capability Center Venice	McKinsey & Confindustria Alto Adriatico, Venice	4/12
Digital Capability Center New Jersey	McKinsey New Jersey	4/12
The Smart Production Lab	FH JOANNEUM, Graz	4/12
Die Lernfabrik	TU Braunschweig	4/12
SEPT Learning Factory	McMaster University, Hamilton	4/12

Table 2 Learning factories with the highest amount of employed concepts and methods.

methods, but the figures are still strikingly low. However, Tisch et al., (2017) have for instance also reported learning factory design rarely follows a structured approach.

When analysing individual learning factories, it is clear that the use of approaches to overcoming constraints is also markedly deficient. While the use of a wide range of concepts does not necessarily indicate superior performance, it does suggest that individual learning factories are not actively seeking to address these constraints. The poor implementation of the proposed methods also contributes to these meagre figures. The dominant approach in most learning factories is to combine digital, virtual, e-learning, multimedia and ICT components.

In addition, it is important to recognise that learning factories can be considered to incorporate these concepts even in cases where their implementation is limited, such as the mere mention of virtual reality tools, data measurement or the use of digital tools such as screens for learning purposes. The presence of these concepts can therefore be observed to varying degrees, influenced by the specific design guide used in the research process.

3.1.3 Best practices

The following section explores some great examples of unique implementations within the learning factory landscape. These best practices are taken from Table 2, which identifies the learning factories that use the highest number of concepts and methods. As discussed earlier, these alternative concepts and methods can serve as valuable starting points for developing unique solutions for individual learning factory contexts, to effectively deal with personal limitations and optimise potential. While this section approaches these learning factories as 'best practice examples', it is worth noting that the use of a large number of concepts does not in itself indicate superior performance. Rather, it demonstrates the implementation of innovative solutions to overcome common limitations.

Figure 18 Pictures of the CubeFactory. Adopted from Muschard & Seliger (2015).

CubeFactory

The CubeFactory is a remarkable best-practice example of a learning factory that effectively addresses and overcomes various constraints through the implementation of innovative concepts. By incorporating essential components such as a Fused Deposition Modelling (FDM) 3D printer, a plastic recycler for filament production, solar cells for energy supply and a tablet interface for knowledge transfer, the CubeFactory becomes a self-contained unit capable of sustainable production. Its compact design, with a footprint of just 1m3 and easy expansion, ensures global accessibility with minimal skills required.

In addition, the CubeFactory embodies mobility, a crucial aspect often overlooked in traditional learning factories. By embracing physical mobility, it transcends the constraints of fixed infrastructure and can be deployed to different locations as required. This flexibility enables the CubeFactory to reach a wider audience and respond to different contexts and learning needs.

Another commendable aspect of the CubeFactory is its commitment to affordability. By focusing on low-cost solutions, it makes learning and production accessible to individuals and communities with limited financial resources (Muschard & Seliger, 2015).

The CubeFactory exemplifies a best practice approach to learning factories, using a range of concepts to overcome limitations. Its digital environment, model scale equipment, physical mobility, low cost and integration of e-learning, ICT and multimedia create an empowering ecosystem that facilitates sustainable production and learning. Through these innovative concepts, the CubeFactory paves the way for inclusive, scalable and adaptable learning factories of the future.

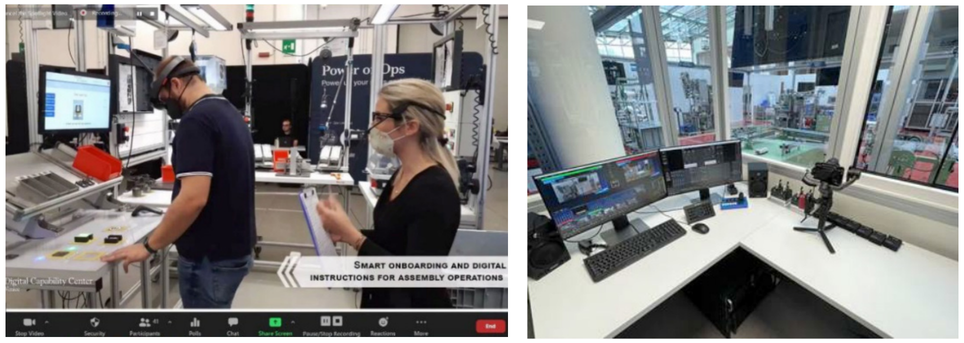


Figure 19 Impressions of the remotely accessible Digital Capability Center. Adopted from Hammer et al. (2022).

Digital Capability Center Venice

When the Digital Capability Center in Venice faced temporary closure in early 2020 due to the pandemic, the Operations Practice Learning team quickly adapted by introducing a remote offering to preserve the center's unique hands-on features. To ensure an immersive and effective learning experience, the team identified three key elements: learner-operator interaction, the from-to journey experience and real operational processes. The resulting Digital Capability Center remote offering is a simulation and experiential learning programme delivered via a video conferencing platform.

During live sessions, staff livestream from the model shop floor or office, allowing participants to interact directly with operators on site in real time. This remote approach provides a convenient and interactive way for learners to explore different operational topics and modules. Crucially, participants spend a significant amount of time interacting with the virtual factory or office environment, expertly guided by instructors and operators (Hammer et al., 2022).

The Digital Capability Center Venice has emerged as a great example of remote capability building in response to the challenges posed by the COVID-19 pandemic, an event that quickly exposed the limitations of standard learning factories. By overcoming the limitations by adapting the concept of remote access, the Center now offers a diverse range of capability building programmes that cater for both remote and face-to-face learning experiences (McKinsey, 2023j).

Die Lernfabrik

One of the key strengths of Die Lernfabrik is its extensive use of active learning methods, such as research-based learning and game-based learning, which enable participants to acquire skills through hands-on experience and collaborative problem-solving. It also encourages the continuous generation of knowledge between the columns of their learning environment. The learning environment consists of three columns: the Research Lab, the Experience Lab and the Education Lab, each contributing to a dynamic cycle of knowledge generation.

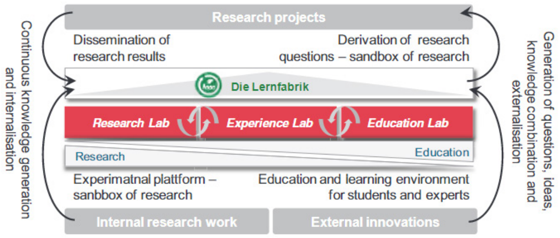


Figure 20 The knowledge generation cycle of Die Lernfabrik. Adopted from Blume et al (2015).

In the Research Lab, participants engage in active research projects in a near-industrial factory environment. By implementing prototypes and solutions developed through research, they contribute to ongoing projects while gaining practical insights. This knowledge is internalised through research work, fuelling the continuous generation of knowledge within the research team.

The Experience Lab provides a hands-on learning environment where participants apply methods and tools to a small-scale modular production system. They have the freedom to modify processes, rearrange equipment and observe the dynamic responses of the system. This hands-on experimentation not only develops practical skills, but also generates new research questions and ideas that feed back into the knowledge generation cycle. The Education Lab focuses on knowledge transfer through predefined learning pathways and guided hands-on experiments. By integrating mobile learning devices and courses, participants engage in closed-loop learning cycles that reinforce theoretical concepts and deepen their understanding. This applied learning approach empowers participants to generate new insights and bridge the gap between knowledge and action. Furthermore, Die Lernfabrik embraces external innovations from research communities and industry, offering a platform for testing and evaluating prototypic equipment, processes, and materials (Blume et al., 2015).

3.2 Current landscape of development methods

The importance of didactic and educational aspects in learning factories cannot be overestimated, as they play a central role in achieving the organisational and learning objectives of these institutions, as outlined in Chapter 2. Learning factories therefore require careful consideration of both technical and didactic aspects in order to achieve their organisational and learning objectives. They are deliberately tailored to fulfil the particular educational, training and/or research objectives of their developers. This makes each learning factory implementation is inherently unique. Learning factory design approaches have consequently emerged in recent years to support the development of different aspects of learning factories.

Nevertheless, the review of the existing learning factory landscape reveals a notable lack of use of structured design approaches, as confirmed by Tisch et al. (2017). As a result, there is a need to assess current design approaches and identify areas that require attention and improvement.

3.2.1 Analysis method

Kreß et al (2021) conducted a systematic literature review and evaluation that provided valuable insights into published design approaches. However, their review did not provide a comprehensive list of all 20 design approaches reviewed. Therefore, to address this limitation, a new literature search was conducted to try to identify the full set of 20 design approaches. Additionally, the evaluation conclusions by Kreß et al (2021) will be summarised.

3.2.2 Results

The literature search conducted identified a total of 20 design approaches, which includes some approaches published after the search period of Kreß et al. (2021). Therefore, not all the design approaches used in the study by Kreß et al. could be identified. Two tables, Table 3 and Table 4, provide an overview of the existing design approaches, including a brief description and their design scope. Table 3 focuses on design methods, while Table 4 presents other types of design approaches such as requirements or guidelines.

The evaluation conducted by Kreß et al. (2021) assesses the identified design approaches and identifies research gaps using five process-based requirements and five outcome-based requirements. The outcome-based requirements are derived from the limitations observed in existing learning factory approaches as identified by Tisch et al. (2017). The five process-based requirements include the integration of didactics, the incorporation of a detailed procedure model, the development of competency-oriented learning modules, target group orientation, and the implementation of a procedure for goal evaluation. The five outcome-based requirements encompass resource consideration, scalability, mapping-ability, mobility consideration, and effectiveness.

Reference	Design scope	Short description
Tschandl et al. (2020)	Learning factory	Learning and research factories with interdisciplinary applied focus addressing a big variety of stakeholders
Tisch et al. (2016)	Learning factory Learning modules Learning situations	Competency oriented approach on three conceptual levels
Wagner et al. (2015)	Learning factory product	Five step approach to develop learning factory products for changeable factories.
Reiner (2009)	Learning factory	Generic three-step approach
Riffelmacher (2013)	Learning factory	Approach description of the development of a learning factory for multi-variant assembly
Küsters (2018)	Learning factory	Five-step approach for designing learning factories addressing the digital transformation of production
Doch et al. (2015)	Learning factory	Three-step approach for the development of learning factories for the implementation of lean management tools
Kaluza et al. (2015)	Learning factory environment (scaled-down)	Generic approach for designing model scale production processes for energy efficiency competencies
Plorin et al. (2015)	Learning factory Learning modules	Reference model dealing with iteration of the learning factory and learning modules in existing learning environments
Petrusch et al. (2020)	Learning factory	Model to evaluate approaches toward the mobility of learning factories
Kreß & Metternich (2022)	Learning factory environment	Method based on optimization problems for choosing the optimal factory element configuration
Enke et al. (2017)	Learning factory	Model to assess the maturity of existing learning factories

Table 3 Identified design methods in the literature search.

Reference	Design scope	Short description
Riemann et al. (2020), Riemann et al. (2022)	Virtual Reality	Technical, didactic and organizational requirements for the agile implementation of virtual reality in learning factories Approach for the competency-oriented and structured design of virtual reality learning environments
Teichmann et al. (2020)	Serious Gaming	Requirements for serious games in the context of learning factories
Ullrich et al. (2017)	Digitization	Roadmap for the digitization of learning factories
Kemény et al. (2018)	Collaborating learning factories	Needs for the implementation of collaboration between learning factories
Rauch et al. (2019)	Industry 4.0 learning factories	20 design guidelines for the implementation of industry 4.0 learning factories
Teichmann et al. (2021)	Age appropriate teaching-learning environments	Design characteristics and attributes of learning factories and learning requirements of older employees. Didactical recommendations for realizing age-appropriate learning designs in learning factories.
Brandenburger & Teichmann (2022)	Participatory Learning	Guidelines for participatory teaching and learning processes for learning factories
Mourtzis et al. (2021)	Remote/hybrid Learning	Offers a Hybrid Teaching-Learning model and framework to allow for remote/hybrid learning

Table 4 Other identified approaches of learning factory design.

Based on the evaluation, it was found that the design approaches adequately address the requirements for detailed procedure models, as well as the content-related and solution-related mapping ability issues. However, there is limited consideration for didactic principles, competency-oriented learning modules, target group orientation, goal evaluation, scalability, space-related and time-related mapping ability issues, mobility, and effectiveness. In terms of meeting the derived requirements, the approach proposed by Tisch et al. (2016), Küsters (2018), and Tschandl et al. (2020) demonstrate the highest level of alignment according to Kreß et al. (2021).

3.2.3 Notable design approaches

In order to further evaluate existing design approaches and identify significant problem areas, this subsection provides further analysis focusing on three specific design approaches. The selection of these approaches is based on the areas of attention previously mentioned in this thesis: didactic aspects, technical aspects and continuous improvement. Firstly, the Learning Factory Curriculum Guide (Tisch et al., 2016) is discussed as it focuses primarily on the didactic aspects of the learning factory. Secondly, the Utility-based Configuration Approach (Kreß & Metternich, 2022) is examined, as it focuses on the technical intricacies of the learning factory at a detailed level. Finally, the Learning Factory Maturity Model (Enke et al., 2017) is discussed, which is designed to facilitate the continuous improvement of learning factory operations.

Tisch et al. (2016) - Learning Factory Curriculum Guide

The LFC-Guide provides an approach for designing action-oriented, competency-based learning factories. It underscores the significance of identifying the specific competencies required for a particular target group of trainees. These competencies are determined through a comprehensive analysis of organizational and personnel factors, including the purpose, production type, and target group of the Learning Factory. Subsequently, the educational level (teaching methods and media) and the technological infrastructure of the learning factory are derived based on these identified competencies. Ensuring alignment between the educational level and the technological infrastructure is essential to achieve a well-rounded Learning Factory design.

The implementation of the LFC-Guide involves two crucial steps in the development of competency-oriented learning systems. The first step, known as the 1st didactic transformation, involves the identification of relevant subject matters and the definition of specific competencies as learning objectives. These competencies serve as the foundation for the subsequent design process. The second step, referred to as the 2nd didactic transformation, focuses on the design of learning systems and the creation of suitable learning situations that effectively foster the development of the intended competencies. This step takes into consideration specific contextual factors, such as technology, participation, and regional characteristics. It encompasses the planning of instruction, interaction, and media within the configured Learning Factory.

Although the LFC-Guide provides valuable support in the competency transformation process and highlights the importance of aligning the educational and didactical levels, it does not extensively address detailed procedure models for creating educational modules or aligning the technical aspects of learning factory design (even though this is mentioned by Kreß et al. (2021) as the focus of the article. Specifically, it does not elaborate on how the educational level influences the technical level within the framework, and thus provides a lack of assistance in designing the technical level of the learning factory.

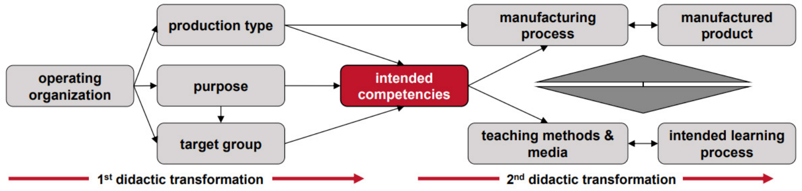


Figure 21 Didactic transformations in the LFC-Guide. Adopted from Tisch et al. (2016).

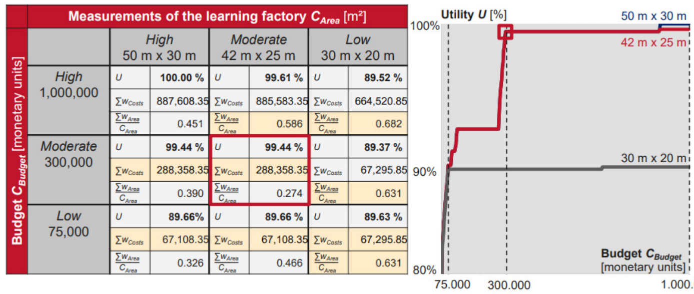
Kreß & Metternich (2022) - Utility-based Configuration Approach

Kreß and Metternich (2020, 2022) present a procedure for configuring learning factories based on optimisation problems that aim to select the optimal configuration of factory elements. The approach involves solving an optimisation problem that takes into account a target function and constraints such as budget and usable area.

In Kreß & Metternich (2020), the authors present a procedure for configuring learning factories and discuss the intuitive selection of factory elements. They then propose an optimisation-based approach to objectively and systematically select the best configuration alternatives.

In a subsequent study (Kreß & Metternich, 2022), the authors deepen the optimisation model used in the configuration procedure described in the first paper. They explain the formulation of the optimisation problem, including the decision variables and constraints. The configuration problem is formulated as a multidimensional multiple-choice knapsack problem (MMKP) with additional constraints derived from the two-dimensional packing problem. The objective of the optimisation model is to select configuration alternatives that maximise utility while taking into account resource constraints such as budget and factory area. The study also mentions the algorithms used to solve the optimisation problem and provides an example of the configuration process using the model.

However, it should be noted that although Kreß and Metternich (2020) acknowledge the importance of selecting appropriate factory elements based on the chosen product and manufacturing process, they do not provide specific methods or guidance on how to navigate this process. This limitation results in a lack of support in



	Measurements of the learning factory C_{Area} [m²]					
Budget C_{Budget} [monetary units]	High 50 m x 30 m		Moderate 42 m x 25 m		Low 30 m x 20 m	
High 1,000,000	U	100.00 %	U	99.61 %	U	89.52 %
	$\sum w_{Costs}$	887,608.35	$\sum w_{Costs}$	885,583.35	$\sum w_{Costs}$	664,520.85
	$\frac{\sum w_{Area}}{C_{Area}}$	0.451	$\frac{\sum w_{Area}}{C_{Area}}$	0.586	$\frac{\sum w_{Area}}{C_{Area}}$	0.682
Moderate 300,000	U	99.44 %	U	99.44 %	U	89.37 %
	$\sum w_{Costs}$	288,358.35	$\sum w_{Costs}$	288,358.35	$\sum w_{Costs}$	67,295.85
	$\frac{\sum w_{Area}}{C_{Area}}$	0.390	$\frac{\sum w_{Area}}{C_{Area}}$	0.274	$\frac{\sum w_{Area}}{C_{Area}}$	0.631
Low 75,000	U	89.66%	U	89.66 %	U	89.63 %
	$\sum w_{Costs}$	67,108.35	$\sum w_{Costs}$	67,108.35	$\sum w_{Costs}$	67,295.85
	$\frac{\sum w_{Area}}{C_{Area}}$	0.326	$\frac{\sum w_{Area}}{C_{Area}}$	0.466	$\frac{\sum w_{Area}}{C_{Area}}$	0.631

Figure 22 Utility-based Configuration Approach. Adopted from Kreß & Metternich (2022).

designing the technical aspects of the learning factory at a detailed level.

Enke et al. (2017) - Learning Factory Maturity Model

Enke et al. (2016, 2017) present a maturity model specifically tailored for learning factories, which face the ongoing challenge of improving their operations in response to stakeholder demands, research advances and socio-economic requirements. To address this challenge, the authors propose a maturity model that acts as a framework for assessing and advancing the maturity of learning factories.

The structure of the model is derived from the Capability Maturity Model Integration (CMMI) framework and consists of five levels: Initial, Managed, Defined, Quantitatively Managed and Optimising. These levels represent different levels of maturity for different facets of a learning factory.

The learning factory maturity model comprises several elements, including maturity levels, action areas and capability levels. Each maturity level represents a stage of maturity for a learning factory, while action areas represent the areas that need to be assessed. Capability levels are assigned to the action fields to indicate the level of capability achieved in each area. The maturity model serves as a self-assessment tool, enabling learning factories to assess their existing level of maturity and identify areas for improvement. It takes a comprehensive approach, covering multiple dimensions such as processes, resources, organisational aspects and technology integration.

While the maturity model itself is not a design approach, it provides a means of assessing current factories and identifying areas for improvement. In addition, the content of the maturity levels can serve as development goals for organisations seeking to establish a learning factory, making the model a valuable resource to guide learning factory design.

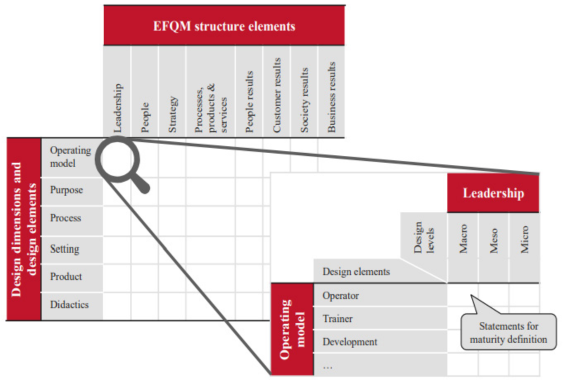


Figure 23 Representation of the Learning Factory Maturity Model. Adopted from Enke et al (2017)

3.3 Chapter conclusion

In conclusion, the current implementation of proposed concepts and strategies to overcome constraints in the existing learning factory landscape falls short. While there are variations in their adoption, the overall application of unique strategies to overcome constraints is inadequate. Best practices show that different adaptations of learning factory concepts creatively address individual learning factory needs. They use alternative concepts and methods to develop unique solutions for specific learning factory contexts, effectively addressing personal limitations and optimising potential. This underlines the need for wider use of these unique concepts and methods to enhance the effectiveness and performance of learning factories.

Furthermore, the current design approaches also face constraints in reaching their goals. A key limitation is the lack of alignment between different aspects of learning factories. While specific approaches focus on particular aspects, there is a lack of a coherent framework with appropriate guidance, particularly in aligning technical and educational perspectives. This hinders the creation of holistic learning environments and limits accessibility for those unfamiliar with the concept. Most approaches focus on the initial design of learning factories, neglecting the necessary continuous (and non-linear) development, which, as mentioned in Chapter 2, is essential for identifying and overcoming limitations while maximising potential. Current methodologies also fail to adequately address the constraints noted by Kreß et al. (2021). Furthermore, approaches do not offer guided selection of unique solutions. Although some methods touch on unique concepts such as virtual learning factories, none of them help to effectively identify and manage personal limitations or optimise potential through tailored, unique solutions for individual learning factory contexts.

These considerations raise questions about the effectiveness of the current learning factory landscape in achieving its primary goal of effective learning. The approaches do not contribute enough to recognising and overcoming limitations, as they do not guide the alignment of multiple perspectives, do not provide adequate guidance, and focus primarily on initial design rather than continuous and non-linear development. Nor do they help to effectively identify and address personal limitations or optimise potential through tailored solutions for individual learning factory contexts.

To establish truly effective learning factories, a multi-perspective, continuous and non-linear design guide is essential. This guidance should ensure that learning factories fulfil their primary purpose of facilitating effective learning. It should provide systematic, coherent design guidance and ongoing decision support, while aligning all aspects. It should also help identify and address personal limitations and optimise potential through tailored, unique solutions for individual learning factory contexts.

Part II

Development & Results

4

Requirements & Solutions

The purpose of this chapter is to lay the groundwork for the development of a design guide. It begins by drawing up a list of requirements for effective learning factories. These requirements are derived from both the traditional prerequisites for learning factories and the need to overcome existing limitations. By considering the limitations identified in current approaches to learning factory design, the chapter formulates the requirements for the new design guide. In order to meet these requirements effectively, a process of translating them into practical solutions is undertaken.

4.1 Approach

As stated earlier, the aim is to contribute to the creation of effective learning factories using a multi-perspective, continuous and non-linear design approach, that guides coherent systematic design and provides decision making support in all aspects, while paying due attention to recognising and overcoming limitations. This chapter aims to outline this process by translating requirements into solutions, which in turn will help to shape the structure and content of the design guide in the next chapter.

However, in order to achieve the goal of developing effective learning factories (which is the end product of the design guide), it is essential to first establish an understanding of what defines an effective learning factory. This requires the formulation of a clear definition of the key characteristics that an effective learning factory should possess. Consequently, this is achieved through the creation of a list of requirements for effective learning factories (covered in Section 4.2). This step is crucial before considering the requirements for the design guide, as a clear definition of the design guide's 'product' (an effective learning factory) will help to determine the content and structure of the design guide.

With a clear definition of the design guide 'product', attention can be shifted to the design guide itself. The purpose of Section 4.3 is to establish the requirements for the multi-perspective design guide by creating a list of requirements for this design guide. This list of requirements for the design guide is influenced by previous findings within this thesis, requirements for the usability of the design guide and the list of requirements for the effective learning factory outlined in Section 4.2.

Now that the design guide has a list of requirements outlined in a requirements list, the next step is to translate these requirements into practical solutions that shape the structure and content of the design guide. This process is described in Section 4.4. Implementing this structured approach ensures alignment with the specific requirements of an effective learning factory design approach and enhances the clarity of the rationale behind the design guide's structure and content choices.

4.2 Requirements learning factory

As emphasised earlier, it is essential to establish a precise definition of the key characteristics that any effective learning factory should possess. This requires the development of a complete list of requirements. Chapter 2 provided a basic definition that all learning factories should adhere to, while recognising the importance of addressing common limitations and working towards realising their full potential as more effective learning factories.

Effective learning factories are therefore expected to meet the standard learning factory requirements in accordance with the defined baseline, while actively recognising and addressing these limitations and working towards their full potential. This divides the requirements into two groups: standard requirements and potential/limitations requirements. Table 5 shows the final list of requirements, with standard requirements in black and potential/limitations requirements in red.

4.2.1 Standard requirements

Despite extensive efforts (as discussed in Section 2.1) to develop a comprehensive definition of learning factories, there is still no predefined and generally accepted list of requirements for learning factories. Consequently, in order to outline the specific characteristics that an effective learning factory should possess, it is essential to formulate a list of requirements that encompasses the standard prerequisites for learning factories.

Abele et al. (2015) divide the design of a learning factory into six dimensions, namely purpose, process, setting, product, didactics and operating model. The identified requirements are based on these categories. By using the insights on the dimensions provided by Abele et al. (2015) and the definition presented by CIRP (Abele, 2016), the standard requirements for learning factories are described in black in Table 5.

4.2.2 Potential/limitations requirements

To realise the full potential as effective learning environments, learning factories should actively recognise and overcome the limitations while maximising full potential. While potentials and limitations should be seen as unique attributes specific to each individual learning factory, the list posed by Tisch & Metternich (2017) can be used to recognise common limitations in all learning factory concepts. These limitations, which consider the resources needed, mapping ability, scalability, mobility and effectiveness, can be formulated as overarching requirements. These overarching requirements have been broken down to more specific requirements within the learning factory dimensions. An example of this process can be seen in Figure 24.

The learning factory should allow for scalability

1. The learning factory should allow for scalability of group sizes of participants (setting)
2. The learning factory should allow for scalability of its setting (setting)

Figure 24 Example of breakdown of limitation requirements.

Dimension	General	Requirement
Operating model	*The learning factory should have a sustainable operating model*	The development and operation of the learning factory should be sustainable and efficient
		The learning factory should continuously keep up with industry innovations
		There should be sufficient funding, personnel and space/facility for development of the learning factory
		There should be sufficient funding, personnel and space/facility for operation of the learning factory
		There should be sufficient funding, personnel and space/facility for improvement of the learning factory
		The learning factory should constantly evaluate the attainment of learning objectives and goals
		The learning factory should constantly implement concepts based on evaluation to improve effectiveness
Purpose	*The learning factory should have a clear purpose, topics, and targets*	The main purpose of the learning factory should be learning through education, training, and/or research
		The purpose of the learning factory should be tailored to the requirements of
		The targets of the learning factory should be tailored to the requirements of
		The content of the learning factory should be tailored to the requirements of
Process	*The learning factory should address a scope of processes*	The learning factory processes should be authentic, multi-stage, technical and organizational
		The learning factory should have changeable and flexible process.
		The learning factory should address processes tailored to the requirements of
		The learning factory processes should fit and support the requirements of the learning factory product
		The learning factory should address a wide scope of life cycle processes
		The learning factory setting should allow for quick feedback cycles in the used methods
		The learning factory should address challenges on all factory levels across the entire value stream
Setting	*The learning factory should have a factory environment setting for learning*	The learning factory setting should represent a real value chain
		The learning factory setting should include multiple work stations (physical/virtual)
		The learning factory should have changeable and flexible setting.
		The learning factory setting should allow for maximum accessibility concerning mobility
		The learning factory should allow for scalability of group sizes of participants
		The learning factory should allow for scalability of the setting
Product	*The learning factory should have a product being manufactured (or a service)*	The learning factory product should be as similar as possible to real industrial products
		The learning factory should have changeable and flexible product.
		The learning factory product should fit and support the learning factory processes and setting
		The learning factory product should be tailored to the requirements of the target group(s) and stakeholders
		The production of the learning factory product should be sustainable
Didactics	*The learning factory should employ a defined didactical concept*	The didactical concept should comprise formal, informal and non-formal learning (on-site or remote)
		The didactical concept should actively employ active learning methods
		The didactical concept should enable intended competency development
		The didactical concept should describe intended learning outcomes and
		The didactical concept should describe learning on learning factory, teaching
		The didactical concept should describe evaluation of learning outcomes

Table 5 Requirement list of an effective learning factory.

4.3 Requirements design guide

The new design guide should support the development of an effective learning factory that meets the requirements outlined in Table 5. These requirements, together with previous findings within this thesis and requirements for the usability of the design guide inform the formulation of the requirements for this new design guide.

4.3.1 Main requirements

The aim is to contribute to the development of effective learning factories through a multi-perspective, continuous and non-linear design approach. This approach is intended to guide a coherent and systematic design process, while at the same time providing decision support for all aspects, with attention to recognising and addressing limitations. This can be broken down into several key requirements for the design guide. To be multi-perspective, the design guide must encompass all dimensions of learning factory design and provide a comprehensive overview of all perspectives. It should facilitate and support systematic decision-making processes throughout all phases of the learning factory's life. In addition, the design guide should ensure transparency and traceability of both the process and its outcomes. It should provide guidance on how to identify and overcome limitations while maximising the potential of the learning factory. In summary, the main requirements for the design guide are as follows

The design guide should...

- » *... encompass all design dimensions of the learning factory, providing a complete overview.*
- » *... continuously facilitate and support systematic decision-making processes, aligning each design dimension of the learning factory.*
- » *... ensure visibility and traceability of both the design processes and their resulting outcomes.*
- » *... offer guidance for recognising and overcoming limitations, while maximising potential in the learning factory.*

4.3.2 Usability requirements

Becerril et al. (2019) highlighted the importance of incorporating usability considerations in the development of design methodologies. Usability refers to how well a product or system enables users to achieve specific goals efficiently while ensuring their satisfaction. Designing for usability involves, for example, adapting to the average knowledge level of users. Essentially, it's about ensuring that a system or product is easy to use and meets users' needs and expectations. Given the identified limitations regarding the accessibility of current design approaches, and in the broader effort to design learning factories, usability requirements were identified as essential components within the design guide requirements. The usability requirements can be found in Table 6.

4.3.3 Dimensions requirements

The requirements for the design guide are derived from the six learning factory dimensions proposed by Abele et al. (2015), which have previously been employed in defining the requirements for a higher-standard learning factory. As the latter requirements list serves as a foundation for developing the content of the design guide, the design guide requirement list adopts the dimensions to delineate the specific aspects that should be considered in its development.

Topic	**Requirement** ***The design guide should...***
Main requirements	*... encompass all design dimensions of the learning factory, providing a complete overview.*
	... continuously facilitate and support systematic decision-making processes, aligning each design dimension of the learning factory.
	... ensure visibility and traceability of both the design processes and their resulting outcomes.
	... offer guidance for recognising and overcoming limitations, while maximising potential in the learning factory.
Usability	*... align with the average knowledge level of users*
	... contain a manageable amount of information
	... require minimum learning process
Design dimensions	*... aid in defining the operational model of the learning factory*
	... aid in defining the purpose of the learning factory
	... aid in defining the processes of the learning factory
	... aid in defining the setting of the learning factory
	... aid in defining the product of the learning factory
	... aid in defining the didactical model of the learning factory

Table 6 Requirements of the multi-perspective design guide (methodology).

4.4 Conversion of requirements

The design guide should be designed to adhere to the pre-defined requirements, ensuring alignment with the unique needs and expectations of an effective learning factory design approach. In order to effectively address these requirements, a process of translating them into workable solutions is carried out.

4.4.1 Main requirements

At the heart of the design guide are the main requirements, which form the foundation of the entire design guide. These requirements have been thoroughly analysed and conversed into solutions to ensure their integration into the design guide.

To meet the first main requirement of encompassing all the design dimensions of the learning factory and providing a comprehensive overview, the design guide includes a number of solutions. First, the design guide should include a graphical *framework* that provides a visual representation that facilitates a clear overview of the structure of the learning factory. Such a visual representation allows for a clear overview of the multiple perspectives in the learning factory. This framework should go beyond mere visualisation, as it should also present organised and hierarchical information about all the development areas within the learning factory. The framework should classify these development areas as *design dimensions*, aligning them with the established dimensions of the learning factory by Abele et al. (2015). Within this classification, specific *design elements* should be further delineated to ensure a thorough design of each dimension. These design elements should be building blocks for the development and operation of an effective learning factory. Finally, the framework should emphasise the links and interdependencies between design dimensions by using *interfaces* that illustrate the relationships between different design elements. This allows the framework to illustrate the dependencies between multiple perspectives, aiding in a multidisciplinary approach to developing a learning factory.

By implementing these solutions, the design guide can effectively address the need to provide a comprehensive and coherent overview of the design dimensions of the learning factory in the form of a framework.

In order to continuously facilitate and support systematic decision-making processes within each design dimension of the learning factory, the design guide should include a series of process steps specifically designed for each design element. These process steps provide come in the form of *methods* that guide decision-making and ensure a structured approach for design elements within the learning factory.

The design guide should encompass all design dimensions of the learning factory, providing a complete overview

1. A graphical framework of the learning factory should be included in the design guide to provide an overview.
2. The framework should present organized and hierarchical information about all the development areas within the learning factory.
3. The development areas in the framework should be classified into design dimensions, utilizing the learning factory dimensions.
4. The design dimensions should be further divided into specific design elements within the framework.
5. The framework should emphasize the relationships between design dimensions by illustrating interfaces connecting the design elements.

Figure 25 Conversion of main requirement 1 into solutions.

Furthermore, the previously mentioned interfaces in the framework between design elements, which aid in showing the interdependencies between multiple perspectives, should be derived from the outputs of the methods employed within the design guide. These interfaces should serve as the foundation for connecting the various design elements, establishing a coherent and interconnected system. On the other hand, the process steps within the methods should also be integrated as inputs within the process steps. By incorporating the interfaces between design elements as input, the design guide ensures that decision-making processes are consistently aligned with the overall design objectives and goals of the learning factory.

The design guide should incorporate the solution of including *requirement lists* for each dimension. These requirement lists play a vital role in establishing a solid foundation for decision-making and ensuring a smooth translation between dimensions. By including comprehensive requirement lists for each dimension, the design guide can ensure that all factors a are properly documented and taken into account during the decision-making process. These requirement lists serve as a reference point, capturing the essential criteria and specifications that need to be addressed within each dimension.

The design guide should embrace the principle of constructive alignment, applied to the context of learning factories. This involves aligning all educational elements that influence learning activities, consequently shaping the learning environment within the learning factory. In practical terms, this means giving priority to education as the starting point in the design guide and then adjusting the rest of the learning factory to align with this educational focus. This approach ensures that the design guide

The design guide should continuously facilitate and support systematic decision-making processes, aligning each design dimension of the learning factory.

1. The design guide should include process steps for design elements, providing effective methods for their design.
2. The interfaces between design elements should be derived from the outputs of the methods, forming a foundation for their connection.
3. The process steps within the methods should utilize the interfaces between design elements as input for seamless integration.
4. The design guide should include comprehensive requirement lists for each dimension, enabling a solid foundation for decision-making and ensuring effective translation between dimensions.
5. The design guide should be build upon the principle of constructive alignment.
6. The framework should visually represent a continuous and non-linear process.

Figure 26 Conversion of main requirement 2 into solutions.

effectively promotes the core objective of a learning factory, which is to enhance the learning process.

The framework should be designed to visually represent a continuous and non-linear process without prescribing a strict starting or ending point, to recognises that the development and application of the design guide are ongoing and adaptable, allowing for continuous improvement and evolvement.

Through creating these methods for design elements, and using the interfaces as inputs and outputs, the design guide should effectively facilitate and supports systematic decision-making processes within each design dimension of the learning factory throughout its entire lifecycle.

The design guide should ensure visibility and traceability of both the design processes and their resulting outcomes.

1. The methods should encourage the documentation of process steps to ensure clear and comprehensive records.
2. The design guide should incorporate specification lists for each design element, serving as documentation for design decisions from methods
3. The methods should provide clarity, documentation, and structure for the required inputs.
4. The methods should clarify, document, and structure the expected outputs.
5. The design guide should indicate the source of information within the design elements.

Figure 27 Conversion of main requirement 3 into solutions.

In order to meet the requirement to ensure the visibility and traceability of both the design process and the resulting results, the methods used within the design guide should encourage the documentation of process steps. By emphasising the importance of clear and comprehensive records, the design guide ensures that the design process is transparent and well documented, enabling easy visibility and traceability.

The design guide incorporates the solution of incorporating *specification lists* for each method. These specification lists play a crucial role in serving as documentation for the design decisions made throughout the process. By including specification lists for each method, the design guide establishes a comprehensive record of the design decisions made at various stages.

In addition, the methods within the design guide should provide clarity, documentation and structure for the required inputs. By providing this level of clarity and documentation, the design guide improves visibility and traceability by allowing stakeholders to easily understand and track the inputs required for each design element. Similarly, the methods also clarify, document and structure the expected outputs. In addition, the design guide should include references to the source of information within the design elements. By highlighting the origin of information for each design element, the design guide improves visibility and traceability by providing a clear understanding of which stakeholders have been involved during the design process.

Through these solutions, the design guide ensures visibility and traceability of both the design process and the resulting results. By promoting documentation, providing clarity and identifying sources of information, the design guide enables stakeholders to easily track and understand the design process, as well as trace the origin and progress of design outcomes.

The design guide should offer guidance for recognising and overcoming limitations, while maximising potential in the learning factory.

1. The design guide should employ the alternative approaches to address limitations as a starting point in providing unique solutions for individual learning factories.
2. The design guide should include a method to select appropriate approaches to address limitations based on individual needs.
3. The methodology should be capable of emphasizing the relevant design elements required for the user's chosen concepts.

Figure 28 Conversion of main requirement 4 into solutions.

In order to meet the need to provide guidance for the implementation of concepts that address and overcome limitations in the learning factory, the design guide includes two key solutions. Firstly, the design guide should include a method for selecting appropriate concepts tailored to the specific constraints identified by the users. This method takes into account user input and preferences to guide the selection process, ensuring that the selected concepts are relevant and effective in addressing the identified constraints.

In addition, the design guide should highlight the relevant design elements required to implement the concepts selected by the user. By focusing on these specific design elements, the design guide provides focused guidance and direction, ensuring that the necessary components and considerations are properly addressed during the implementation process. This helps to streamline the implementation effort and ensures that the chosen concepts are effectively integrated into the learning factory.

4.4.2 Usability requirements

As stated in the usability requirements, the design guide should aim to support users with different levels of knowledge, prevent information overload and minimise the learning curve. This user-centred approach should enhance accessibility, usability and practicality, making the design guide an effective tool for users to navigate the intricacies of learning factory design.

The design guide should include methods with small, understandable steps that support brainstorming and promote a low learning curve. By breaking down complex processes into manageable and comprehensible steps, users should be able to easily follow and understand the design guide. This approach encourages user engagement and ensures that the design guide remains accessible to people with different levels of knowledge and experience. Secondly, the design guide should provide easy-to-understand instructions for each method. Clear and concise instructions help users navigate through the design guide without confusion or ambiguity. By using plain language and providing practical examples, the design guide facilitates understanding and ensures that users can implement the methods effectively. Finally, the design guide should use a layered and structured approach to presenting information in the framework. By organising information hierarchically within the framework, users can access the relevant details without being overwhelmed by excessive information. This layered structure allows users to focus on the specific areas of interest, while providing the flexibility to explore additional details as needed.

4.4.3 Dimension requirements

The design guide is constructed based on the dimensional requirements, which provide the foundation for its content and structure. These dimensional requirements are carefully considered in order to develop the design elements for the effective learning factory. Each design element is placed within their specific dimension to ensure a comprehensive and coherent approach. This alignment between design elements and dimensional requirements ensures that the design guide addresses all the necessary components of an effective learning factory.

Furthermore, the design elements are influenced by the requirements of an effective learning factory that were identified in the previous chapter. These requirements encompass broader aspects of the learning factory and contribute to the overall representation of an effective learning factory within the design guide.

Additionally, the design guide incorporates elements from the learning factory morphology proposed by Tisch et al. (2015). These elements serve to enhance and expand upon the aspects covered by the dimension requirements and effective learning factory requirements, providing a more comprehensive framework for the design guide.

4.5 Chapter conclusion

The development of the design guide for an effective learning factory requires careful consideration of various essential requirements and characteristics. Firstly, in order to establish a clear definition of an effective learning factory, a comprehensive list of requirements is formulated. As it is intended to represent an effective learning factory, it includes both the standard requirements for learning factories and requirements to overcome inherent limitations. The standard requirements, outline the necessary aspects related to all dimensions, ensuring that all crucial dimensions of the learning factory are addressed. In addition, the limitation requirements address how learning factories should overcome ns to these limitations.

Based on these requirements for an effective learning factory, the main requirements for the design guide are formulated. The design guide should be able to provide a comprehensive overview of the design dimensions of the learning factory, support systematic decision-making processes, and ensure visibility and traceability of the design process and its outcomes. In addition, usability requirements are essential to make the design guide accessible and practical for users with different levels of knowledge, while dimensional requirements are the basis for the structure for the design guide.

The key requirements form the foundation of the design guide and have been carefully analysed and deconstructed to ensure their integration. To encompass all design dimensions and provide a comprehensive overview, the design guide should include a graphical framework that visually represents the structure of the learning factory. It also should include methods to facilitate systematic decision making within each design dimension. In addition to these two main components, requirement lists should be implemented to provide a solid basis for decision making, while interfaces between design elements ensure alignment with the overall design objectives.

Visibility and traceability of the design process and results are emphasised by documenting process steps and including specification lists for each method. In addition, the design guide provides guidance for implementing concepts that address constraints by including a method for selecting appropriate concepts and highlighting the relevant design elements required for implementation. Usability requirements are also considered, such as including methods with understandable steps to support user engagement and a low learning curve. Clear instructions and a layered presentation of information prevent information overload and allow users to focus on specific areas of interest.

5

Design Guide Development

This chapter proposes the main structure and explains the central principle of the design guide. The focus is on examining the design guide and explaining how its content was derived from the previously formulated solutions. The aim is to provide a comprehensive understanding of the structure and content of the proposed design guide and its relationship to the previously formulated solutions.

5.1 Design guide approach

In the previous chapter, the basis of the design guide was established by analysing the requirements and formulating appropriate solutions. The key requirements form the foundation of the design guide and have been carefully analysed and deconstructed and conversed into solutions to ensure their integration in the design guide.

This process revealed that the design guide consists of two main components: a graphical framework and methods for designing specific elements. In addition, other elements such as requirement lists, specification lists and method instructions emerged during the translation of the requirements. The central principle of the design guide is built upon the collaboration of these elements. The following sections will examine the developed design guide and explain how its content was derived from the previously formulated solutions. For a more thorough understanding, a general explanation of the design guide is given in this section. Figure 29 also illustrates the central principle of the design guide, showing the collaboration between its elements in relation to the structure of the framework.

As mentioned, the design guide involves two essential aspects: the creation of a framework and the development of methods. The framework acts as a graphical and structural backbone, organising the different design dimensions and elements in a clear and logical way. Methods, on the other hand, provide a systematic approach to designing specific elements within the framework. By integrating the framework and the methods, the design guide provides a comprehensive and coherent approach to designing a learning factory.

In general, the framework within the design guide serves as a structured organisational system that visually represents all aspects of an effective learning factory. It includes design dimensions, design areas and design elements that together make up the framework. In addition, interfaces play a vital role in visualising the important connections between design elements. These interfaces show how design elements interact, exchange information and influence each other within the design of the learning factory. The relationship between design dimensions, design areas and design elements is hierarchical, with design dimensions providing overarching categories, design domains further subdividing these dimensions into specific focus areas, and design elements representing the specific components within these focus areas.

Methods, on the other hand, are developed to provide a systematic and practical process for designing the specific elements within the learning factory. Each method corresponds to a specific design element within the framework. They guide designers through a step-by-step process, providing instructions on how to gather the necessary inputs, carry out the required actions and produce specific outputs that specify the corresponding design element.

Interfaces play a crucial role in both the framework and the methods by illustrating the connections and interactions between design elements. These interfaces show how design elements interact, exchange information and influence each other within the learning factory design. They help to identify dependencies and relationships between elements, and highlight the flow of inputs and outputs between methods.

Lastly, lists of requirements and specifications play a crucial role within the design guide. Requirements lists outline the essential criteria and specifications for each design dimension in the learning factory, providing a basis for decision making and alignment with desired outcomes. This requirements list is based on the requirements of an effective learning factory as can be seen in Table 5. Specification lists complement requirement lists by summarising the outputs generated by design methods for each specific design element. They capture the specific outputs and facilitate effective communication and decision making in the design process by working in conjunction with the requirements lists. The requirement list is therefore updated throughout the process based on outputs from methods. In this way, requirements from multiple perspectives can be communicated throughout the learning factory design.

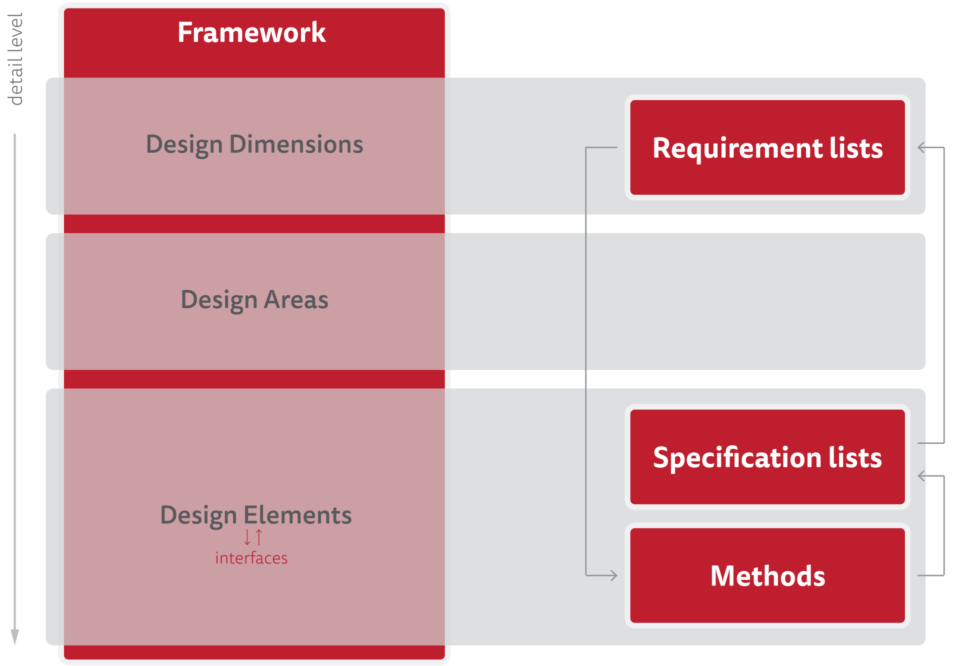


Figure 29 Basic principle and interactions in the design guide.

5.2 Development of framework

The previous section provided an introduction to the general approach of the design guide. This section focusses on the framework in more detail. It aims to explain the process of constructing the framework, to clarify the reasoning behind the design choices made, and to present the visual representation of the framework as a proposal.

The design guide should be able to effectively addresses the need to provide a comprehensive and coherent overview of the design dimensions of the learning factory. In essence, the framework establishes the structure and organization of the design dimensions and design elements, providing a clear and logical framework for decision-making. Within the scope of this thesis, the framework's primary objective is to provide a comprehensive overview as a proof of principle. It may not include all critical design elements of a complete learning factory but demonstrates the viability and effectiveness of the framework.

The framework is constructed by breaking down design dimensions into design elements, which are then positioned within specific dimensional areas. Design dimensions are the key conceptual categories that encompass various aspects of the learning factory design. Each dimension represents a distinct aspect of the learning factory and contributes to its overall design and operation. These design dimensions align with the established dimensions of the learning factory proposed by Abele et al. (2015):

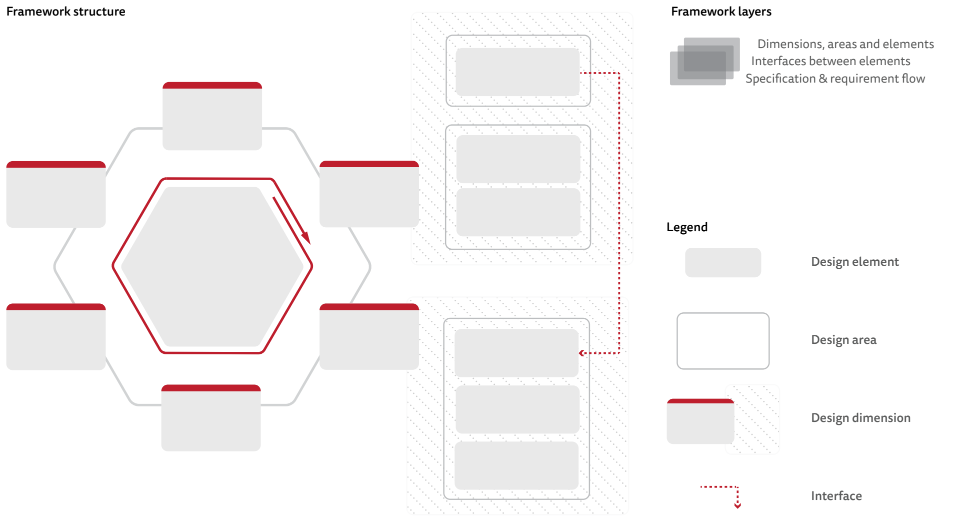


Figure 30 Visual explanation framework (DE, DD, DA, layers, interfaces).

Operating Model, Purpose, Didactics, Product, Process, and Setting. To ensure a solid foundation for decision-making, each dimension should include a requirement list, which is visualized in the framework.

The design of a learning factory is a continuous and non-linear process due to the multidisciplinary nature. However, the framework should still present the design dimensions in a specific order due to the dependencies that exist among them. The order of the dimensions mentioned in the previous paragraph is necessary to ensure that certain dimensions build on the foundations laid by previous dimensions. The framework starts with the operating model and the purpose, as they establish the fundamental functioning, goals, and target groups of the learning factory. Following that, didactics come into play, as they define the activities aimed at achieving the primary goal of the learning factory, which is learning. The product dimension follows, as the learning activities determine the type of product required within the learning factory. Next is process, as the type of product primarily determines the specific processes needed for its production (next to some needs from the learning activities). Lastly, the setting dimension is considered, as the setting largely depends on the types of processes necessary in the factory. However, it's important to note that the framework is designed to visually represent a continuous and non-linear process without prescribing a strict starting or ending point. It recognises that the development and application of the design guide are ongoing and adaptable, allowing for continuous improvement and evolvement.

Within each dimension, the relevant design elements are placed. As mentioned in subsection 4.4.3, these design elements are derived from the requirements for an effective learning factory discussed in the previous chapter, specifically in Table 5. These requirements align with the necessary design elements for an effective learning factory. For example, within the Operational Model dimension, design elements such as funding, performance, personnel, and improvement are included. Additionally, the concept choice design element, which holds great importance and shapes the main idea of the learning factory, is positioned at the centre of the framework.

To enhance the organization of design elements within the dimensions, dimensional areas are created. For example, using the previous examples, the design elements funding and personnel are placed within the resources dimensional area, while performance and improvement are more suitably located within the Organisation dimensional area.

The framework also illustrates the interfaces between design elements. These interfaces are established in two ways. Firstly, through the detailed development of methods, where inputs and outputs are defined for each design element. Secondly,

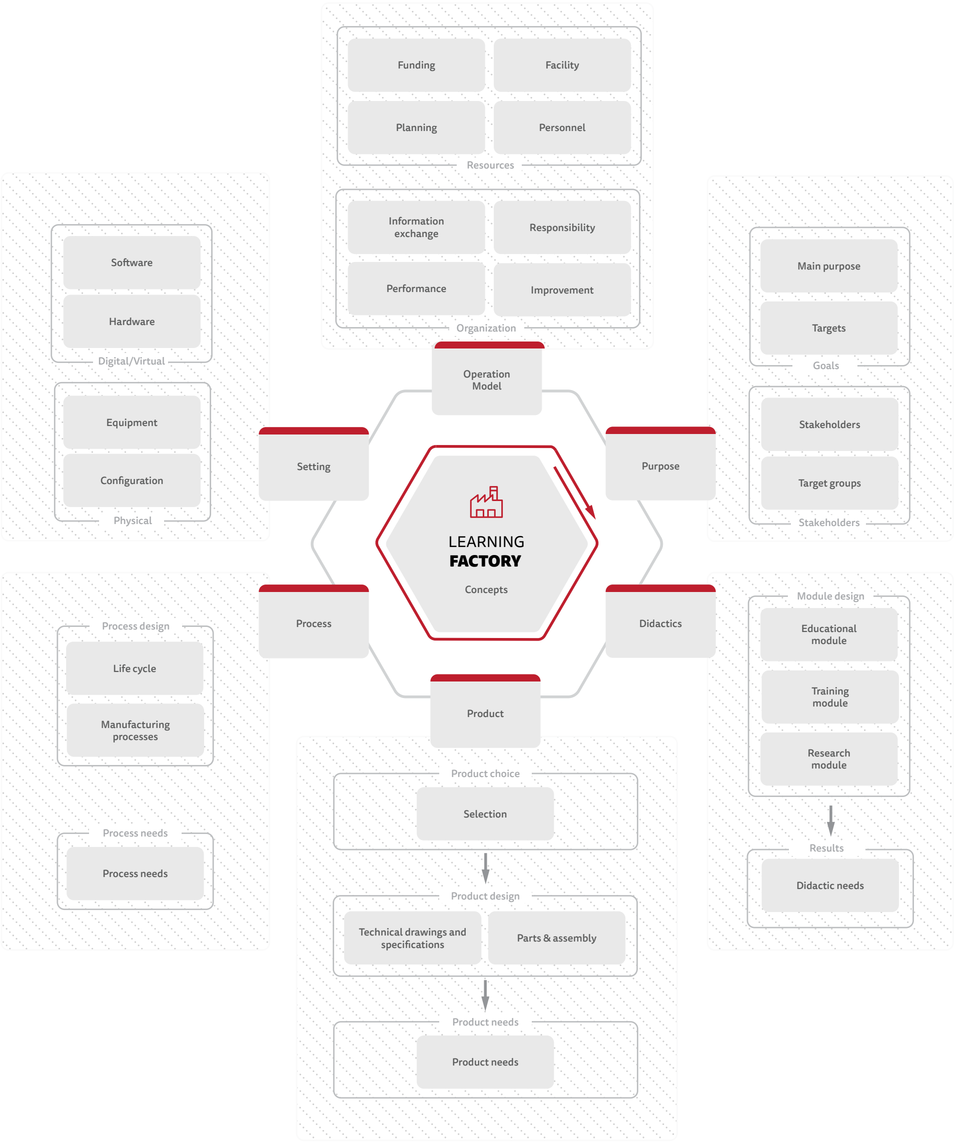


Figure 31 Design proposal of the basis framework structure.

through general knowledge, such as recognizing the logical interface between funding and equipment.

To avoid overwhelming users with excessive information, the framework can be viewed in layers. These layers help structure and organize the information within the framework, making it easier for users to navigate and comprehend.

5.3 Development of methods

In this thesis, the scope is limited to establishing the basis for the design guide. Therefore, the primary objective is to develop sufficient and satisfactory methods for design elements that are able to provide a proof of principle. The methods provide a systematic approach to designing these elements within the framework. As a result, not all design elements within the framework will have (fully developed) methods. Their purpose is to serve as a proof of principle for the design guide rather than providing comprehensive guidance for complete learning factory designs.

The content of the developed methods in the framework is derived from a combination of theoretical knowledge, logical reasoning, and insights from existing design approaches. This approach ensures that the methods are well-grounded and incorporate established principles. The exact nature of specific methods is described in section 5.3.1.

As mentioned earlier, the framework illustrates interfaces between design elements, serving as inputs and outputs. Methods require input from other elements and, once a user has gone through all the necessary process steps in the method, generate specific outputs. The outputs produced by the methods should be documented and presented in the specification lists of design elements. These specifications serve two important purposes. Firstly, they provide a concise representation of the outputs themselves, enabling clear communication and understanding of the results. Secondly, the specifications inform the requirement lists within the framework, allowing for a solid foundation for decision-making and ensuring effective translation between dimensions. Hence, in addition to referring to the specification list to gather the required inputs when starting a method, it is equally crucial to consult the requirement list. This ensures that any important considerations or guidelines are taken into account while using the method. Spreadsheets are used to develop a proof of principle for the specification and requirement list in this thesis.

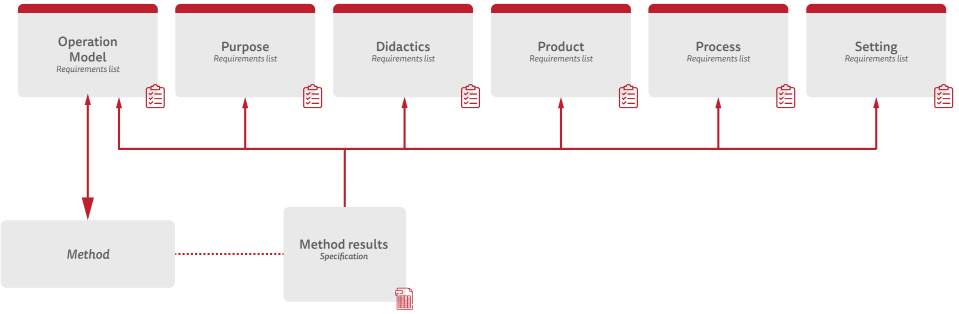
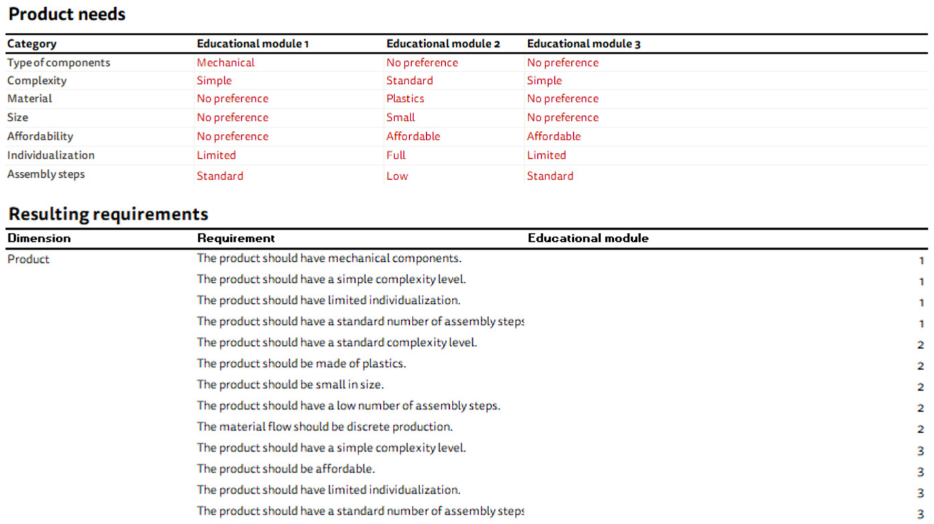


Figure 32 Visual explanation requirement lists and specification.



Product needs

Category	Educational module 1	Educational module 2	Educational module 3
Type of components	Mechanical	No preference	No preference
Complexity	Simple	Standard	Simple
Material	No preference	Plastics	No preference
Size	No preference	Small	No preference
Affordability	No preference	Affordable	Affordable
Individualization	Limited	Full	Limited
Assembly steps	Standard	Low	Standard

Resulting requirements

Dimension	Requirement	Educational module
Product	The product should have mechanical components.	1
	The product should have a simple complexity level.	1
	The product should have limited individualization.	1
	The product should have a standard number of assembly steps	1
	The product should have a standard complexity level.	2
	The product should be made of plastics.	2
	The product should be small in size.	2
	The product should have a low number of assembly steps.	2
	The material flow should be discrete production.	2
	The product should have a simple complexity level.	3
	The product should be affordable.	3
	The product should have limited individualization.	3
	The product should have a standard number of assembly steps	3

Figure 33 Specification and additions to requirement list example.

The breakdown of a design element into methods is illustrated in Figure 34. Each design element may have several methods. The diagram shows that the outputs of each method contribute to the specification of the particular design element. In addition, the diagram shows the availability of instructions for the method steps. To ensure clarity within the methods, a separate document is provided with more detailed instructions for the method steps. In addition, examples are included throughout the instructions to inspire and assist the user. An example of such an instruction for a method can be seen in Figure 35.

Each method is visually presented using the same graphic style. Although the methods can be used as documents on digital devices, the graphic design of the methods is intended to encourage users to use printed documents. This approach facilitates collaboration among developers during brainstorming sessions, allowing ample space for discussion and exploration of creative solutions. By having the methods in

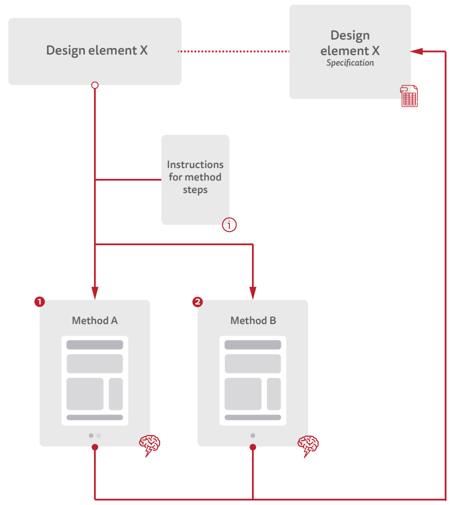


Figure 34 Visual explanation of the breakdown of a design element.

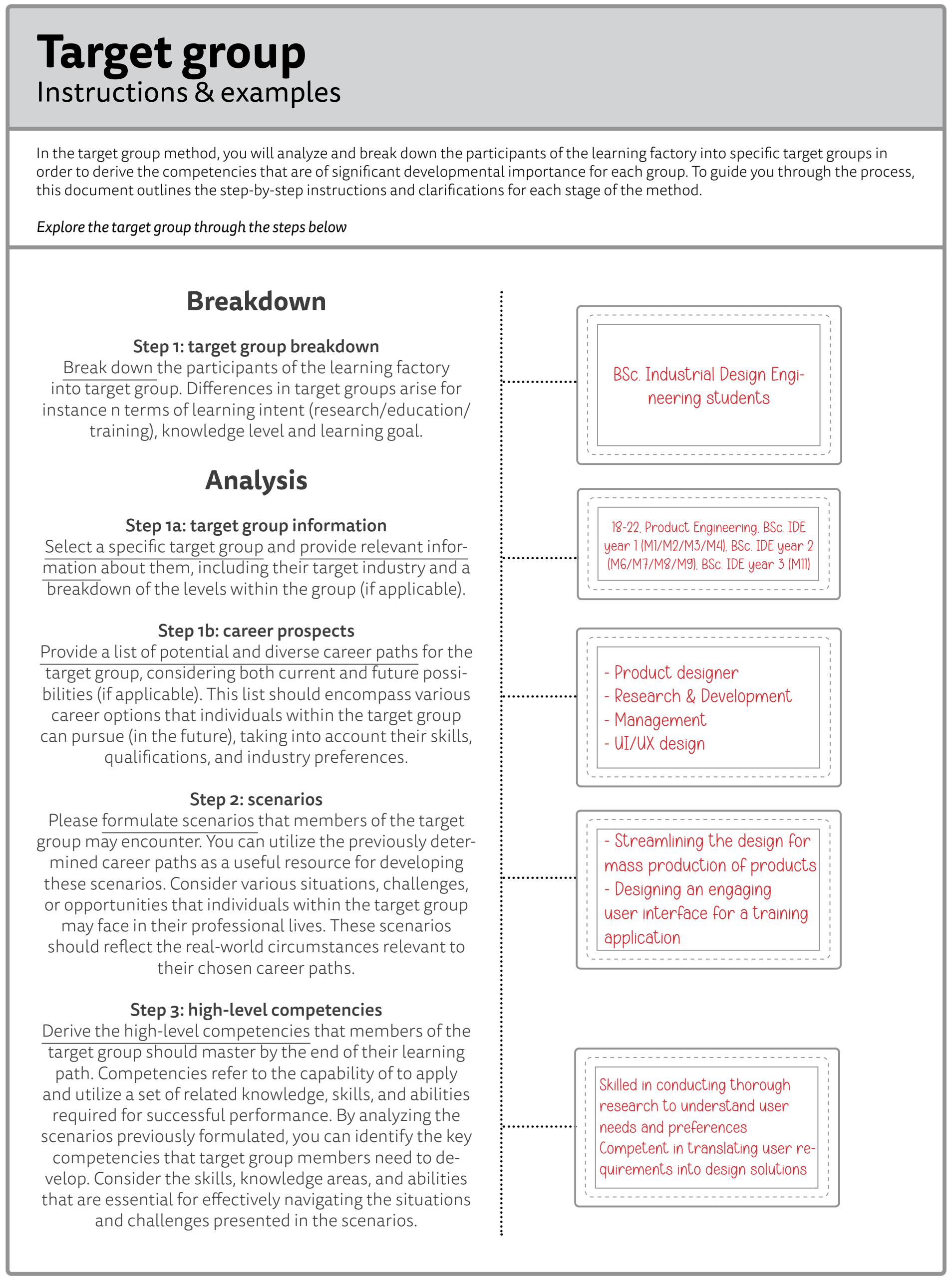
a tangible format, developers can gather around them, engage in conversations, and collectively contribute their ideas and expertise to improve the design process. An example of how such a method is visualised can be found in Figure 36.

5.3.1 Method overview

The following part of this subsection describes the methods that have been (partially) established for the design guide. It provides an explanation for the selection of these methods for the proposal and outlines the way they have been derived. This thesis emphasises the educational aspects of a learning factory and, as a result, the methods that have been developed mainly revolve around the educational perspective of the learning factory. In addition, critical methods that are essential for establishing a foundation for the learning factory are included in the current design guide.

Concept choice method

As mentioned earlier, the concept choice design element plays a central role in shaping the main idea of the learning factory. Recognising its significance within the design guide, a method has been developed for the proposal. Essentially, the method's content is based on variations of learning factory concepts proposed by Tisch & Metternich (2017) and Abele et al. (2019). The objective of this method is to determine which concepts or methods should be implemented within the learning factory. While all the concepts and methods aim to address limitations of learning factories and maximize the potential of the learning factory approach, the suitability of each



Target group
Instructions & examples

In the target group method, you will analyze and break down the participants of the learning factory into specific target groups in order to derive the competencies that are of significant developmental importance for each group. To guide you through the process, this document outlines the step-by-step instructions and clarifications for each stage of the method.

Explore the target group through the steps below

Breakdown

Step 1: target group breakdown
Break down the participants of the learning factory into target group. Differences in target groups arise for instance n terms of learning intent (research/education/training), knowledge level and learning goal.

BSc. Industrial Design Engineering students

Analysis

Step 1a: target group information
Select a specific target group and provide relevant information about them, including their target industry and a breakdown of the levels within the group (if applicable).

18-22, Product Engineering, BSc. IDE year 1 (M1/M2/M3/M4), BSc. IDE year 2 (M6/M7/M8/M9), BSc. IDE year 3 (M11)

Step 1b: career prospects
Provide a list of potential and diverse career paths for the target group, considering both current and future possibilities (if applicable). This list should encompass various career options that individuals within the target group can pursue (in the future), taking into account their skills, qualifications, and industry preferences.

- Product designer
- Research & Development
- Management
- UI/UX design

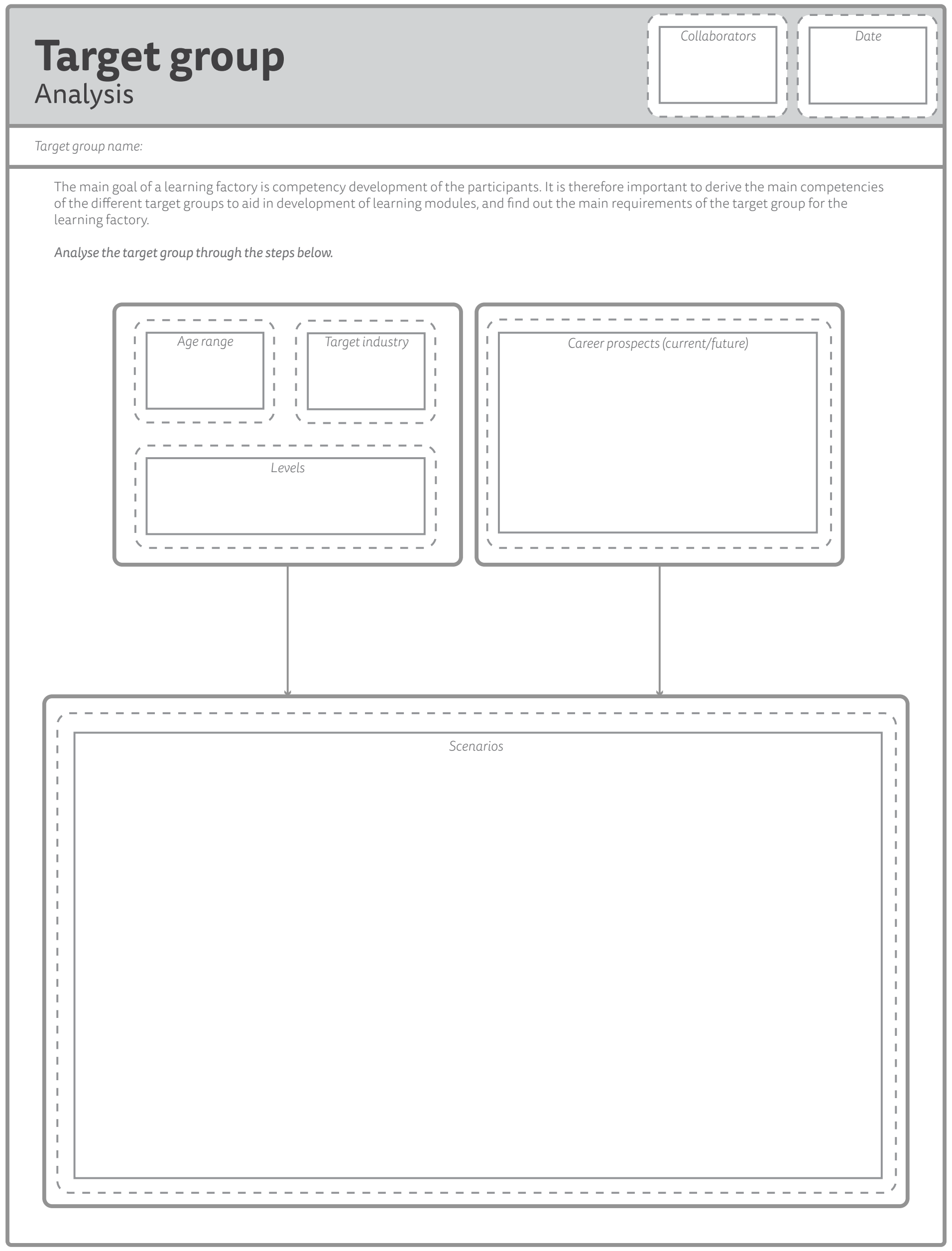
Step 2: scenarios
Please formulate scenarios that members of the target group may encounter. You can utilize the previously determined career paths as a useful resource for developing these scenarios. Consider various situations, challenges, or opportunities that individuals within the target group may face in their professional lives. These scenarios should reflect the real-world circumstances relevant to their chosen career paths.

- Streamlining the design for mass production of products
- Designing an engaging user interface for a training application

Step 3: high-level competencies
Derive the high-level competencies that members of the target group should master by the end of their learning path. Competencies refer to the capability of to apply and utilize a set of related knowledge, skills, and abilities required for successful performance. By analyzing the scenarios previously formulated, you can identify the key competencies that target group members need to develop. Consider the skills, knowledge areas, and abilities that are essential for effectively navigating the situations and challenges presented in the scenarios.

Skilled in conducting thorough research to understand user needs and preferences
Competent in translating user requirements into design solutions

Figure 35 Example of the instructions for a method.



Target group
Analysis

Collaborators

Date

Target group name:

The main goal of a learning factory is competency development of the participants. It is therefore important to derive the main competencies of the different target groups to aid in development of learning modules, and find out the main requirements of the target group for the learning factory.

Analyse the target group through the steps below.

Figure 36 Example of a method in the design guide.

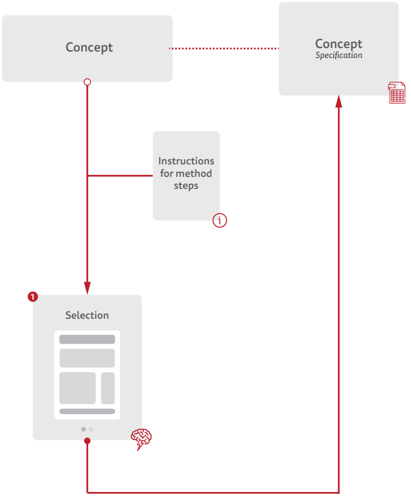


Figure 37 Breakdown of the concept selection design element.

concept and method depends on the specific needs and preferences of the learning factory developers. Thus, the purpose of this method is to analyse the requirements and preferences of the learning factory and provide the user with the most appropriate concepts or methods to implement.

Each concept and method has previously been scored based on how effectively they address individual limitations, as documented by Tisch & Metternich (2017) and Abele et al. (2019). However, the authors do not provide details of the evaluation process for these concepts. Furthermore, they do not consider the possibility that certain concepts or methods may have a negative impact on the limitations. For example, while the concept of a digital, virtual and hybrid learning factory effectively addresses limitations such as mapping ability, its implementation typically requires significant personal and financial resources. This implies that the positive impact of the concept should be balanced against the additional effort and financial investment required when considering its use. To take these considerations into account, the concepts are reassessed using a Likert scale that allows both positive and negative influences to be taken into account. Some limitations are split for a more thorough approach (for instance, resources is split into financial, personal and spacial resources). The scoring process follows a systematic approach, using the advantages and disadvantages outlined for each concept and method in Abele et al. (2019). Further details of this scoring process can be found in Appendix D in D.1.

The method is designed to align with the specific requirements and preferences of the learning factory developers since the suitability of concepts and methods relies on these factors. To facilitate this, users should assess their capabilities and interests in relation to different categories associated with the limitations, using the previously created Likert scale as a tool. By doing so, they can establish boundaries that indicate the desired scoring range for the concepts and methods.

Target group method

In order to tailor learning factories effectively to the needs of the target group, it is necessary to develop methods specifically for the design element of the target group. In the context of the learning factory approach, target groups refer to different types of audiences or groups that will engage in learning activities within the learning factory. The primary aim of these methods is to analyse the target groups and identify their specific needs within the learning factory.

Given that the primary focus of the learning factory's target groups is learning, the methods should help to determine what the target group wants or needs in terms of learning content, based on their characteristics. As mentioned in Chapter 2, competences include the specific knowledge and skills needed to excel in a particular field. It is therefore essential to identify the competences required by the target group. The methods are designed to analyse the target groups on the basis of their characteristics and to extract high-level competences from this analysis. This approach is inspired by the competency transformation table in the LFC guide by Tisch et al. (2016).

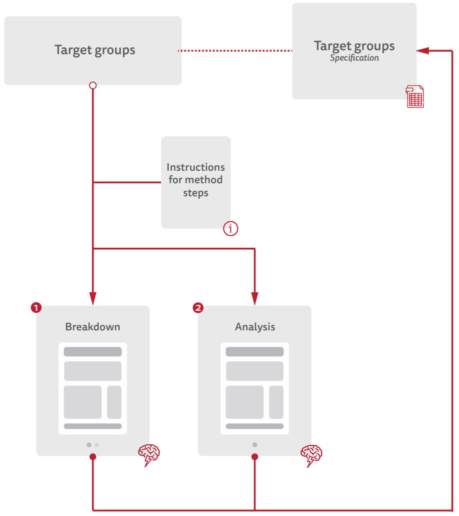


Figure 38 Breakdown of the target group design element.

Educational module method

The success of learning factories depends heavily on well-designed learning activities that meet the needs of the target groups. Therefore, proper design of learning activities is of utmost importance. Within the design guide, this design aspect is addressed through the design elements of education, research and/or training modules, depending on the type of learning in the learning factory. For the proposal, methods are developed for the educational module design element.

The primary objective of these methods is to create comprehensive and detailed designs for the educational modules within the learning factory. The key aspect of these methods is the use of a high-level competency obtained from the target group design element as an input. By analysing this competence and following a step-by-step process based on the educational concepts introduced in Chapter 2, a thorough educational module can be designed. Again, this method incorporates some elements also used in the LFC Guide by Tisch et al. (2016) due to its competency-based nature.

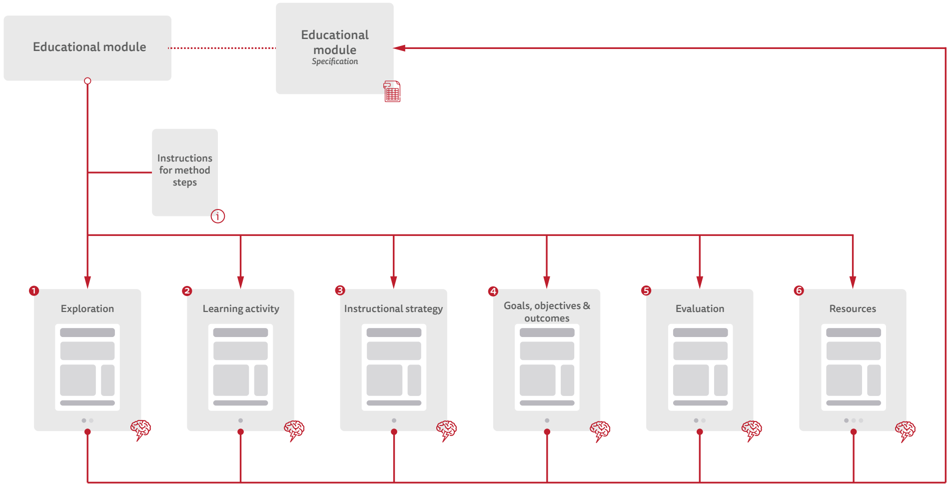


Figure 39 Breakdown of the educational module design element.

Didactic needs method

The learning activities in the learning factory directly influence the type of product and processes required. Therefore, the design element of didactic needs is instrumental in determining the important requirements for the product and process dimensions.

To identify these didactic needs, the learning activities are analysed. These activities should reveal specific needs and preferences related to the product and process dimensions. By categorising these needs based on the characteristics outlined in the product dimension of the learning factory morphology (Tisch et al., 2015), clear product and process characteristics emerge for each learning module. As the output of this design element influences other design dimensions, it is crucial to utilise the specification and requirements lists within this method. By defining each need within the appropriate category in the specification for each learning module, the relevant requirements are extracted and effectively communicated to the appropriate dimensions.

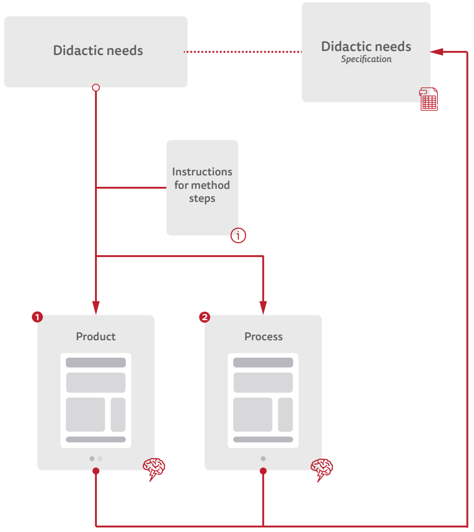


Figure 40 Breakdown of the didactic needs design element.

Product selection method

Selecting the appropriate product(s) for the learning factory is a critical aspect of its design. However, due to the interdependencies with other factors, this task can be quite challenging. To assist in this process, the design guide includes a product selection method aimed at defining the necessary product(s) and potential variations to ensure an effective learning factory.

The product selection method takes into account the requirements listed in the product dimension. However, conflicting requirements may arise due to diverse needs, such as those stemming from learning activities. By analysing these conflicting requirements, the method identifies the need for potential variations in the product(s) or even multiple products. This process enables the separation of requirements and facilitates ideation and selection of the most suitable products later on in the method.

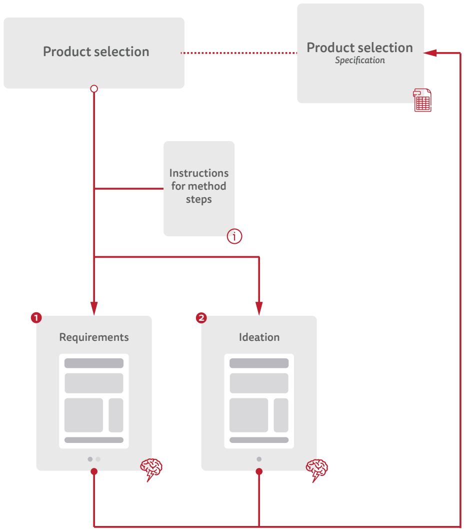
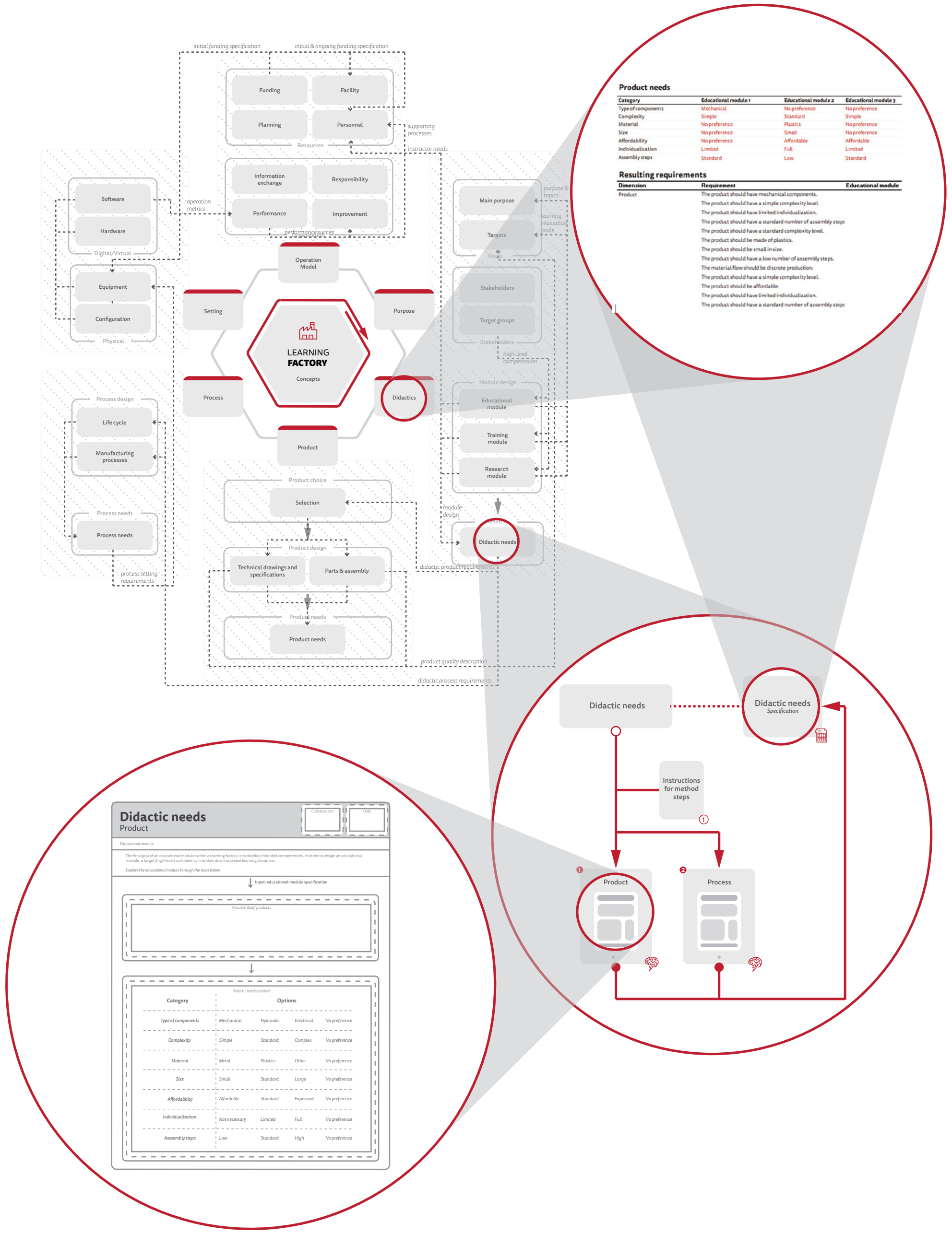


Figure 41 Breakdown of the product selection design element.

Other methods

This thesis focuses primarily on the educational aspect of learning factories, prioritising the design guide's starting point on education and adapting the rest of the learning factory accordingly. This has resulted in some of the technical content of the design guide, such as the setting, being excluded. Although the thesis includes a translation from education to technology through the principle of specification and requirements lists, further testing and elaboration on the technology side within the design guide is needed. It is more interesting to focus initially on the educational side, as the current landscape already offers many methods that focus on the technological side. However, it is important to address this limitation by expanding the content of the design guide and ensuring a strong translation from education to technology.



Product needs

Category	Educational module 1	Educational module 2	Educational module 3
Type of components	Mechanical	No preference	No preference
Complexity	Simple	Standard	Simple
Material	No preference	Plastics	No preference
Size	No preference	Small	No preference
Affordability	No preference	Affordable	Affordable
Individualization	Limited	Full	Limited
Assembly steps	Standard	Low	Standard

Resulting requirements

Dimension	Requirement	Educational module
Product	The product should have mechanical components.	
	The product should have a simple complexity level.	
	The product should have limited individualization.	
	The product should have a standard number of assembly steps	
	The product should have a standard complexity level.	
	The product should be made of plastics.	
	The product should be small in size.	
	The product should have a low number of assembly steps.	
	The material flow should be discrete production.	
	The product should have a simple complexity level.	
	The product should be affordable.	
	The product should have limited individualization.	
	The product should have a standard number of assembly steps	

Didactic needs
Product

Collaborators
Date

Educational module:

The final goal of an educational module within a learning factory is to develop intended competencies. In order to design an educational module, a target (high-level) competency is broken down to create learning situations.

Explore the educational module through the steps below

Input: educational module specification

Possible 'daily' products

Didactic needs product

Category	Options			
Type of components	*Mechanical*	*Hydraulic*	*Electrical*	*No preference*
Complexity	*Simple*	*Standard*	*Complex*	*No preference*
Material	*Metal*	*Plastics*	*Other*	*No preference*
Size	*Small*	*Standard*	*Large*	*No preference*
Affordability	*Affordable*	*Standard*	*Expensive*	*No preference*
Individualization	*Not necessary*	*Limited*	*Full*	*No preference*
Asssembly steps	*Low*	*Standard*	*High*	*No preference*

Figure 42 Overview and example of the principle elements in the design guide.

5.4 Chapter conclusion

In conclusion, the key components of the design guide proof of principle are structured in a systematic and comprehensive manner. The design guide has two main components: a framework and methods. These components, together with the requirements and specifications lists form the central principle of the design guide. This principle is built on the collaboration of these elements.

The framework serves as a structured organisational system that visually represents the design dimensions, design areas and design elements of an effective learning factory. It aims to provide a clear and logical backbone for decision making and to help designers understand the overall structure and organisation of the learning factory design. Interfaces within the framework illustrate the connections and interactions between design elements, highlighting dependencies and the flow of inputs and outputs.

The methods, on the other hand, provide a systematic approach to designing specific elements within the framework. Each method corresponds to a particular design element and provides step-by-step instructions and guidance for gathering inputs, performing actions and producing outputs. The methods are derived from a combination of theoretical knowledge, logical reasoning and insights from existing design approaches, ensuring that they are well founded and incorporate established principles.

Throughout the design guide, requirements and specification lists play a crucial role. Requirements lists outline the essential criteria and specifications for each design dimension, providing a basis for decision making and alignment with desired outcomes. Specification lists complement the requirements lists by summarising the outputs generated by the design methods for each specific design element. The specifications inform the requirements lists within the framework, providing a solid basis for decision making and ensuring effective translation between dimensions. These lists facilitate effective communication and decision making by providing concise representations of the outputs and guiding the design process.

In summary, the design guide for a learning factory is structured through the integration of the principal elements: a framework, methods specification lists and requirement lists. An overview and example of how the principal elements are positioned in the design guide can be seen in Figure 42. The framework organises the design dimensions and elements. The methods provide a systematic process for designing specific elements within the framework. The specification and requirements lists ensure communication and decision making throughout the development process. Together, these components aim to provide a multi-perspective, continuous and non-linear approach to learning factory development.

Part III

Evaluation

6

Case Study

This chapter provides an explanation of the conducted case study, including the process and results. The primary objective is to evaluate the effectiveness and practicality of the current proposed design guide using the findings of the case study. By analysing the results of the case study, this chapter will evaluate the performance of the design guide.

6.1 Case study approach

A case study will be conducted to evaluate the design guide proof of concept. By applying the design guide in a real learning factory context, the study aims to evaluate its effectiveness and practicality. This evaluation will validate the guide's ability to support decision making, improve efficiency and enhance overall design outcomes. Through the case study, the strengths and weaknesses of the design guide can be identified and used to inform future iterations. The case study serves as a critical step in validating and refining the design guide, ensuring its effectiveness in practical scenarios.

The case study will involve the application of the previously developed proof of concept for the framework and methods, including the use of spreadsheets that represent the proof of concept for the specification and requirements lists.

Whilst a full case study involving the development of a complete learning factory design is beyond the scope of this thesis, the case study will serve to demonstrate the effectiveness of the design guide in supporting multi-perspective decision making within the learning factory. This will be achieved by using the methods and tools developed, such as the requirements and specification lists, as outlined in the design guide. It is important to acknowledge potential limitations before diving into the case study. Firstly, the case study was conducted at one specific institution, the University of Twente, which may not fully represent the diversity of learning factory contexts and user perspectives. It is particularly important to note that the research in this case study focused primarily on the educational aspect of learning, rather than on research or training as learning. Therefore, the conclusions may not be fully generalisable to other learning factory contexts. It should also be noted that the methods used in the case study were carried out by the author of the thesis alone, rather than by a group of learning factory developers. As the use of the design guide requires the collaboration of several developers and users with different levels of knowledge, this may lead to limitations in the conclusions. The findings from a single researcher's perspective may not fully capture the challenges and perspectives that arise in a collaborative development process.

6.2 Case study

The following sections present the details of the case study, providing an overview of the steps taken throughout the study. A full description of the case study steps can be found in the Appendix G.

6.2.1 Case description

The University of Twente (UT) is in the process of building a new workshop that will include a specific learning factory. This workshop will be approximately 3000 m2 and will contain different 'environments' designed to facilitate specific sets of processes and materials at different levels of aggregation. Activities within these environments range from exposing learners to individual production processes to planning and monitoring approaches for multiple environments. Whilst the whole facility functions as a learning factory, there is one particular environment that is designated as a specific learning factory. The development of this learning factory is still ongoing, and many creative ideas have been proposed for its design.

The main concept behind this learning factory, which covers an area of approximately 150 m2, is to allow the repositioning and reconfiguration of assets and resources to create modular production or assembly lines. It aims to provide different levels of involvement for students with different perspectives and at different stages of their academic journey. For example, beginning students will have the opportunity to gain an understanding of the processes and workflows involved by experiencing the different production and assembly stations. Advanced learners, on the other hand, may be responsible for configuring and optimising the production and assembly lines encountered by the less experienced students (Damgrave et al., 2023; Lutters et al., 2022). Given the importance of considering multiple perspectives in design, the development of the learning factory could benefit from a structured approach.

Although the development process is already underway, this case study could contribute to the learning factory's further development. Using the proof of concept developed within the design guide, the study will establish certain aspects of the learning factory through a structured approach. This case study aims to provide valuable insights and inform the ongoing development of the learning factory, enhancing its effectiveness and aligning it with the objectives outlined in the design guide.

As the educational programme of Industrial Design Engineering (BSc. IDE) is currently working on a redesign of the curriculum, the case study will focus on the target group BSc. Industrial Design Engineering students. The case study will specifically address two modules within the new curriculum, aiming to design the learning factory from different perspectives as outlined in the design guide.

6.2.2 Case study description

This section provides a brief summary of the steps outlined in the design guide. For a comprehensive examination of the case study, including the results of each step in the methods, Appendix G provides the detailed information.

Figure 43 Scope of the case study in the framework

Concept choice method

Based on the interests and capabilities of the developers in the UT learning factory, the concept selection method is used. This method considers available resources, scalability and mobility requirements to determine the suitability of different concepts. Due to the significant resources allocated by the UT and minimal concerns about mobility constraints, a large number of concepts are found to be suitable.

To further narrow down the choices, the impact of each concept and associated methods on mapping ability and effectiveness will be considered. The aim is to improve these aspects and minimise limitations, taking into account the suitability identified in the previous step. In addition, the existing interests of the university, such as the use of a hybrid learning factory, will also be considered in the decision-making process.

Among the various suitable concepts, the hybrid and changeable learning factory concepts offer the most advantages. These concepts are in line with the interests of the UT and have already been considered during the development of the UT learning factory. Similarly, the method selection process takes into account methods that complement a hybrid learning factory, such as e-learning, ICT and multimedia. In addition, methods that contribute to monitoring and improving the performance of the learning factory, such as quality systems, are selected.

The selected concepts and methods are then incorporated into the specification list, which consequently adds specific requirements to each dimension.

Target group method

In the target group method, the primary objective is to understand and extract the characteristics and high-level competences of the target group. In the context of this learning factory, the target groups consist of students from different study programmes and levels, as well as researchers from different groups. Although there may be additional target groups for the UT learning factory, they are not considered due to the scope of the study.

As the case study focuses specifically on the BSc. IDE curriculum, further analysis will be carried out on this particular target group following the breakdown process. By analysing the characteristics of BSc. IDE students, future scenarios are developed that they should be able to successfully complete by the end of their studies. These scenarios represent specific skills and, based on them, a comprehensive list of competences will be compiled. The aim of this list is to cover the range of skills and knowledge that students are expected to have when they graduate.

Educational module method

The case study focuses on two specific quartiles within the new curriculum. To address this, the educational module method is applied twice, each time targeting different groups of students. For each quartile, the first step is to select high-level competences aligned with the theme of the quartile. These competences are then analysed in detail to design a comprehensive learning module for the learning factory. The aim is to create a detailed and structured module that meets the specific needs and requirements of the students in each quartile.

The first target group consists of BSc. IDE students in their first year, specifically in the fourth quartile. In this module, the main project requires students to turn a prototype into a mass production product. As a result, students need to have the ability to create innovative and mass-producible technical products, taking into account the broad needs of clients and making choices about construction materials and elements. Therefore, the high-level competence selected for further exploration is 'proficient in designing and adapting various products for mass production'. Taking into account the students' current level of knowledge and their future educational path, the primary competence of the educational module is defined as "designing and optimising products for mass production, taking into account process planning in a manufacturing environment". Following the steps of the method, a general scenario is developed that outlines the actions and knowledge elements that students must demonstrate to demonstrate mastery of the primary competence. In addition, other elements of the learning module design, such as specific details of the learning activity and the formulation of learning objectives, targets and outcomes, are further developed using other methods within the learning module design process.

The second target group consists of BSc. IDE students in their second year, specifically in the first quartile. This module focuses on understanding and evaluating the value of data in the design process. Each course within the module contributes to the overarching aim of 'acquiring, understanding and using data' for both the design and use phases. The high-level competence chosen for this module is 'competent in using data-driven design to inform decision making and optimise design solutions'. This competency reflects the desired outcome of the module, as students should be skilled in this area upon the completion of the module. Therefore, the selected high-level competence also serves as the main competence for the educational module. The main competence guides the design of the learning activity and other details within the educational module. Next, the other methods within the educational module design element are used to develop the learning activity to ensure alignment with the key competence and to address the specific needs of the target group.

Didactic needs method

This method involves analysing the impact of learning activities within the learning factory on the type of product and processes being studied. The aim is to identify critical requirements for the product and process dimensions. To determine these requirements for the UT learning factory, the specifications from the educational modules of both target group levels are taken into account. To start the thinking process, a general idea of a potential product is first documented. Based on this idea and the specifications of the educational module, requirements for specific aspects of the product are defined.

For the BSc. IDE first year students, for example, an important requirement is that the product should be simple so as not to complicate the learning process. In addition, an important requirement for the process is that the life cycle should include assembly, as the learning activity involves assembling the product. For the BSc. IDE second year students, the learning module has fewer requirements for the product and the process. However, the product should include some electrical components to facilitate data collection during the use phase and the life cycle should include product design to enable data driven design.

The result of this analysis is a comprehensive list of requirements for the product and process dimensions, specifically tailored to the BSc. IDE target group participating in the UT learning factory.

Product selection method

The product selection method is guided by the list of requirements generated by previous methods, such as the concept selection method and the didactic needs method. These requirements serve as the basis for determining the appropriate product selection.

The product selection process begins with the identification of any conflicting requirements. In the case of the educational modules, as they didn't generate many specific product or process requirements, there are no significant conflicting requirements other than the need for both mechanical and electrical components while maintaining simplicity. Initially, this may suggest the potential for product variation through the method. However, considering that data collection can be simulated or calculated without actual electrical components, there is no need for a product variation specifically incorporating electrical components. Therefore, the requirement for electrical components can be ignored.

With the product requirements established, the next step is to generate ideas for potential products. As the case study didn't produce many specific product requirements, a wide range of simple, mechanical products are suitable. Examples of such products include mechanical household appliances such as hand mixers, or mechanical toys such as toy cars.

6.2.3 Case study results

The implementation of the developed proof of concept within the UT case study has resulted in specifications for design elements and an extensive list of requirements across different dimensions of the learning factory. The module has successfully facilitated the creation of specifications for concept choices, target groups and two educational modules. It also identified potential products suitable for the learning factory. However, it should be noted that the educational modules did not generate a substantial list of product requirements. To address this, further analysis of additional target groups and educational (and research) modules is needed. This will enable the development of more product requirements and allow for a more informed product choice.

Product

General	Requirement
General	The learning factory product should be as similar as possible to real industrial products
	The production of the learning factory product should be sustainable
	The learning factory product should fit and support the learning factory processes and setting
	The learning factory product should be tailored to the requirements of the target group(s) and stakeholders
Limitations	The learning factory should have changeable and flexible product.
Concept selection	The physical equipment in the learning factory should be appropriate for collecting data.
	The learning factory should have a digital product that represents the physical product.
	The learning factory product should be traceable
	The learning factory product should be designed to support data collection.
	The learning factory should have a virtual product that represents the digital product.
	The learning factory product should be changeable depending on the needs of the target group
	The learning factory product should be simplified to reduce complexity, remaining close to reality and allow a large number of product variants.
Didactic needs	The product should have mechanical components.
	The product should have a simple complexity level.
	The product should have limited individualization.
	The product should have a standard number of assembly steps.
	~~The product should have electrical components.~~

Figure 44 Example of resulting requirements

6.3 Evaluation

The main objective of the case study was to evaluate principle of the design guide. As a full case study involving the development of a complete learning factory design was beyond the scope of this thesis, the case study involved the application of the previously developed proof of concept for the framework and methods, including the use of spreadsheets that represent the proof of concept for the specification and requirements lists. The following sections delve into a detailed evaluation of the components of the design guide.

6.3.1 Case study results evaluation

Despite the small size of the case study, the propsed design guide produced significant results for the learning factory at the UT. Overall, the design guide successfully guided the development of specifications for concept choices, target groups and two educational modules, while also generating a comprehensive list of requirements for various dimensions. The results of the case study serve as valuable starting points for further development of the learning factory and the IDE curriculum. They provide a solid foundation on which to build and inform future decisions and actions.

6.3.2 Framework evaluation

The framework is designed to provide a comprehensive overview of all dimensions and aspects of the learning factory. It serves as a tool that provides a complete overview of the design elements of the development process, while highlighting the crucial relationships between these elements through interfaces.

During the case study, the framework successfully provided the desired overview and demonstrated the relationships between design elements. However, due to the case study's specific circumstances, the framework was not consulted frequently. The methods themselves provided sufficient guidance on the relationships between design elements and indicated the necessary inputs from other elements. In addition, as the case study was carried out by a single person, the communication of inputs and outputs proceeded in a chronological manner, minimising the need for extensive communication support. Nevertheless, if other design elements were to be developed in the case study, the interfaces within the framework would prove useful in identifying which methods should be consulted first to ensure the provision of accurate inputs.

It should be noted that the functionality of highlighting design elements that are relevant to the chosen approach, as derived from the requirements, has not yet been implemented in the framework. While this did not impede the case study process due to its limited scope, it is crucial to include this feature in future iterations to increase the effectiveness of the framework.

In conclusion, the proposal of the framework was successful in providing a comprehensive overview of the learning factory in general. However, as the case study did not provide a thorough evaluation of the framework, it is recommended that an evaluation be conducted using a larger learning factory project to further assess its effectiveness.

6.3.3 Methods evaluation

The design guide contains methods that act as tools to facilitate and support systematic decision-making processes for the design elements of the learning factory. These methods aim to provide clear, step-by-step processes for developing design elements. The steps should be small and understandable, encouraging brainstorming and promoting a low learning curve. Practical examples should be provided in the form of instructions to assist users.

During the case study, the methods were effective in guiding decision-making processes. They provided clear and structured results that could easily be used as input for other methods within the case study. The instructions that accompanied the methods played a key role in enabling users to fully utilise the methods and guide them in the right direction. However, further testing with developers from different backgrounds is needed to fully evaluate the usability of the methods.

The graphic design of the methods aims to communicate the need to use them as brainstorming tools, while maintaining clarity in the presentation of the steps. In terms of content, the propsed methods guided users to the required outputs. However, some methods in the proposal were too detailed for the stage of the process in which they were used, such as the instructional strategy method. This highlights the challenge that certain methods may be more difficult to apply with limited information. This observation was also evident in the product choice method. It suggests that different uses of the design guide at different stages in the development of the learning factory may need to be implemented.

In summary, the methods within the design guide effectively guided the decision-making processes during the case study. They provided clear and structured results, and the guidance was instrumental in their use. However, further testing with developers from different backgrounds is needed to fully evaluate the usability of the methods. The current content of the methods in the proposal may require adaptation for different stages of the development process.

6.3.4 Requirements and specification lists evaluation

The purpose of the requirements and specification lists is to facilitate clear communication and understanding of the results, to provide a solid basis for decision making and effective translation between dimensions. The outputs generated by the methods are documented in the design element specification lists, which in turn inform the requirements lists within the framework. Spreadsheets were used in this thesis to develop a proposal for the specification and requirements lists.

During the case study, these spreadsheets were used to evaluate the principle of using the requirements and specification lists from the design guide. The specification lists effectively documented the outputs of the methods and provided a clear overview of the results. With these well-defined specifications, the requirements lists were updated, resulting in comprehensive and detailed lists of requirements for each dimension, derived from the results of various design elements. This approach successfully ensured that important considerations and guidelines were taken into account.

However, while the methods clearly indicate the necessary use of inputs from other methods, they do not sufficiently emphasise the necessary use of requirement lists. This aspect should be addressed in future iterations of the design guide to ensure their proper integration and use.

6.4 Chapter conclusion

Overall, the initial proposal of the design guide is effective in facilitating a design process within the learning factory. The case study conducted at the University of Twente demonstrated the ability of the design guide to support decision making and increase development efficiency. The case study successfully applied the framework and methods of the design guide, resulting in the development of specifications for concept selection, target groups and two educational modules. The guiding principle of the design guide provides a clear and structured approach that guides the decision-making processes and generates lists of requirements across different dimensions of the learning factory.

The framework of the design guide proved useful in providing an overview of the design elements and their relationships. Although not used extensively in the case study, the framework highlighted the interfaces between design elements and could be valuable in developing additional elements in larger learning factory projects. Further evaluation of the framework is recommended to assess its effectiveness in broader scenarios.

The methods within the design guide were effective in guiding decision making, providing step-by-step processes and practical guidance. They provided clear and structured results that could easily be used as input for other methods. However, further testing with developers from different backgrounds is needed to fully evaluate the usability of the methods. Moreover, some methods were too detailed for the specific stage of the development process. This suggest the need for different versions of the design guide for different stages of learning factory development, leading to an adaptable design guide to the stage of the learning factory.

The requirements and specification lists implemented in the proof of principle through spreadsheets facilitated clear communication and understanding of the results. The specification lists effectively documented the results of the methods, while the requirements lists were updated accordingly, resulting in comprehensive and detailed lists of requirements for each dimension. However, future iterations of the design guide should emphasise the integration and use of the requirements lists to ensure their proper use.

In conclusion, the case study was able to validate the guiding principles and initial proposal of the design guide. The current design guide provides a solid foundation for guiding the learning factory design process, through the collaboration between its principal elements working together to fulfil its primary objectives. The case study provides important insight in defining the approach for the guide's evolvement.

7

Design Guide Evolvement

This chapter begins the evolvement process of the design guide, building on the insights gained from the case study. It is based on the premise that the development of the design guide is an ongoing process: its basic structure and principles remain consistent, but it is constantly evolving through practical implementation and research. This chapter aims to begin the process of creating different versions of the design guide by presenting a design guide proposal specifically for the early stages of learning factory development.

7.1 Evolvement approach

At the start of this thesis, it was defined that the developed design guide and the proof of principle should act as foundational elements for further research and development in the field of learning factory design approaches. The existing design guide offers a foundational structure for future evolvement of the design guide, through case studies and additional research.

The previous chapter validates this approach to the design guide's evolvement. A single case study has already provided valuable insights for its development. This shows that the development of the design guide is continuous: the structure and basic principles remain the same, but the design guide evolves through practical application. This evolvement can take various directions: the design guide can expand its breadth by including multiple perspectives and aspects (design elements), and it can increase its depth by providing more guidance on more details within those design elements (methods).

The case study played a crucial role in validating the current proposal of the design guide, providing valuable insights for this evolvement process. While the current design guide provided a strong basis for guiding the design process of learning factories, the evaluation identified areas for further improvement. One particular aspect that needs attention is the level of detail of certain methods used in the proposal. Some methods were too detailed for the specific stage of the development process, suggesting the need for different versions of the design guide for different stages of learning factory development.

This requirement for multiple versions aligns with the notion that learning factory development is an ongoing process. A single version of the design guide cannot effectively support the changing needs of an efficient learning factory. This signifies the need that the design guide should be inherently adaptable to the current phase or state of the learning factory. This introduces an additional challenge to the previously mentioned directions of design guide evolvement. In addition to expanding in breadth and depth, it is imperative to explore which design elements and methods within this breadth and depth are necessary at different stages of the learning factory and how the guide can adapt accordingly. The process may begin with the creation of different versions of the design guide, tailored to specific stages in the development of the learning factory. In addition, case studies should be used to evolve the necessary breadth and depth of the design guide to meet the needs of each stage of development. In addition, research should explore how the design guide can adapt itself to the different needs and stages of individual projects. To facilitate the evolvement process of the design guide, it is essential to conduct case studies of different learning factory concepts, at different stages. Chapter 10 provides a more detailed explanation of the approach to conducting these case studies.

7.1.1 Early-stage design guide approach

This chapter aims to start the process of the creation of different versions of the design guide, tailored to specific stages in the development of the learning factory. This is done by introducing a proposal of the design guide specifically designed for the early stages of learning factory development. This version will focus primarily on generating a basic idea of the learning factory, outlining its conceptual design, and identifying the resources needed for the development process of that particular learning factory.

By providing a clear starting point and guiding initial ideation and resource planning, this early-stage version of the design guide would facilitate a more structured and informed approach to the multi-perspective nature of learning factory development. In the more general context of this thesis, an early-stage version of the design guide can support more accessible case studies of new learning factory projects.

To develop the early-stage version of the design guide, the first step is to extract what outputs the design guide should produce, to determine the goal of the early-stage version. The next step is to determine how the current components of the design guide will be used in this version. A draft of the early-stage framework is then produced, incorporating the necessary adjustments based on the intended focus and requirements of the early stages of learning factory development. It is important to note that this chapter focuses on presenting a draft framework rather than the methods within the design guide. Subsection 7.2.2 describes the main idea behind the methods and illustrates it using a previously created method. This shows how the methods can be iterated and demonstrates their intended function within the design guide.

7.2 Early-stage design guide

The version for the early development of learning factories is build on the current proposal of the design guide, complementing it rather than replacing it. The elements tthat collaborate within the design guide, namely the framework, the methods, and the lists of requirements and specifications, should be present in this version as their collaboration has proven to be effective in the case study. However, adjustments need to be made to these components to reflect the different level of detail required in the early stages.

The main objective of this version of the design guide for early stage learning factory development is to generate a basic idea of the learning factory. In order to achieve this, the design guide should help to create a general definition for each dimension of the learning factory.

The design guide uses a list of requirements as an essential part of its functioning. In this version, a first version of the requirements list for each dimension should serve as a crucial output. These requirement lists capture the essential criteria and specifications needed to design the learning factory in its initial stages. By focusing on the development of requirement lists, the design guide should be able to provide a structured and tangible output that allows stakeholders to clearly define the basic elements and parameters of the learning factory design.

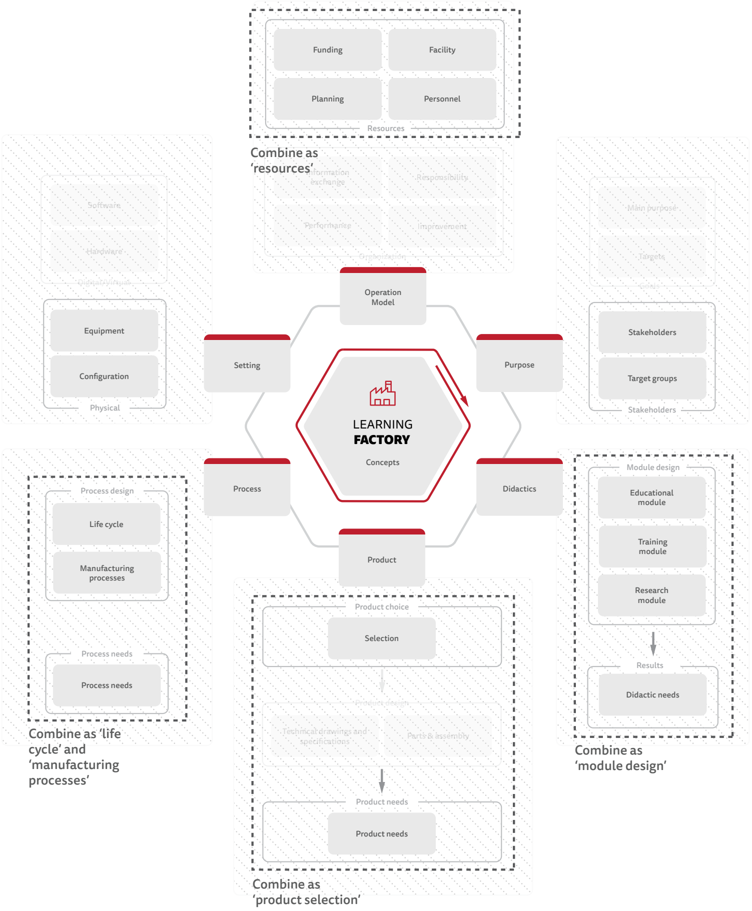


Figure 45 Representation of the included and excluded methods from the framework.

7.2.1 Early-stage framework

Firstly, the foundation of the framework, which includes design dimensions and design elements, can still be used. In this version of the framework for the early stages of learning factory development, certain design elements that are not essential for defining a basic idea of the learning factory are deliberately removed. This can be seen in Figure 46. As the focus of the early stages is on generating a preliminary concept, the framework is simplified by removing unnecessary design elements. This streamlined framework allows for a more efficient and focused approach to shaping the initial idea of the learning factory without unnecessary complexity. Due to this, the design elements do not need to be placed in areas as the amount of the design elements is significantly reduced.

The previous framework was designed to visually represent a continuous and non-linear process without prescribing a strict starting or ending point. However, the establishment of a basic idea of a learning factory in the early stages tends can follow a more linear process, as it requires less back-and-forth due to the limited details within methods. Therefore, the framework in this version should also reflect a more linear progression.

In addition, in the case study the interfaces between design elements were not consulted often as the methods themselves provided sufficient guidance on the relationships between design elements and indicated the necessary inputs from other elements. In the more linear framework of the design guide version, it is not necessary to visualise these interfaces.

By adapting the framework of the design guide version for the early stages of learning factory development to better reflect the linear nature of the early stages, and by removing the visualisation of interfaces, the framework can provide a more streamlined and focused overview for generating a basic idea of a learning factory.

7.2.2 Early-stage methods

In this version of the methods of the design guide for the early development of learning factories, certain changes are made while retaining their effective aspects. The function and idea of the methods, as well as the graphic design, remain unchanged. The main change is to reduce the number of methods. It has already been mentioned in the framework that the framework will be simplified by removing unnecessary design elements. Additionally, this process adds onto this by condensing the methods for each design element into a single 'exploration' method, rather than having multiple methods for each design element to create a detailed design.

This approach is inspired by the first version of the design guide presented in chapter 5, in the design element of the educational module. In this design element, several methods are provided, including an exploration method. The exploration method proved to be valuable as it generated substantial information that could be used for decision making in other design elements, even without the need for specific details through other methods on aspects such as the evaluation of the educational module.

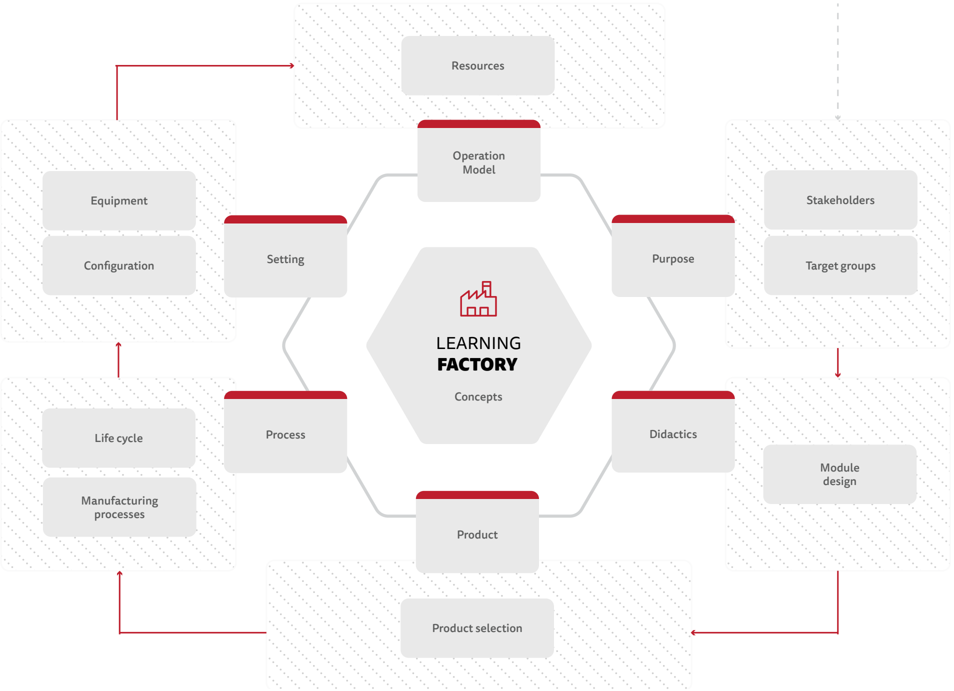


Figure 46 Evolvement of the framework in the design guide for early-stage development.

A similar approach can be applied to other design elements. This allows for a more streamlined and efficient early stage development process where the focus is on exploring and gathering essential information without the need for extensive detailed designs at this stage. By utilising the insights gained from the exploration method, decisions in various design elements can be made more informed and effective.

The specification and requirements lists within the methods of the initial proposal are crucial components. The main output in this early-stage version of the design guide are the requirement lists for each dimension, that allows stakeholders to clearly define the basic elements and parameters of the learning factory design. In this version of the design guide, both the requirement lists and specification lists will remain unchanged from the proposal implementation.

7.3 Chapter conclusion

The initial proposal for the design guide lays the foundation for its further development. While maintaining its core structure and principles, the design guide should evolve and adapt through practical use. This evolvement can take several forms: broadening its scope by including different perspectives and aspects (design elements) and deepening its content by providing more detailed guidance within these design elements (methods).

Through the case study, it was recognised that single version of the design guide cannot effectively support the changing needs of an effective learning factory. It is therefore essential that the design guide is inherently adaptable to the current phase or state of the learning factory. Therefore, it is crucial to explore which design elements and methods are needed at different stages of the learning factory and how the design guide can adapt accordingly. This process begins with the creation of different versions of the design guide, tailored to specific stages in the development of the learning factory.

This chapter initiates the development of these different versions of the guide, starting with one designed for the early stages of learning factory development. This early version focuses on conceptualising the learning factory, outlining its basic design and identifying the resources needed to develop it.

The creation of this version involves adjustments to the framework, methods and lists of requirements and specifications. In the framework, unnecessary design elements are removed to simplify the process and reflect the linear progression of the early stages. The visual representation of interfaces between design elements are also removed. These changes result in a streamlined and focused framework that helps to create a basic understanding of the learning factory.

The number of methods is reduced by combining them into a single 'exploration' method for each design element. This approach promotes efficiency during the early stages of the development process where the focus is on exploration and gathering essential information rather than detailed design. The specification and requirements lists within the methods remain unchanged and serve as critical components, providing stakeholders with a clear output of definitions and parameters for the design of the learning factory.

Overall, the development of the design guide follows a continuous approach, maintaining its core structure and principles while evolving through practical application. While the design guide may not yet be ready for full practical use, this continuous approach outlines the method for its future development, allowing for continuous refinement.

Part IV

Conclusions

8

Conclusion

What are the foundational concepts and principles related to learning factories?

Exploring the basic principles associated with learning factories provides valuable insights into the design and implementation of these educational environments. Learning factories are facilities that replicate elements of a real manufacturing environment, specifically tailored for learning purposes. The integration of technical and educational aspects is at the core of learning factories, aiming to create a comprehensive and unified learning experience. The concept of learning factories places a strong emphasis on experiential and problem-based learning, incorporating different approaches such as non-formal, work-based and active learning. Educational concepts and didactics play a crucial role in their design and implementation, with constructive alignment being an important principle. Addressing the individual potential and limitations of learning factories is also essential to fully realise their effectiveness and optimise their implementation.

What is the current state of learning factories and existing design approaches?

The current implementation of proposed concepts and strategies to overcome constraints in the existing learning factory landscape falls shorts. The overall application of unique strategies to overcome constraints is inadequate, even though these are essential to address limitations and maximise potential. Moreover, design approaches do not contribute enough to recognising and overcoming limitations, as they do not guide the alignment of multiple perspectives, do not provide adequate guidance, and focus primarily on initial design rather than continuous and non-linear development. Nor do they help to effectively identify and address personal limitations or optimise potential through tailored solutions for individual learning factory contexts. To realize their full potential of effective learning, a multi-perspective, continuous and non-linear design guide is essential.

What are the essential requirements and characteristics that need to be considered in the development of the design guide?

The development of the design guide for an effective learning factory requires careful consideration of various essential requirements and characteristics. The requirements of an effective learning factory are important to take into account in the design guide, as it should aid in the development of such a factory. The main requirements of the design guide are based on this description of an effective learning factory. The design guide should be able to provide a comprehensive overview of the design dimensions of the learning factory, support systematic decision-making processes, and ensure visibility and traceability of the design process and its outcomes. In addition, usability requirements are essential to make the design guide accessible and practical for users with different levels of knowledge, while dimensional requirements are the basis for the structure for the design guide. The design guide's key requirements have been carefully analyzed and integrated to form its foundation. It includes a graphical framework to encompass all design dimensions, along with methods for systematic decision making within each dimension. Requirement lists provide a basis for decision making, and interfaces ensure alignment with design objectives. Visibility and traceability are enhanced through process documentation and specification lists. The guide also offers guidance for implementing constraint-addressing concepts, usability considerations, clear instructions, and layered information presentation for user engagement and focus.

How are the key components of the design guide structured?

The key components of the design guide are structured in a systematic and comprehensive manner. The design guide has two main components: a framework and methods. These components, together with the requirements and specifications lists form the central principle of the design guide. This principle is built on the collaboration of these elements. Together, these components aim to provide a multi-perspective, continuous and non-linear approach to learning factory development. The framework acts as a structured organisational system that visually represents the design dimensions, areas and elements of an effective learning factory. It provides a clear and logical backbone for decision making and helps designers to understand the overall structure and organisation of the learning factory design. Interfaces within the framework illustrate the connections and interactions between design elements. The methods provide a systematic approach to designing specific elements within the framework, offering step-by-step instructions and guidance. Requirements and specification lists play a crucial role in guiding decision making and ensuring effective communication. They outline essential criteria and specifications, providing a basis for decision making and alignment with desired outcomes.

How effective is the current proposal of the design guide in facilitating the design process of learning factories?

A case study conducted at the University of Twente demonstrated the ability of the design guide to support decision making and increase development efficiency. The framework provided an overview of the design elements and their relationships, while the methods provided clear and structured processes for decision making. The requirements and specification lists facilitated clear communication and understanding of the results. The current design guide provides a solid foundation for guiding the learning factory design process, through the collaboration between its principal elements working together to fulfil its primary objectives. Further evaluation and refinement of the design guide is recommended to assess its effectiveness in broader scenarios and to ensure usability for developers from different backgrounds.

How can the design guide be improved to enhance its effectiveness in supporting the design process of learning factories?

The initial proposal for a design guide for learning factories provides a strong basis for guiding the design process. While maintaining its core structure and principles, the guide should be adapted through practical use, with possible changes including broadening its scope and deepening its content within different design elements (methods). It's important to explore which design elements and methods are needed at different stages of the learning factory and how the guide can adapt. This process begins with the creation of different versions of the guide, starting with one for the early stages of learning factory development. This early version focuses on conceptualising the learning factory, outlining its basic design and identifying resource requirements. It streamlines the framework by removing unnecessary elements and consolidating methods into a single 'exploration' method per design element. The specification and requirements lists remain unchanged to provide clarity for stakeholders. Overall, the development of the design guide follows a continuous approach, preserving its core structure and principles while evolving through practical application.

How can the development of effective learning factories be promoted and enhanced by a multi-perspective design guide?

The design of learning factories is complex, requiring the proper integration of different perspectives (such as education and technology) to meet unique learning objectives, while remaining adaptable to evolving technologies and emerging challenges. Despite their potential, current implementations of learning factories often face limitations that hinder their primary goal: effective learning. The development of a multi-perspective, continuous and non-linear design guide should ensure that learning factories fulfil this primary purpose. Such a design guide provides systematic, coherent design guidance and ongoing decision support, while aligning all aspects. It helps to identify and address personal limitations and optimise potential through tailored, unique solutions for individual learning factory contexts. The design guide should adopt a continuous approach with practical application to ensure its evolvement: providing a flexible approach to creating effective learning factories that can adapt and expand in response to the ever-changing landscape of education and technology.

9

Reflection

Learning factories, which replicate real industrial environments for educational purposes, have attracted attention for their potential to enhance learning, problem solving and critical thinking in the manufacturing sector. The complex nature of learning factory design requires the seamless integration of different perspectives, such as education and technology, to achieve specific learning objectives while remaining adaptable to evolving technologies and emerging challenges. However, despite their promise, existing implementations of learning factories often face limitations that hinder effective learning outcomes. This indicated at need for a strong design approach capable of addressing the inherent complexities, adaptability requirements and limitations associated with these educational environments.

The primary objective of this thesis was to address the design and implementation of effective learning factories by initiating the development of a multi-perspective, continuous and non-linear design guide. This endeavour began with a comprehensive analysis of the learning factory concept and an examination of the current state of learning factories and design methodologies. From this, the basic structure of the design guide was formulated and a preliminary design guide proposal was put forward. To validate the guiding principles and the initial design guide proposal, a small-scale case study was conducted, which provided valuable insights for ongoing evolvement. Building on the insights gained from the case study, the evolvement process of the design guide is started by introducing a proposal of the design guide specifically designed for the early stages of learning factory development.

In the course of this work, some interesting findings emerged that impacted results of this research.

In exploring the fundamental principles that underpin learning factories, a key concept that emerged was constructive alignment. This concept, which intentionally aligns learning outcomes, teaching and learning activities, and assessment processes, ensures a coherent and cohesive learning experience. In the context of learning factories, constructive alignment must also include the integration of competences and ensure that learning activities are well suited to the learning environment of the factory. Interestingly, although the idea of aligning the learning factory environment with educational goals has been used in previous design approaches, the concept of constructive alignment has not been associated with it. Constructive alignment played a key role in the multi-perspective approach within the design guide, starting from an educational standpoint and adapting the rest of the learning factory accordingly.

While theoretical potentials and general limitations within the learning factory landscape had previously been identified, this work underlined the significant impact of the unique context of each learning factory implementation on both potentials and limitations. This highlighted the importance of adopting a non-linear and continuous approach that focuses on recognising and addressing limitations while maximising potentials. It became clear that it is crucial to consider different variations of the learning factory concept in order to address the specific needs of individual cases. This led to a focus on alternative approaches to mitigating limitations, which served as a valuable starting point for providing tailored solutions within the design guide for individual learning factories.

Through a systematic approach, essential requirements and characteristics were delineated to guide the development of the design guide and establish its fundamental principles. Collaboration between various elements, including a framework and methods, emerged as a central principle of the design guide, working in tandem to fulfil its primary objectives. A small case study was used to validate the guiding principle and the initial design guide proposal, with interesting results. While the current design guide provided a solid foundation for guiding the learning factory design process, the case study proved instrumental in defining the approach for the guide's ongoing development. It underscored the notion that the design guide is a dynamic entity that retains its structural integrity and core principles while evolving through practical application. This evolvement can take several paths: broadening its scope by including different perspectives and facets (design elements) and deepening its guidance by delving into finer details within these design elements (methods). Furthermore, the importance of the adaptability of the design guide to the specific phase or state of the learning factory was highlighted.

At its core, the thesis offers a proposal that lays the groundwork for a design guide for effective learning factories. While this proposal is a promising starting point, it's important to acknowledge that in its current form the guide is not fully equipped for immediate practical application in the development of effective learning factories. The complexity and multifaceted nature of these learning environments require a more comprehensive and refined set of tools. Nevertheless, the central principle of the design guide, which emphasises the collaboration of different elements, has great potential for achieving its main objectives. This principle provides a comprehensive and coherent approach to the design of learning factories, facilitating the development of efficient and effective learning environments.

Interestingly, the conclusions drawn regarding the further development of the design guide may be as important as the main output of the design guide of this thesis. While the design guide itself isn't yet ready for full practical application, the evolvement approach outlines a method for its future development. This continuous approach is intended to allow the design guide to be constantly refined.

In essence, the findings of the thesis, including the design guide proposal and insights into its future development, provide a robust starting point for the evolvement of the design guide. Together, they aim to create an evolved design guide that not only contributes to effective learning factory design, but also provides a flexible approach that can adapt and expand in response to the ever-changing landscape of education and technology.

10

Recommendations

This thesis has explored the implementation of a multi-perspective design guide for effective learning factories. However, due to the limited scope of this research, this thesis intended to develop a design guide and provide a proof of principle that act as foundational elements for further research and development in the field of learning factory design. The existing design guide offers a foundational structure for future evolvement on the content of the design guide, through case studies and additional research. As a result, this thesis presents recommendations for the further development of the design guide. The recommendations can be categorised into three categories: the first focuses on research into existing learning factories, the second relates to the evolvement of the design guide, while the third focuses specifically on recommendations for additional case studies.

Research existing learning factories

As mentioned in Chapter 3, it is recommended to carry out a thorough study of existing learning factories, which the aim of serving several purposes.

Firstly, this research aims to verify the conclusions drawn from the systematic analysis of learning factories. Although Tisch & Metternich (2017) previously identified the limitations, it is important to assess whether the current landscape of learning factories still reflects the identified limitations and findings. This review process will ensure the validity and relevance of the conclusions drawn based on the current landscape of learning factories.

In addition, research should focus on understanding the impact of the concepts and methods to overcome limitations implemented in learning factories. At present, the impacts used in this thesis are based on logical reasoning, but gathering actual evidence of the impact of the concepts is crucial. This includes, for example, gathering more specific data on the financial resource requirements of the concepts and obtaining evidence of their positive influence on effectiveness. This will further validate the integration of these concepts and methods into the design guide, whilst the content of the design guide will benefit from more quantified input.

In addition, a comprehensive study of the designs of individual learning factories and their development approaches is highly recommended. This research will provide valuable insights into best practices and design elements that are crucial for the design guide. The experience of learning factories in operation will help to incorporate important design elements that may not be present in current design approaches. This will enable the storage of tacit knowledge specific to learning factory development, thereby enhancing the effectiveness of the design guide.

Evolvement design guide

At the start of this thesis, it was defined that the developed design guide and the proof of principle should act as foundational elements for further research and development in the field of learning factory design approaches. The existing design guide offers a foundational structure for future evolvement of the design guide. This section presents recommendations on how to approach this evolvement, and gives suggestions of areas to explore for this evolvement.

Chapter 7 previously illustrated the dynamic evolvement of the design guide. This evolvement shows that the design guide remains structurally sound and adheres to its core principles while adapting through practical use. This adaptation includes broadening its scope by considering multiple perspectives and aspects, and deepening its content. Furthermore, given the need for adaptability to different stages of the learning factory process, it is crucial to assess which design elements and methods are relevant at different stages and to explore how the design guide can automatically adapt to the stage of the learning factory. To facilitate this development, additional research on existing learning factories, design approaches and case studies is recommended.

Priority should be given to the development of an early stage design guide for learning factory development. A more advanced version of this guide, equipped to effectively support early-stage development and lay the foundations for learning factory design, would be highly beneficial. This enhanced guide would be valuable for conducting case studies of new learning factory projects, allowing its principles to be validated and verified through real-world application. This would allow an assessment of its effectiveness, applicability to different scenarios and usability. To make this version suitable for these purposes, it should be extended and deepened as necessary. This may include adding essential design elements and creating exploration methods to facilitate early stage development. Incorporating design suggestions based on existing learning factory solutions, such as creating a database of such products, could be a valuable addition. In addition, drawing inspiration from successful design approaches from relevant contexts, especially for technical dimensions such as the environment, can enrich the design guide with established best practices.

While the process starts with the creation of different stage versions of the design guide, the ultimate goal is to make the design guide inherently adaptable to the current phase of the learning factory. This inherent adaptability is essential to the evolvement of the guide. While different stage versions help to validate the breadth and depth of the guide, the guide should adapt organically based on what is specified within it. This may involve adding methods within a design element after certain elements have been specified, or expanding design elements after others have been specified. Case studies can play a crucial role in finding and testing these relationships for adaptability.

Currently, the design guide exists in a variety of document-based formats. However, further research is needed to determine the most effective format for supporting the development of learning factories. Challenges such as translating between dimensions, managing specifications and requirements, and adapting the guide according to the stage of development highlight the limitations of the document-based format. It is therefore necessary to explore alternative options, such as the development of an online tool, to improve the usability and practicality of the design guide. An online tool is proposed as it can provide interactive and automated features, streamlining dimension translation, specification management and dynamic adaptation based on the progress of the learning factory. By considering different formats and the potential benefits of an online tool, the design guide can become more accessible, user-friendly and efficient in supporting the development of the learning factory.

Case studies

Previous recommendations for the development of the design guide have emphasised the importance of using case studies. The design guide, which remains structurally sound and true to its core principles while evolving through practical application, relies heavily on these case studies for its development.

Case studies serve several important purposes in this process. They should extend the scope and depth of the design guide at each stage of the learning factory process, validate its core principles, test different versions of the guide for usability and explore its adaptability. To fully exploit the potential of the design guide's continuous development through practical application, these case studies need to include different learning factory projects from different contexts and stages.

As suggested earlier, it is advisable to start by extending the early version of the design guide for evaluation in case studies. This early-stage version provides an opportunity to validate the guide using smaller, more manageable case studies. Early-stage learning factory development projects are often less resource-intensive and have fewer constraints, making them suitable for building confidence in the core principles and basic structure of the design guide before moving on to larger case study projects.

During the entire evolvement of the design guide, it is important to conduct case studies on a variety of learning factory projects from different contexts and stages to facilitate the evolvement and research the needed adaptability of the design guide. This approach allows for thorough testing and ensures the applicability of the guide to a wide range of scenarios. This involves conducting case studies on learning factories that are in different stages of development, located in various countries, serving different purposes, and focusing on different topics.

When conducting these case studies for any purpose, it's crucial to minimise expert intervention to simulate real-world conditions and to assess whether the guide is performing as intended. To achieve this, it is essential to involve developers with different backgrounds, knowledge levels and working on different topics within the case studies. This diversity ensures a more accurate representation of the target users and the different contexts in which the design guide will be used. By involving developers with different perspectives and expertise, the effectiveness and adaptability of the design guide can be comprehensively assessed and improved. In addition, this approach allows for ongoing evaluation of the usability of the guide throughout its development process.

In summary, these recommendations serve as a starting point for maximising the potential of the design guide in supporting effective learning factories. It is important to note that this thesis represents only the beginning of the development of the design guide, and there are potentially numerous additional areas to explore and refine.

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DEVELOPING A MULTI-PERSPECTIVE DESIGN GUIDE FOR EFFECTIVE LEARNING FACTORIES

APPENDICES

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APPENDICES

JANNEKE MASSA

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List of AI tools utilised

During the preparation of this work the author used ***ChatGPT*** *and* ***DeepL Write*** *in order to provide inspiration for improved formulation of own content, with the aim of enhancing the overall quality of the writing. After using these tools/services, the author reviewed and edited the content as needed and takes full responsibility for the content of the work.*

During the preparation of this work the author used ***Bing Image Creator*** *in order to generate an image, serving as the foundation for the visuals featured on the front page and in the introduction sections. After using this tool/service, the author reviewed and edited the content as needed and takes full responsibility for the content of the work.*

A

History of learning factories

Appendix A History of learning factories

A. History of learning factories

In order to gain a better understanding of learning factories, it is important to examine and comprehend the evolutionary trajectory and developmental process of the learning factory paradigm, as well as situating the concept within its wider historical context of work-related learning.

A.1 History of work-related learning

For centuries, work-related learning has played an integral role in daily life. Prior to the Industrial Revolution, individuals acquired skills and knowledge predominantly through apprenticeships, which involved working under the tutelage of a master craftsman. This Master-Apprentice model developed during the Middle Ages, when the guild system provided a structured approach to ensure the quality of work produced by its members. In the model, an apprentice acquires necessary knowledge and skills through observation and experience. It is known to be effective in the transfer of tacit knowledge, due to its context-specific and social nature (Kurti, 2011).

However, the Industrial Revolution marked a significant turning point in the evolution of work-related learning. With the emergence of mass production and factory work, the apprenticeship model lost its popularity. Formal and vocational education, detached from the work-area, replaced the previous methods of learning. Due to inconsistencies in the learning experience and workplace requirements, negative effects such as learning and motivation problems, increased learning costs, and extended training periods emerged.

The detachment of the learning experience from the workplace persisted until a few key concepts were established to bring learning processes back into closer alignment with working processes. This transition began with the implementation of systematic quality systems in Japan during the 1960s, which resulted in the formation of quality circles - groups of employees who address and resolve work-related issues. In the 1970s, language barriers and the necessity of transferring specialized knowledge in German companies caused the development of Lernstatt, an operationally focused form of learning. In the 1980s, the disparity between training situations and real-world scenarios was slowly starting to be recognized, as well as extra needs due to increasingly complex production environments. This shift in learning was facilitated by the introduction of new information and communication technologies, leading to the development of improved learning situations.

These concepts laid the foundation for new theoretical learning approaches in the early 1990s, which emphasized the importance of situating learning within context and circumstance, utilizing realistic and authentic learning tasks and problems. These theoretical learning approaches were instrumental in enabling the development of novel learning concepts, such as the first learning factories.

A.2 Development of learning factories

With the development of novel learning concepts in the 1990s, the development and evolution of the learning factory concept took off. The historical development of the learning factory concept has previously been described by Abele et al. (2019) in three phases.

In the first phase, local learning factories were established primarily in the United States, such as the Bernard M. Gordon Learning Factory at Penn State University. This facility was developed in 1994 with a grant from the National Science Foundation and has since completed numerous design projects sponsored by industry partners (PSU, 2022). Additionally, a more industry-directed “Lernfabrik” was established at the IAO in Stuttgart, Germany in the late 1980s, which aimed to qualify industrial personnel in computer-integrated manufacturing (Reith, 1988). Another concept, the Teaching Factory, emerged at the turn of the millennium and attracted interest primarily in the United States, with pilot activities addressing both educational and business purposes. Even though it was named ''teaching factory'' instead of ''learning factory'', the two methods are very similar. The concept of the Teaching Factory originated from the medical industry, particularly from Teaching Hospitals, which serve as a model where medical schools collaborate with hospitals to provide practical training and real-life hospital experience to students (Alptekin et al., 2001).

The second phase, which took place predominantly in Europe approximately a decade ago, saw the implementation of the learning factory concept in a wide range of applications, industries, and target groups (Abele et al., 2015). One of the first learning factories of this wave was the Process Learning Factory CiP in TU Darmstadt, which was inaugurated in 2007. The Process Learning Factory includes machining, manual and semi-automatic assembly, as well as integrated functions of logistics and quality assurance. The facility provides an environment where lean manufacturing and Industrie 4.0 can be experienced and learned to ensure a sustainable transfer of knowledge (TUD, n.d.).

In the third phase, which began in 2011, a group of European academic learning factory operators founded the Initiative on European Learning Factories (IELF) during the “1st Conference on Learning Factories” in Darmstadt. The aim was to start joint research projects, make the learning factory concept known worldwide, and improve it together. In 2016, the IELF was renamed the “International Association of Learning Factories”. As a result of these activities, a joint Europe-wide collaboration was established, and conferences on Learning Factories have been held in various locations since 2012. Since 2015, the conference has been CIRP-sponsored, indicating the growing importance of learning factories in manufacturing research. In addition, the Network of Innovative Learning Factories (NIL) was established to enhance the quality of existing and future Learning Factories, supported by the German Academic Exchange Service (DAAD) and the Federal Ministry of Education and Research (BMBF) (IALF, 2021).

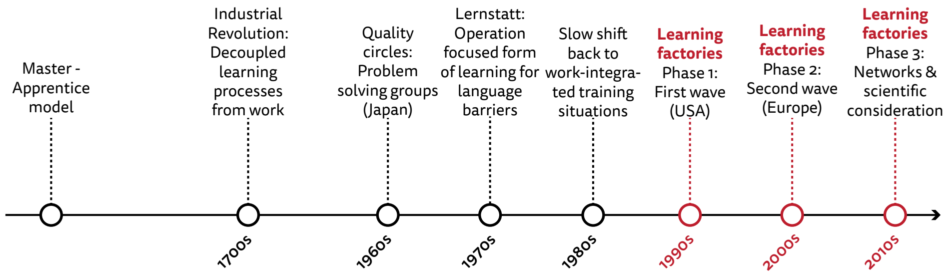


Figure 2.x. Historical development of work-related learning and learning factories

B

Learning factory landscape analysis

Appendix B Learning factory landscape analysis

B. Learning factory landscape analysis

B.1 Keywords per concept

Physical:

» When there is a physical factory environment present in the Learning Factory.

» Keywords: physical, machine(s), equipment, industrial equipment, machinery

Digital

» When a Learning Factory concept has a digital learning environment instead of alongside a physical learning environment through the implementation of software tools.

» Keywords: software, digital extension, digital learning environment, digital model, data, PLM, ERP, PPS, MRP, SPS, MES, BDE, CAE/CAD, etc.

Virtual

» Virtual learning factories use virtual or augmented reality tools for visualization of digital operations simulations at factory level, this way, virtual process and layout planning, simulation of tasks and the evaluation of alternative factory designs before start of production is enabled

» Keywords: virtual, augmented reality, VR, AR, XR, simulation

Model scale

» When the LF is utilized with scaled-down or model scale replicas of original factory equipment within the physical factory environment.

» Keywords: model scale, scaled down, Festo Didactic

Physically mobile

» When the physical factory environment has the complete ability to easily move to different locations by being physically mobile.

» Keywords: physically mobile, location independent, mobile equipment

Low-cost

» When the Learning Factory uses low-cost methods of representing a realistic factory environment, by focusing on mapping cost-effective productoin processes (such as assembly and logistics), the use of learnstruments, and/or the use of simulation games (such as LEGO building blocks).

» Keywords: low-cost, low financial resources, cost-effective, learnstruments, simulation games, LEGO.

Use of e-Learning, Multimedia and ICT

» When the Learning Factory is supported by digital devices, by using e-learning, multimedia, and/or ICT.

» Keywords: e-learning, multimedia, ICT, digital tools, device, screen

Real production

» When the Learning Factory manufactures actual goods available for order or for the market.

» Keywords: real production, market offering

Remotely accessible

» When a physical factory environment is accessible from remote locations, by providing remote control, visualizations (for instance by live streaming footage), and/or real-time data.

» Keywords: remote-control, remote learning environment, remote learning, co-vid-19, pandemic, live streaming

Systematic design method

» When the Learning Factory has utilized an existing design method or listed a new systematic approach involving both technical and didactical aspects to achieve organisational and learning targets of learning factories (COPIED).

» Keywords: design, approach, method, framework, systematic

Turnkey LF

» When (a part of) the Learning Factory is a replication of (an) existing learning factory/factories.

» Keywords: turnkey, replica, clone

Learning success measurement

» When methods of learning success measurement are implemented in the functioning of the Learning Factory.

» Key words: learning success, evaluation, successfulness, effectiveness, performance, questionnaire, survey, feedback

Quality system

» When a systematic approach is implemented for assessing current state of the Learning Factory, the potential for improvement in relation to the target state and for deriving improvement measures.

» Keywords: quality system, maturity model, quality standards, CMM, CMMI, EFQM

B.2 Spreadsheet learning factory landscape

Name	Operator & location	Country	Product	Purpose	Industry	Learning subjects	Physical	Digital	Virtual	Model scale	Physically mobile	Low-cost	Use of e-learning, ICT & multimedia	Real production	Remotely accessible	Systematic design method	Turnkey LF	Learning success measurement	Quality system	TOTAL CONCEPTS	Reference
AAU Smart Production Labaratory	DMP, Aalborg University	Denmark	Electric product	Education, Training	Manufacturing Engineering	Industry 4.0, Smart production		×		×										2/12	Madsen & Møller, 2017
Additive Manufacturing Model Factory	Friedrich Alexander Universität Erlangen-Nürnberg, McKinsev	Germany	Various products	Training, Research	Manufacturing Engineering	Additive Manufacturing	×													0/12	Yoo et al., 2016
Advanced Manufacturing Technology Center (AMTC)	Tongji University	China	5G adapter	Education, Research	Manufacturing Engineering	Industry 4.0	×	×					×							2/12	Zhang et al., 2020
AllFactory	University of Alberta	Canada	Lego based 3D printing machine	Education, Training, Research	Manufacturing Engineering	Lean production, Industry 4.0	×					×								1/12	Ahmad et al., 2018
Anglo American Training Center	Anglo American, Johannesburg	South Africa	Not stated	Training	Mining Engineering	Lean production, Business improvement	×											×		1/12	Makumbe et al., 2018
Aquaponics 4.0 Learning Factory	University of Alberta	Canada	Crops	Education, Training, Research	Bio Engineering	Industry 4.0, Resource and Energy Efficiency, Digital Twin, Robotics	×	×					×							2/12	Martinez & Ahmad, 2021
AutFab	University of AS Darmstadt	Germany	Relay	Education, Training, Research	Manufacturing Engineering	Industry 4.0, IoT	×	×	×	×										3/12	Simons et al., 2017
Bernard M. Gordon Learning Factory	Penn State University	United States of America	Various products	Education	Manufacturing Engineering	Product development, Industrial Engineering	×													0/12	PSU, 2022
BERTHA	Bremen Institute for Mechanical Engineering	Germany	Bulky assembly products	Education, Training, Research	Manufacturing Engineering	Manual Assembly	×			×								×		2/12	Schreiber et al., 2016
CubeFactory	TU Berlin (no fixed location)	Germany	Various products	Training	Manufacturing Engineering	Additive Manufacturing, Resource and Energy Efficiency	×	×		×	×	×	×							5/12	Muschard & Seliger, 2015
Cyber-Physical Learning Factory	Norwegian University of Science and Technology	Norway	Roller ski, skate	Education, Research	Manufacturing Engineering	Industry 4.0, Cyber Physical Production systems	×	×		×										2/12	NTNU, n.d.
DFA Demofabrik Aachen	RWTH Aachen	Germany	E-Mobility vehicles	Training, Research	Manufacturing Engineering	Industry 4.0, Prototyping, Industrialization	×	×					×	×						3/12	Schuh et al., 2015 + Abele 2018
Die Lernfabrik	TU Braunschweig	Germany	Various products	Education, Training, Research	Manufacturing Engineering	Resource and Energy Efficiency, Industry 4.0, Urban production	×	×	×	×								×		4/12	Blume et al., 2015
Digital Capability Center Aachen / Textile Model Factory 4.0	McKinsey & ITA Acedemy Aachen	Germany	Wristband	Training, Research	Textile Engineering	Lean production, Digital manufacturing, Quality management, Leadership development, Industry 4.0	×	×					×		×					3/12	Küsters et al., 2017
Digital Capability Center Atlanta	McKinsey Atlanta	United States of America	Product–refrigerator compressors	Training, Research	Manufacturing Engineering	Lean production, Digital manufacturing, Resource and Energy Efficiency	×	×					×		×					3/12	McKinsey, 2023
Digital Capability Center Beijing	McKinsey Bejing & Tsinghua University	China	Gearbox	Training, Research	Manufacturing Engineering	Lean production, Digital manufacturing	×	×					×							2/12	McKinsey, 2023

Figure B.1. Learning factory landscape spreadsheet, A-D

Name	Operator & location	Country	Product	Purpose	Industry	Learning subjects	Physical	Digital	Virtual	Model scale	Physically mobile	Low-cost	Use of e-learning, ICT & multimedia	Real production	Remotely accessible	Systematic design method	Turnkey LF	Learning success measurement	Quality system	TOTAL CONCEPTS	Reference
Digital Capability Center Gurugram	McKinsey Gurugram	India	Not stated	Training, Research	Manufacturing Engineering	Lean production, Digital manufacturing	X	X												1/12	McKinsey, 2023
Digital Capability Center Istanbul	McKinsey Istanbul	Turkey	Not stated	Training, Research	Manufacturing Engineering	Lean production, Digital manufacturing	X	X												1/12	McKinsey, 2023
Digital Capability Center Jakarta	McKinsey Jakarta	Indonesia	Gearbox	Training, Research	Manufacturing Engineering	Lean production, Digital manufacturing	X	X					X							2/12	McKinsey, 2023
Digital Capability Center New Jersey	McKinsey New Jersey	United States of America	Cell and gene products	Training, Research	Bio Engineering	Lean production, Digital manufacturing, Quality management, Leadership development	X	X	X				X		X					4/12	McKinsey, 2023
Digital Capability Center Salvador	McKinsey & SENAI, Salvador	Brazil	Pneumatic cylinder	Training, Research	Manufacturing Engineering	Lean production	X													0/12	McKinsey, 2023
Digital Capability Center Sao Paulo	McKinsey Sao Paulo	Brazil	Not stated	Training, Research	Manufacturing Engineering	Lean production, Digital manufacturing	X	X												1/12	McKinsey, 2023
Digital Capability Center Singapore	McKinsey & ARTC, Singapore	Singapore	Gearbox	Training, Research	Manufacturing Engineering	Digital manufacturing	X	X					X							2/12	McKinsey, 2023
Digital Capability Center Venice	McKinsey & Confindustria Alto Adriatico, Venice	Italy	Various products	Training, Research	Manufacturing Engineering	Lean production, Digital manufacturing	X	X	X				X		X					4/12	McKinsey, 2023
E | Drive-Center	Friedrich Alexander Universitat Erlangen Nurnberg	Germany	Electric motors	Education, Training, Research	Manufacturing Engineering	Production technology	X	X												1/12	Franke & Kühl, 2019
E3-Forschungsfabrik	Fraunhofer IWU, Chemnitz	Germany	Automobile doors	Research	Automotive Engineering	Industry 4.0, Resource and Energy Efficiency	X	X												1/12	Fraunhofer IWU, 2022
ESB Logistics Learning Factory	Reutlingen University ESB Business school	Germany	City scooter and Accessoires	Education, Training, Research	Manufacturing Engineering	Logistics, Product development, Industry 4.0, Digital manufacturing, Industrial Engineering	X	X	X											2/12	Hummel et al., 2019
ETA-Factory	TU, Darmstadt	Germany	Control disc for hydraulic pumps, gear shaft combination	Education, Training, Research	Manufacturing Engineering	Industry 4.0, Resource and Energy Efficiency	X	X					X							2/12	Abele et al., 2019
Experimentier und Digitalfabrik (EDF)	TU Chemnitz	Germany	Various products	Education, Training, Research	Manufacturing Engineering	Planning, Operation optimization	X	X	X				X							3/12	TU Chemnitz, 2019
Festo-Learning Factory Scharnhausen	Festo SE & Co. KG, Scharnhausen	Germany	Valves, electronics	Training, Research	Manufacturing Engineering	Lean production, Industry 4.0	X	X		X										2/12	Festo AG & Co. KG, 2015
FIM Learning Factory	Universiti Malaysia Pahang	Malaysia	Hand dryer	Education	Manufacturing Engineering	Lean production, Supply Chain and Operation Management, Flexible production	X													0/12	Maarof et al., 2019
FleXtory	University of Strassbourg	France	Not stated	Education	Manufacturing Engineering	Lean production	X	X												1/12	Marmier et al., 2021
FMS Training Center	Tampere University of Technology	Finland	Not stated	Education	Manufacturing Engineering	Automation Technology, Digital Twin	X	X	X				X							3/12	Toivonen et al., 2018

Figure B.2. Learning factory landscape spreadsheet, D-F

Name	Operator & location	Country	Product	Purpose	Industry	Learning subjects	Physical	Digital	Virtual	Model scale	Physically mobile	Low-cost	Use of e-learning, ICT & multimedia	Real production	Remotely accessible	Systematic design method	Turnkey LF	Learning success measurement	Quality system	TOTAL CONCEPTS	Reference
FSRE Learning Factory	University of Mostar	Bosnia and Herzegovina	Scissors, lifting platform	Training, Research	Manufacturing Engineering	Lean production, CAD tools, Welding	X	X												1/12	Stojkića & Bošnjak, 2019
Global Production Learning Factory	Karsruhe Institute of Technology	Germany	Electric drive	Education, Training	Manufacturing Engineering	Lean production, Industry 4.0, Industrial Engineering, Global Production, Planning	X	X	X				X							3/12	Lanza et al., 2015
Green Factory Bavaria	12 universities and Fraunhover institutes, Bavaria	Germany	Not stated	Training, Research	Manufacturing Engineering	Resource and Energy Efficiency	X	X												1/12	Green Factory, n.d.
iFactory	University of Windsor	Canada	Belt tensioner, various metal parts	Education, Training, Research	Manufacturing Engineering	Industry 4.0, Industrial Engineering, Integrated products-systems	X	X		X										2/12	Elmaraghy, 2017
IFA-Learning Factory	Leibniz Unviersity, Hannover	Germany	Helicopters and components	Education, Training, Research	Manufacturing Engineering	Planning, Lean production, Industrial Engineering	X	X	X				X							3/12	Hingst et al., 2022
Industrial Engineering Labatory	IPS, TU Dortmund	Germany	Gearbox and pump	Education	Manufacturing Engineering	Industry 4.0, Industrial Engineering	X	X	X											2/12	Steffen et al., 2012
Integrated Learning Factory	University of Washington	United States of America	Not stated	Education	Manufacturing Engineering	Product development	X													0/10	UW, 1999
Integrated Learning Factory LPE & LPS,	Ruhr University Bochum	Germany	Percussion drilling machine	Education, Research	Manufacturing Engineering	Product development, Lean production	X	X												1/12	Song et al., 2016
Intelligent Learning Factory (ILF)	Purdue University	United States of America	Not stated	Education	Manufacturing Engineering	Industry 4.0	X	X												1/12	Purdue University, 2019
ISE Learning Factory	Virginia Tech University	United States of America	Not stated	Education, Research	Manufacturing Engineering	Industry 4.0, Additive Manufacturing	X	X	X				X							3/12	Hemphill, 2022
Laboratory for flexible industrial automation	Heinz Nixdorf Institute, Unversity of Paderborn	Germany	Remote-controlled car	Education, Research	Manufacturing Engineering	Cyber Physical Production systems, Product development	X	X												1/12	Gräßler et al., 2016
LEAD Factory / LeanLab	TU Graz	Austria	Scooter	Education, Training, Research	Manufacturing Engineering	Lean production, Industry 4.0, Logistics, Product development	X	X												1/12	Karre et al., 2018
Lean Academy	Kärcher	Worldwide	Kärcher products	Training	Manufacturing Engineering	Lean production, Industry 4.0	X	X												1/12	Kärcher, 2023
Lean Laboratory	NTNU, Gjovik	Norway	Wooden house mockup	Education, Training	Manufacturing Engineering	Lean production	X	X					X					X		3/12	Tvenge et al., 2016
Lean Learning Factory	University of Split	Croatia	Not mentioned	Education, Training	Manufacturing Engineering	Lean production	X	X					X							2/12	Celar et al., 2016
Lean Learning Factory	University of Pitesti	Romania	Steering wheel	Education	Manufacturing Engineering	Lean production, Digital manufacturing, Industry 4.0	X	X												1/12	Nitu & Gavriluta, 2019
LEAN-Factory	Fraunhofer IPK, TU Berlin, ITCL	Germany	Pharmaceutical products	Education, Training	Manufacturing Engineering	Lean production, Resource and Energy Efficiency	X			X										1/12	Fraunhofer IPK, 2023

Figure B.3. Learning factory landscape spreadsheet, F-L

Name	Operator & location	Country	Product	Purpose	Industry	Learning subjects	Physical	Digital	Virtual	Model scale	Physically mobile	Low-cost	Use of e-learning, ICT & multimedia	Real production	Remotely accessible	Systematic design method	Turnkey LF	Learning success measurement	Quality system	TOTAL CONCEPTS	Reference
Learning and Innovation Factory (LIF)	TU Wien	Austria	Toy car	Education	Manufacturing Engineering	Industry 4.0, Product development, Industrial Engineering, Cyber Physical Production systems	X	X												1/12	Kemény et al., 2016
Learning Factory aIE	University of Stuttgart	Germany	Desk set	Education, Training, Research	Manufacturing Engineering	Lean production, Industrial Engineering, Quality management	X	X		X								X		3/12	Rossmeissl et al., 2019
Learning Factory at the Campus Velbert/Heiligenhaus	University of Applied Sciences, Bochum	Germany	Not mentioned	Education, Training	Manufacturing Engineering	Industry 4.0, Resource and Energy Efficiency, Automation	X	X												1/12	Faller & Feldmüller, 2015
Learning Factory for Electronics Production	FAPS, FAU Erlangen-Nürnberg	Germany	Electronic Components	Education, Training, Research	Electrical Engineering	Electronics production	X	X												1/12	Reitberger & Franke, 2019
Learning Factory JumpING	Heilbronn University of Applied Sciences	Germany	New products every semester	Education, Research	Manufacturing Engineering	Industrial Engineering, Manufacturing skills	X	X					X					X		3/12	Balve & Albert, 2015 & Balve & Albert, 2022
Lego Factory	Politecnico di Milano	Italy	No product	Education	Manufacturing Engineering	Lean production, Resource and Energy Efficiency, Digital manufacturing	X					X								1/12	Lugaresi et al., 2020
Lernfabrik für Optimale Zerspanung (LOZ)	TU München	Germany	No product	Training, Research	Manufacturing Engineering	Vibration	X	X												1/12	Kleinwort et al., 2018
Lernfabrik für Schlanke Produktion (LSP)	TU München	Germany	Gears	Education, Training	Manufacturing Engineering	Lean production, Assembly	X	X			X									2/12	Bauer et al., 2018
Lernfabrik für vernetzte Produktion (LVP)	Fraunhofer IGCV	Germany	Remote controlled cars	Training	Manufacturing Engineering	Industry 4.0, Resource and Energy Efficiency, Digital manufacturing	X	X					X							2/12	Merkel et al., 2017
Lernfabriken 4.0 in Baden-Württemberg	37 Vocational Schools Baden-Württemberg	Germany	Various products	Education	Manufacturing Engineering	Industry 4.0	X	X												1/12	ALLIANZ, 2021
LMS Factory	University of Patras	Greece	Two-speed gearbox, toy car, student formula	Education, Training, Research	Manufacturing Engineering	Industrial problems, Product development	X	X			X				X					3/12	Chryssolouris et al., 2016
LPS Learning Factory	LPS, Ruhr University Bochum	Germany	bottle-cap and bottle-cap holder, make to order products	Education, Training, Research	Manufacturing Engineering	Lean production, Industry 4.0, Industrial Engineering, Resource and Energy Efficiency	X	X												1/12	Bender et al., 2015 & Oberc et al., 2018
MAN Learning Factory	Man Diesel & Turbo SE, Berlin	Germany	Integrally geared compressor	Education, Training	Manufacturing Engineering	Assembly, Maintenance	X	X												1/12	Menn & Ulbrich, 2019
Micromanu / Stellenbosch Learning Factory	Stellenbosch University	South Africa	Toy train set	Education, Training	Manufacturing Engineering	Additive Manufacturing, Prototyping, Industrial Engineering, Quality management	X	X												1/12	Van der Merwe et al., 2016
Model Factory	SIMTech	Singapore	Not defined	Education, Training, Research	Manufacturing Engineering	Industry 4.0, Cyber Physical Production systems	X	X	X				X							3/12	SIMTech, 2022
Model Factory	University of Puerto Rico	Puerto Rico	Charger, display and driver	Education	Manufacturing Engineering	Manufacturing systems	X													0/12	RUM, n.d.

Figure B.4. Learning factory landscape spreadsheet, L-M

Name	Operator & location	Country	Product	Purpose	Industry	Learning subjects	Physical	Digital	Virtual	Model scale	Physically mobile	Low-cost	Use of e-learning, ICT & multimedia	Real production	Remotely accessible	Systematic design method	Turnkey LF	Learning success measurement	Quality system	TOTAL CONCEPTS	Reference
Move Academy	Schaeffler, Herzogenaurach	Germany	Not mentioned	Training	Manufacturing Engineering	Lean production	X						X					X		2/12	Beauvais, 2013
MPS Lernplattform	Daimler AG, Sindelfingen	Germany	Different products	Education, Training	Manufacturing Engineering	Lean production	X	X		X			X							3/12	Schwarz, 2019
MTA Sztaki Learning Factory Gyor	MTA Sztaki, Györ Hungary	Hungary	Assembled products that are dis- and re-assembled	Education, Training, Research	Manufacturing Engineering	Industry 4.0, Cyber Physical Production systems, Robotics, Planning	X	X	X											2/12	Kemény, 2018
Operational Excellence Labatory / Lean Manufacturing Labatory	Universite du Luxembourg	Luxembourg	Hole puncher	Education, Research	Manufacturing Engineering	Lean production	X													0/12	Oberhausen & Plapper, 2015
Pilot Factory Industry 4.0	TU Wien	Austria	3D printer	Training, Research	Manufacturing Engineering	Logistics, Cyber Physical Production systems	X	X												1/12	Hennig et al., 2019
Process Learning Factory CiP	TU, Darmstadt	Germany	Pneumatic cylinder	Education, Training, Research	Manufacturing Engineering	Lean production, Industry 4.0	X	X								X		X		3/12	TUD, n.d.
Product Development Process Learning Factory	University of Piracicaba	Brazil	Crosshead axis	Education	Manufacturing Engineering	Product development	X	X												1/12	Schützer et al., 2017
Railway Operation Research Center	TU Darmstadt	Germany	No product	Education, Training, Research	Railway Engineering	Railway operation	X	X												1/12	Streitzig & Oetting, 2016
SEPT Learning Factory	McMaster University, Hamilton	Canada	Various products	Education, Training, Research	Manufacturing Engineering	Industry 4.0	X	X	X				X			X				4/12	Elbestawi et al., 2018
SEW DriveAcademy	SEW Eurodrive, Bruchsal	Germany	Multiple types of drives	Training	Manufacturing Engineering	Lean production	X	X												1/12	SEW-EURODRIVE, 2012
Smart Factory MTA SZTAKI	MTA SZTAKI, Budapest	Hungary	Recyclable dummy workpieces	Education, Research	Manufacturing Engineering	Cyber Physical Production systems, Automation, Industry 4.0, Planning, Mechatronics	X	X	X	X										3/12	Kemény et al., 2016
Smart Factory-KL Industrie 4.0 production plant	TU Kaiserslautern	Germany	Various components	Research	Manufacturing Engineering	Industry 4.0, Automation, Digital manufacturing	X	X		X										2/12	SmartFactoryKL, 2018
Smart Mini Factory	Libera Universita di Bolzano	Italy	Pneumatic cylinder, camping burner	Education, Training, Research	Manufacturing Engineering	Automation, Industry 4.0, Smart production	X	X	X											2/12	Matt & Rauch, 2019
The PuLL Learning Factory	University of Applied Sciences Landshut	Germany	Trolley	Education, Research	Manufacturing Engineering	Lean production	X	X					X					X		3/12	Blöchl & Schneider, 2016
The Smart Production Lab	FH JOANNEUM, Graz	Austria	Not stated	Education, Training, Research	Manufacturing Engineering	Industry 4.0	X	X	X				X			X				4/12	Tschandl et al., 2020
The Virtual Learning Factory (VLF) Toolkit	UT Tallinn	Location independent	No product	Education	Manufacturing Engineering	Digital manufacturing			X				X							2/12	Mahmood et al., 2021
Value Stream Academy	Knorr Bremse, several locations	Multiple locations	Not mentioned	Training	Manufacturing Engineering	Lean production	X													0/10	U2, 2018 & Abele et al., 2018
Virtual Model Factory	McKinsey	Online	Not mentioned	Training, Research	Textile Engineering	Lean production			X		X									2/12	McKinsey, 2013

Figure B.5. Learning factory landscape spreadsheet, M-V

Name	Operator & location	Country	Product	Purpose	Industry	Learning subjects	Physical	Digital	Virtual	Model scale	Physically mobile	Low-cost	Use of e-learning, ICT & multimedia	Real production	Remotely accessible	Systematic design method	Turnkey LF	Learning success measurement	Quality system	TOTAL CONCEPTS	Reference
VPS Center of the Production Academy	BMW, Munich	Germany	Engines	Training, Research	Automotive Engineering	Lean production	X	X					X							2/12	*BMW Group, 2014*
World Class Manufacturing Academy	Chrysler, Michigan	United States of America	Not mentioned	Training	Manufacturing Engineering	Global Production	X													0/12	*Abele et al., 2019*
XPRES Laboratory	KTH Stockholm	Sweden	Not mentioned	Education, Research	Manufacturing Engineering	R&D		X	X				X							3/12	*Sivard & Lundholm, 2013*
87							95%	80%	23%	15%	5%	3%	34%	1%	6%	3%	0%	10%	0%		

Figure B.6. Learning factory landscape spreadsheet, V-X

C

Framework visualisations

Appendix C Framework visualisations

C. Framework visualisations

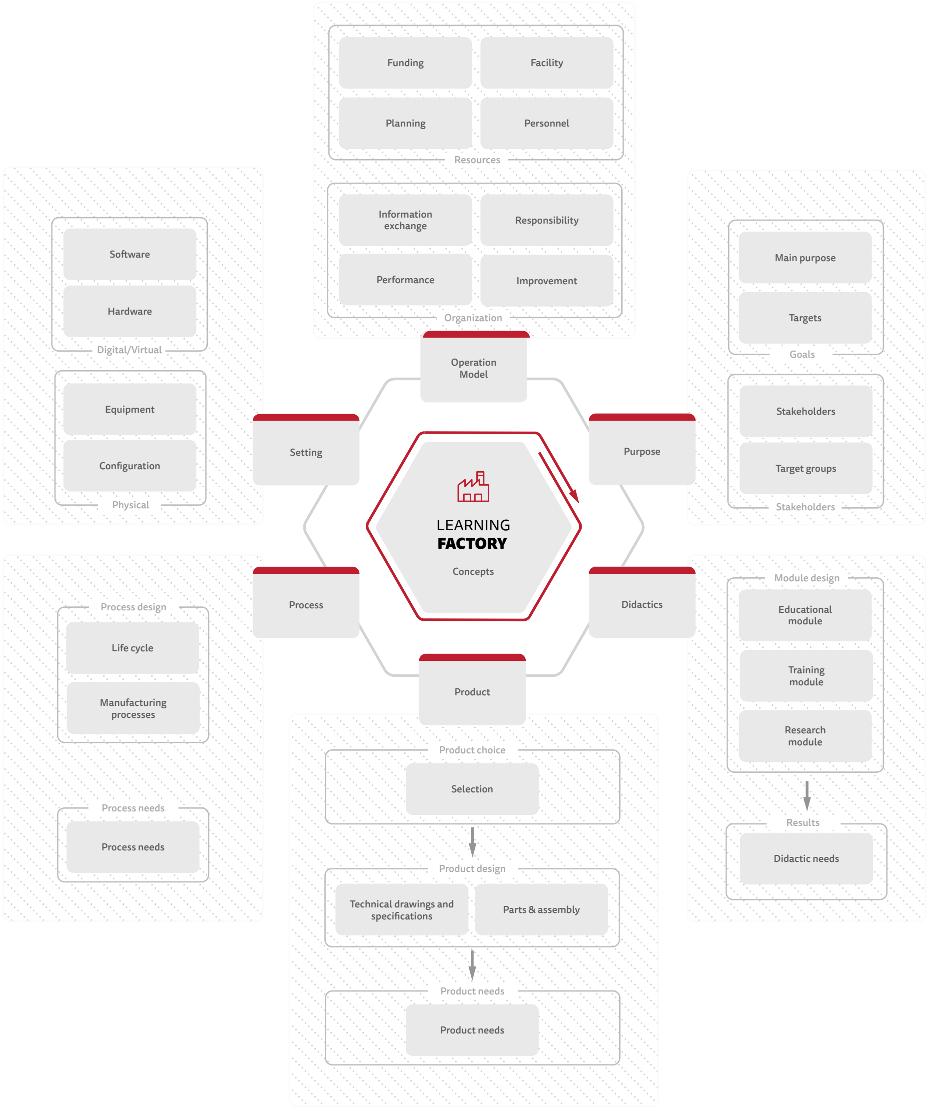


Figure C.1. Framework showing dimensions, areas, and elements

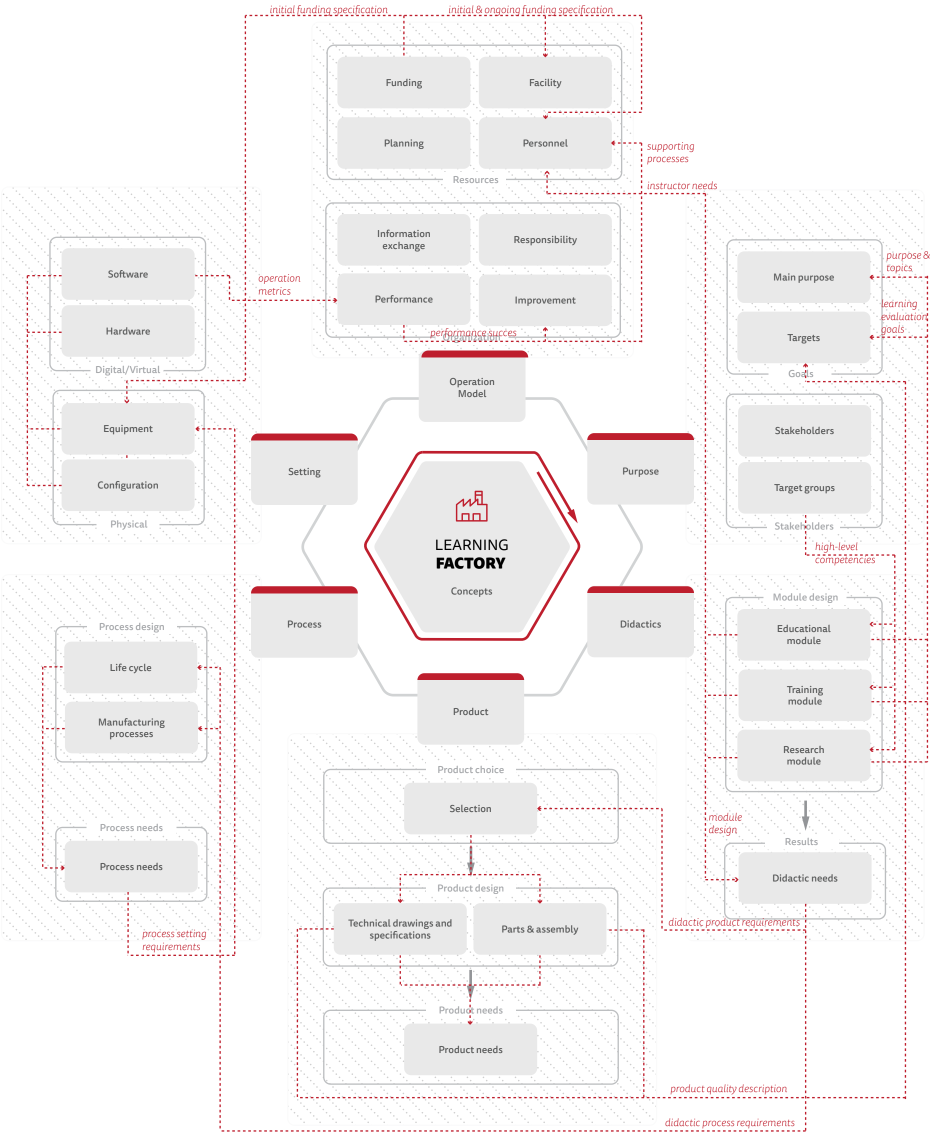


Figure C.2. Framework showing dimensions, areas, elements and interfaces

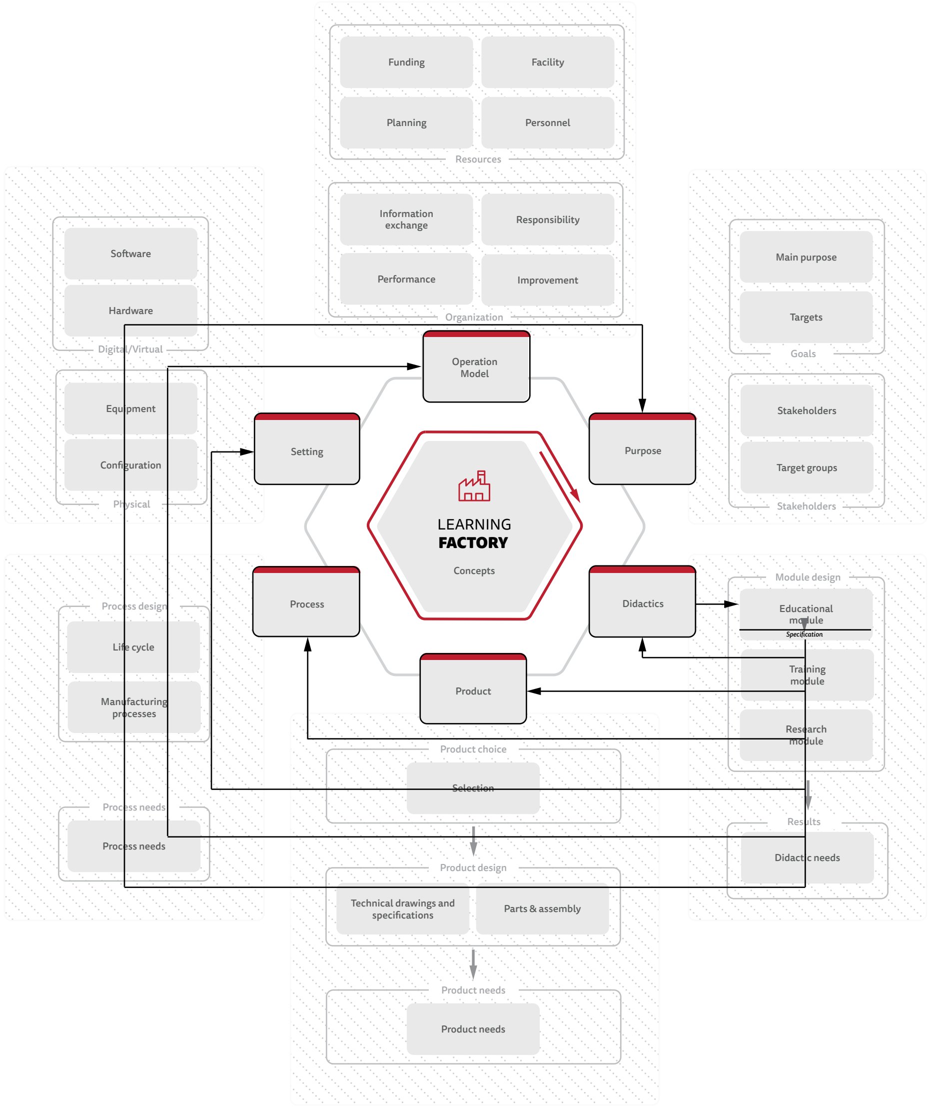


Figure C.1. Framework illustrating the flow of specificatoins to requirements

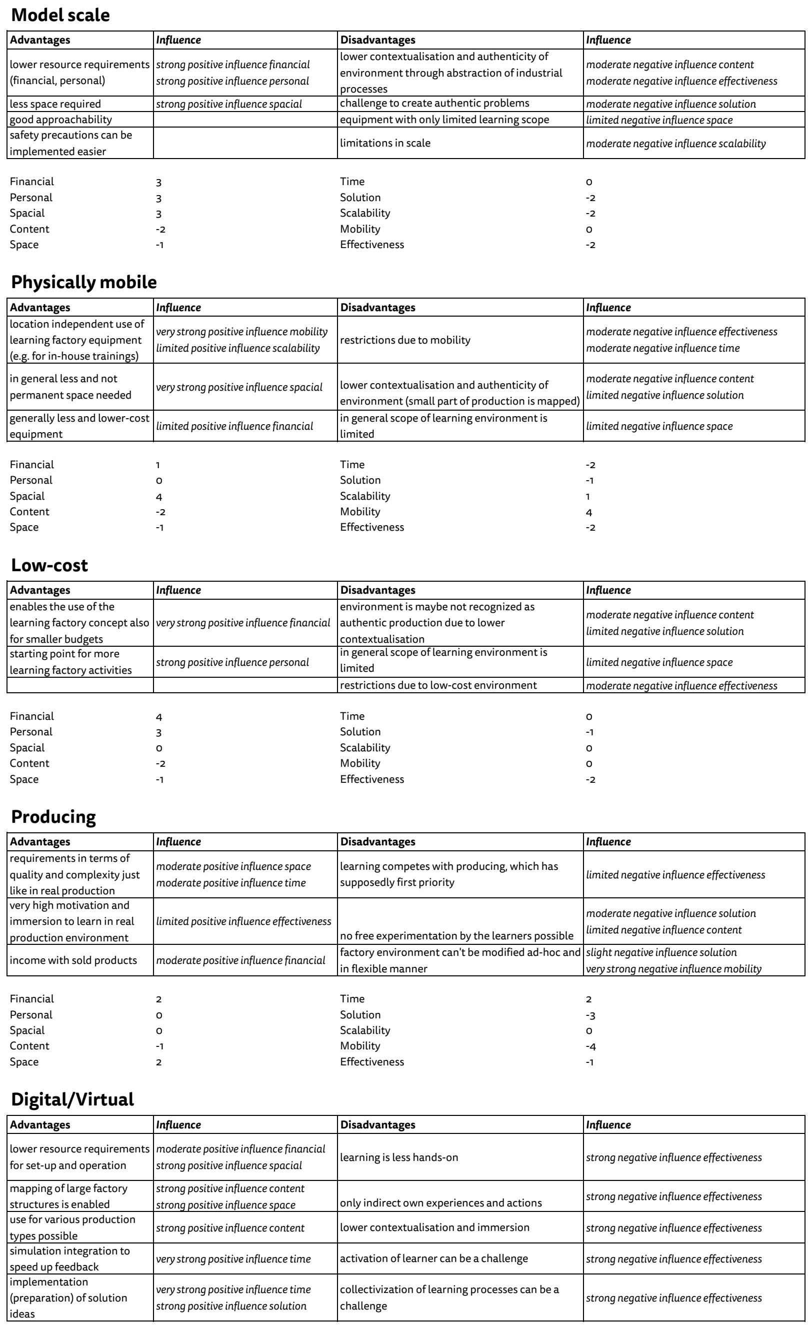
D

Analysis of limitation concepts

Appendix D Analysis of limitation concepts

D. Analysis of limitation concepts

D.1 Scoring of limitation concepts



Model scale

Advantages	*Influence*	Disadvantages	*Influence*
lower resource requirements (financial, personal)	*strong positive influence financial* *strong positive influence personal*	lower contextualisation and authenticity of environment through abstraction of industrial processes	*moderate negative influence content* *moderate negative influence effectiveness*
less space required	*strong positive influence spacial*	challenge to create authentic problems	*moderate negative influence solution*
good approachability		equipment with only limited learning scope	*limited negative influence space*
safety precautions can be implemented easier		limitations in scale	*moderate negative influence scalability*

Financial	3	Time	0
Personal	3	Solution	-2
Spacial	3	Scalability	-2
Content	-2	Mobility	0
Space	-1	Effectiveness	-2

Physically mobile

Advantages	*Influence*	Disadvantages	*Influence*
location independent use of learning factory equipment (e.g. for in-house trainings)	*very strong positive influence mobility* *limited positive influence scalability*	restrictions due to mobility	*moderate negative influence effectiveness* *moderate negative influence time*
in general less and not permanent space needed	*very strong positive influence spacial*	lower contextualisation and authenticity of environment (small part of production is mapped)	*moderate negative influence content* *limited negative influence solution*
generally less and lower-cost equipment	*limited positive influence financial*	in general scope of learning environment is limited	*limited negative influence space*

Financial	1	Time	-2
Personal	0	Solution	-1
Spacial	4	Scalability	1
Content	-2	Mobility	4
Space	-1	Effectiveness	-2

Low-cost

Advantages	*Influence*	Disadvantages	*Influence*
enables the use of the learning factory concept also for smaller budgets	*very strong positive influence financial*	environment is maybe not recognized as authentic production due to lower contextualisation	*moderate negative influence content* *limited negative influence solution*
starting point for more learning factory activities	*strong positive influence personal*	in general scope of learning environment is limited	*limited negative influence space*
		restrictions due to low-cost environment	*moderate negative influence effectiveness*

Financial	4	Time	0
Personal	3	Solution	-1
Spacial	0	Scalability	0
Content	-2	Mobility	0
Space	-1	Effectiveness	-2

Producing

Advantages	*Influence*	Disadvantages	*Influence*
requirements in terms of quality and complexity just like in real production	*moderate positive influence space* *moderate positive influence time*	learning competes with producing, which has supposedly first priority	*limited negative influence effectiveness*
very high motivation and immersion to learn in real production environment	*limited positive influence effectiveness*	no free experimentation by the learners possible	*moderate negative influence solution* *limited negative influence content*
income with sold products	*moderate positive influence financial*	factory environment can't be modified ad-hoc and in flexible manner	*slight negative influence solution* *very strong negative influence mobility*

Financial	2	Time	2
Personal	0	Solution	-3
Spacial	0	Scalability	0
Content	-1	Mobility	-4
Space	2	Effectiveness	-1

Digital/Virtual

Advantages	*Influence*	Disadvantages	*Influence*
lower resource requirements for set-up and operation	*moderate positive influence financial* *strong positive influence spacial*	learning is less hands-on	*strong negative influence effectiveness*
mapping of large factory structures is enabled	*strong positive influence content* *strong positive influence space*	only indirect own experiences and actions	*strong negative influence effectiveness*
use for various production types possible	*strong positive influence content*	lower contextualisation and immersion	*strong negative influence effectiveness*
simulation integration to speed up feedback	*very strong positive influence time*	activation of learner can be a challenge	*strong negative influence effectiveness*
implementation (preparation) of solution ideas	*very strong positive influence time* *strong positive influence solution*	collectivization of learning processes can be a challenge	*strong negative influence effectiveness*

Figure D.1. Analysis limitation concepts part 1

good scalability of learning approach	*strong positive influence scalability*	complicated integration of thinking and doing	*strong negative influence effectiveness*
mobility and location-indendent approaches	*very strong positive influence mobility*	self-regulation and self-direction limited to the predefined possibilities of virtual environment	*strong negative influence effectiveness*
time-independent approaches are enabled	*very strong positive influence time*		

Financial	2	Time	4
Personal	0	Solution	3
Spacial	3	Scalability	3
Content	4	Mobility	4
Space	3	Effectiveness	-4

Hybrid

Advantages	***Influence***	**Disadvantages**	***Influence***
extension of the scope and application range	*strong positive influence content*	effort for the creating of additional digital and virtual environment	*strong negative influence personal*
simulation opens up possibility for longterm topics +mapping of bigger factory structures in a virtual environment	*very strong positive influence time* *strong positive influence content* *strong positive influence space*	efforts to combine physical, digital, and virtual learning factory	*strong negative influence personal*
issues can be analysed in physical as well as in virtual environment	*strong positive influence solution* *moderate positive influence scalability* *limited positive influence mobility*	additional resources for set-up and operation	*strong negative influence financial*
best accessibility to factory processes	*very strong positive influence effectiveness*		

Financial	-3	Time	4
Personal	-3	Solution	3
Spacial	0	Scalability	2
Content	4	Mobility	1
Space	3	Effectiveness	4

Remotely accessible

Advantages	***Influence***	**Disadvantages**	***Influence***
location-independent use	*very strong positive influence mobility*	effort for the remote access to the factory environment	*limited negative influence personal*
better scalability + industrial environments can be used as learning environments, no dedicated learning environment needed	*very strong positive influence scalability* *very strong positive influence spacial* *strong positive influence space*	remote access less immersive, less hands-on, less active	*strong negative influence effectiveness*
little resources needed for set-up and operation	*strong positive influence financial* *strong positive influence personal*	remote access may hampers communication	*strong negative influence effectiveness*
authentic industrial problems are the basis for learning	*strong positive influence content* *strong positive influence solution*		

Financial	3	Time	0
Personal	2	Solution	3
Spacial	4	Scalability	4
Content	3	Mobility	4
Space	3	Effectiveness	-4

Changeable

Advantages	***Influence***	**Disadvantages**	***Influence***
highly flexible and adaptable environment	*strong influence solution*	high level of complexity of setting	
flexibility of the scope and application range	*strong positive influence content*	requires effort for implementaton of changeability	*strong negative influence personal*
scalable based on requirements	*moderate positive influence scalability*	additional resources for modular or adaptable features, flexible infrastructure, customizable equipment, etc.	*strong negative influence financial*
	strong positive influence effectiveness		

Financial	-3	Time	0
Personal	-3	Solution	3
Spacial	0	Scalability	2
Content	3	Mobility	0
Space	0	Effectiveness	3

Turnkey

Advantages	***Influence***	**Disadvantages**	***Influence***
lower cost compared to completely indivually developed learning factory	*limited positive influence financial*	in turnkey factories, the design of the learning factory is not directly created for the target group	*moderate negative influence effectiveness*

Figure D.2. Analysis limitation concepts part 2

no expertise and personnel regarding the establishment of learning factories in the customer organization are needed	*strong positive influence personal*	turnkey gives limitations in customization and flexibility of learning modules	*moderate negative influence content* *moderate negative influence solution*

Financial	2	Time	0
Personal	3	Solution	-2
Spacial	0	Scalability	0
Content	-2	Mobility	0
Space	0	Effectiveness	-2

Systematic design

Advantages	***Influence***	**Disadvantages**	***Influence***
systematic design offers an efficient approach to learning factory design	*moderate positive influence personal*		
systematic approach should create effective learning factories	*moderate positive influence effectiveness*		

Financial	0	Time	0
Personal	2	Solution	0
Spacial	0	Scalability	0
Content	0	Mobility	0
Space	0	Effectiveness	2

Learning success measurement

Advantages	***Influence***	**Disadvantages**	***Influence***
learning success measurement causes learning factory improvement	*moderate positive influence effectiveness*	effort for carrying out learning succes measurement	*limited negative influence personal*

Financial	0	Time	0
Personal	-1	Solution	0
Spacial	0	Scalability	0
Content	0	Mobility	0
Space	0	Effectiveness	2

Quality systems

Advantages	***Influence***	**Disadvantages**	***Influence***
quality monitoring should improve learning factory	*strong positive influence effectiveness*	effort for implementation and operation of quality systems	*limited negative influence financial*
		resources for implementation and operation of quality systems	*limited negative influence personal*

Financial	-1	Time	0
Personal	-1	Solution	0
Spacial	0	Scalability	0
Content	0	Mobility	0
Space	0	Effectiveness	3

Network

Advantages	***Influence***	**Disadvantages**	***Influence***
reduce resource intensity of development of individual learning factories			

Financial	1	Time	0
Personal	1	Solution	0
Spacial	0	Scalability	0
Content	0	Mobility	0
Space	0	Effectiveness	1

eLearning, ICT & Multimedia

Advantages	***Influence***	**Disadvantages**	***Influence***
better use of scarce learning factory capacities (e-learning)	*limited positive influence scalability*	effort for the creating of additional e learning and multimedia	*limited negative influence personal* *limited negative influence financial*

Figure D.3. Analysis limitation concepts part 3

individual learning paths (multimedia)	*limited positive influence effectiveness*	short cycles between theoretical and practical phases often not feasible in blended learning setups (e -learning & physical learning factory)	

Financial	-1	Time	0
Personal	-1	Solution	0
Spacial	0	Scalability	1
Content	0	Mobility	0
Space	0	Effectiveness	1

Figure D.4 Analysis limitation concepts part 4

D.2 Requirements of limitation concepts

Model scale

Dimension	**Requirement**
Operating model	
Purpose	
Process	The learning factory should employ a reduced functional complexity process in comparison to standard learning factories.
Setting	The learning factory setting should be exclusively made from smaller equivalents of original factory equipment
	The learning factory equipment should be able to keep characteristic functions while having a reduced complexity
Product	The learning factory product should be producable with model scale factory equipment
Didactics	

Physically mobile

Dimension	**Requirement**
Operating model	The learning factory should be independent to specific facility locations
Purpose	The learning factory should be capable of serving target groups from various locations
Process	
Setting	The learning factory equipment should allow for full mobility within short time frames
	The learning factory equipment should be minimized in weight and size to facilitate mobility
	The learning factory equipment must have components that facilitate effortless movement (such as wheels)
	The learning factory equipment should maintain full functionality at any location
Product	The learning factory product should be manufacturable at every location
Didactics	The learning factory learning modules should be tailored to target groups regardless of location

Low-cost

Dimension	**Requirement**
Operating model	The learning factory should require a minimum amount of financial efforts
Purpose	
Process	The learning factory should map cost-effective processes
Setting	
Product	
Didactics	

eLearning, ICT & Multimedia

Dimension	**Requirement**
Operating model	
Purpose	
Process	
Setting	The learning factory setting should contain Multimedia tools that allow for monitoring of the learning process
	The learning factory setting should contain ICT tools for visualisation of information
Product	
Didactics	The learning factory learning modules should employ eLearning methods

Producing

Dimension	**Requirement**
Operating model	The funding strategy for the learning factory should include revenue generated from product sales
Purpose	The learning factory must have an adequate number of participants or personnel to ensure smooth operation
Process	The primary goal of the learning factory is to provide products for sale in the market.
Setting	The learning factory should implement quality control measures to ensure the safety and quality of its products for the market.
Product	The learning factory should have a setting that facilitates both learning and production processes.
Didactics	The products manufactured by the learning factory should meet safety and quality standards required for market offering.

Figure D.5 Requirements per concept part 1

Digital/Virtual

Dimension	Requirement
Operating model	
Purpose	
Process	The learning factory should encompass both digital and virtual aspects at the factory level.
Setting	The learning factory should have a digital and virtual setting
	The learning factory setting should include tools that enable the visualization and interaction of data.
	The learning factory setting should include tools that enable the visualization and interaction of the virtual representation.
Product	The learning factory should have a digital product.
	The learning factory should have a virtual product that represents the digital product.
Didactics	

Hybrid

Dimension	Requirement
Operating model	
Purpose	
Process	The learning factory should encompass both physical and virtual aspects at the factory level.
Setting	The digital setting of the learning factory should be built upon the foundation of its physical setting.
	The virtual setting of the learning factory should be created based on the digital setting.
	The learning factory setting should include tools that enable the visualization and interaction of data.
	The learning factory setting should include tools that enable the visualization and interaction of the virtual representation.
	The learning factory setting should include tools that facilitate interaction with the physical equipment.
	The learning factory should provide capabilities for storing and analyzing data.
Product	The physical equipment in the learning factory should be appropriate for collecting data.
	The learning factory should have a digital product that represents the physical product.
	The learning factory product should be traceable
	The learning factory product should be designed to support data collection.
	The learning factory should have a virtual product that represents the digital product.
Didactics	

Remotely accessible

Dimension	Requirement
Operating model	
Purpose	
Process	The processes of the learning factory should be observable from remote locations.
Setting	The physical equipment in the learning factory should be suitable for remote control.
	The learning factory setting has the option to utilize an existing, tangible industrial environment.
Product	
Didactics	The learning modules of the learning factory can be conducted regardless of the specific location.

Systematic design

Dimension	Requirement
Operating model	The learning factory should follow systematic methods for learning factory design
	The learning factory should foster documentation during systematic design for proper choice justification
Purpose	
Process	
Setting	
Product	
Didactics	

Turnkey

Dimension	Requirement
Operating model	
Purpose	The purpose and topics of the learning factory is standardized and replicated
Process	The processes of the learning factory are standardized and replicated
Setting	The learning factory setting should be a standardized, replicated environment
Product	The learning factory product should be standardized and replicated
Didactics	

Figure D.6 Requirements per concept part 2

Learning success measurement

Dimension	Requirement
Operating model	
Purpose	
Process	
Setting	
Product	
Didactics	The learning factory should employ systematic methods of learning success evaluation
	The learning factory should implement results from learning success evaluation for improvement of learning success

Quality system

Dimension	Requirement
Operating model	The learning factory should employ systematic approaches for assessing the current state
	The learning factory should employ systematic approaches for assessing the potential for improvement in relation to the targ
	The learning factory should employ systematic approaches for deriving improvement measures
Purpose	
Process	
Setting	The learning factory setting should include tools that enable quality control
Product	
Didactics	The learning factory should employ systematic methods of evaluation

Network

Dimension	Requirement
Operating model	The operating model of the learning factory should be effectively communicated to other learning factories within the netwo
Purpose	The purpose of the learning factory should be effectively communicated to other learning factories within the network.
Process	The process of the learning factory should be effectively communicated to other learning factories within the network.
Setting	The setting of the learning factory should be effectively communicated to other learning factories within the network.
Product	The product of the learning factory should be effectively communicated to other learning factories within the network.
Didactics	The didactic model of the learning factory should be effectively communicated to other learning factories within the network

Changeabilty

Dimension	Requirement
Operating model	
Purpose	The learning factory should have changeable and flexible process, setting and/or product
Process	The learning factory should allow for a changeable process depending on the needs of the target group
Setting	The physical learning factory equipment should allow for mobility within the learning factory
	The physical learning factory equipment should be modular to allow for different configurations
	The learning factory equipment must have components that facilitate effortless movement (such as wheels)
	The learning factory facility should allow for different configurations of equipment
Product	The learning factory product should be changeable depending on the needs of the target group
	The learning factory product should be sufficiently simplified to reduce complexity while remaining close to reality and to all
Didactics	

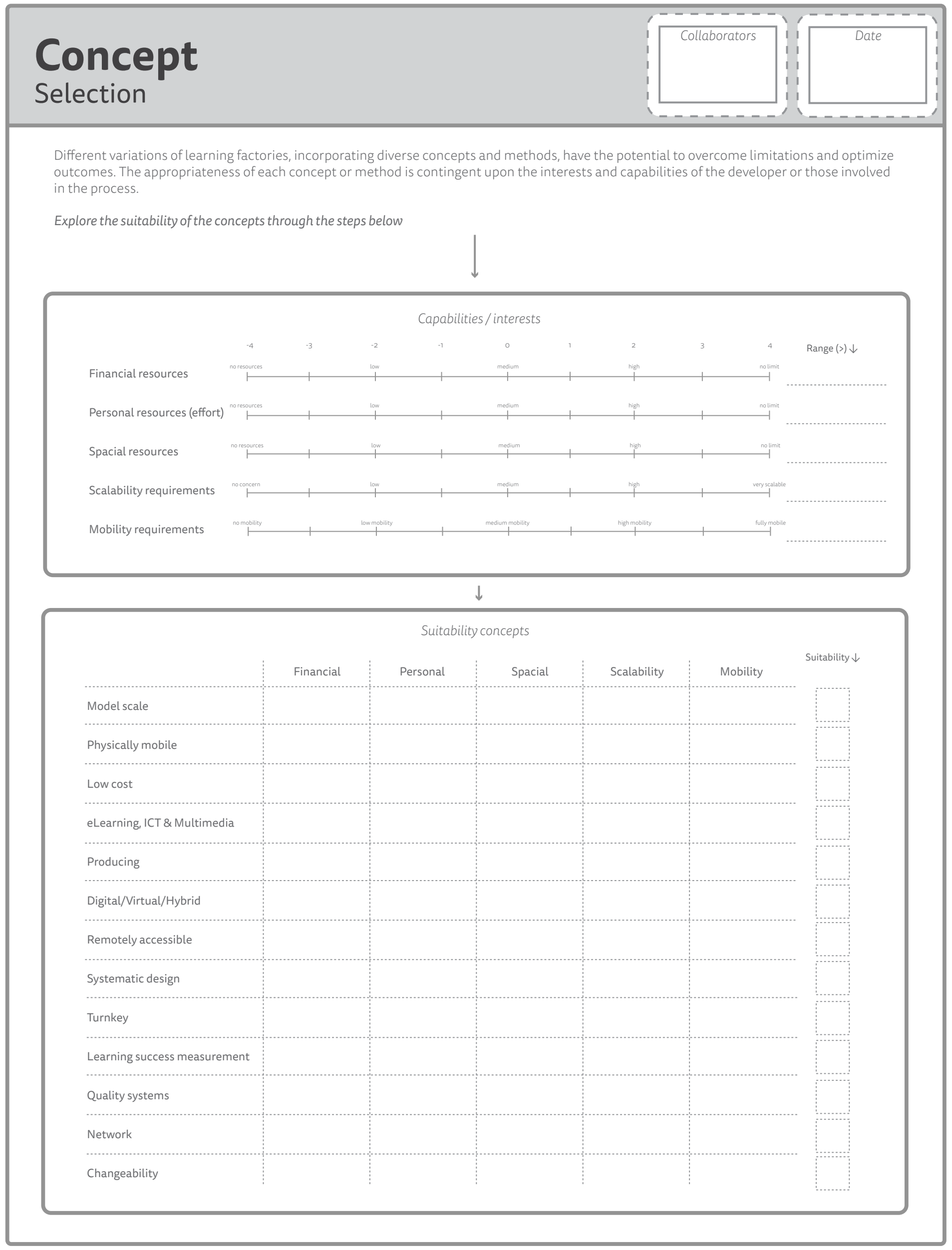
Figure D.7 Requirements per concept part 3

E

Methods

Appendix E Methods for proof of principle

E. Methods



Concept
Selection

Collaborators

Date

Different variations of learning factories, incorporating diverse concepts and methods, have the potential to overcome limitations and optimize outcomes. The appropriateness of each concept or method is contingent upon the interests and capabilities of the developer or those involved in the process.

Explore the suitability of the concepts through the steps below

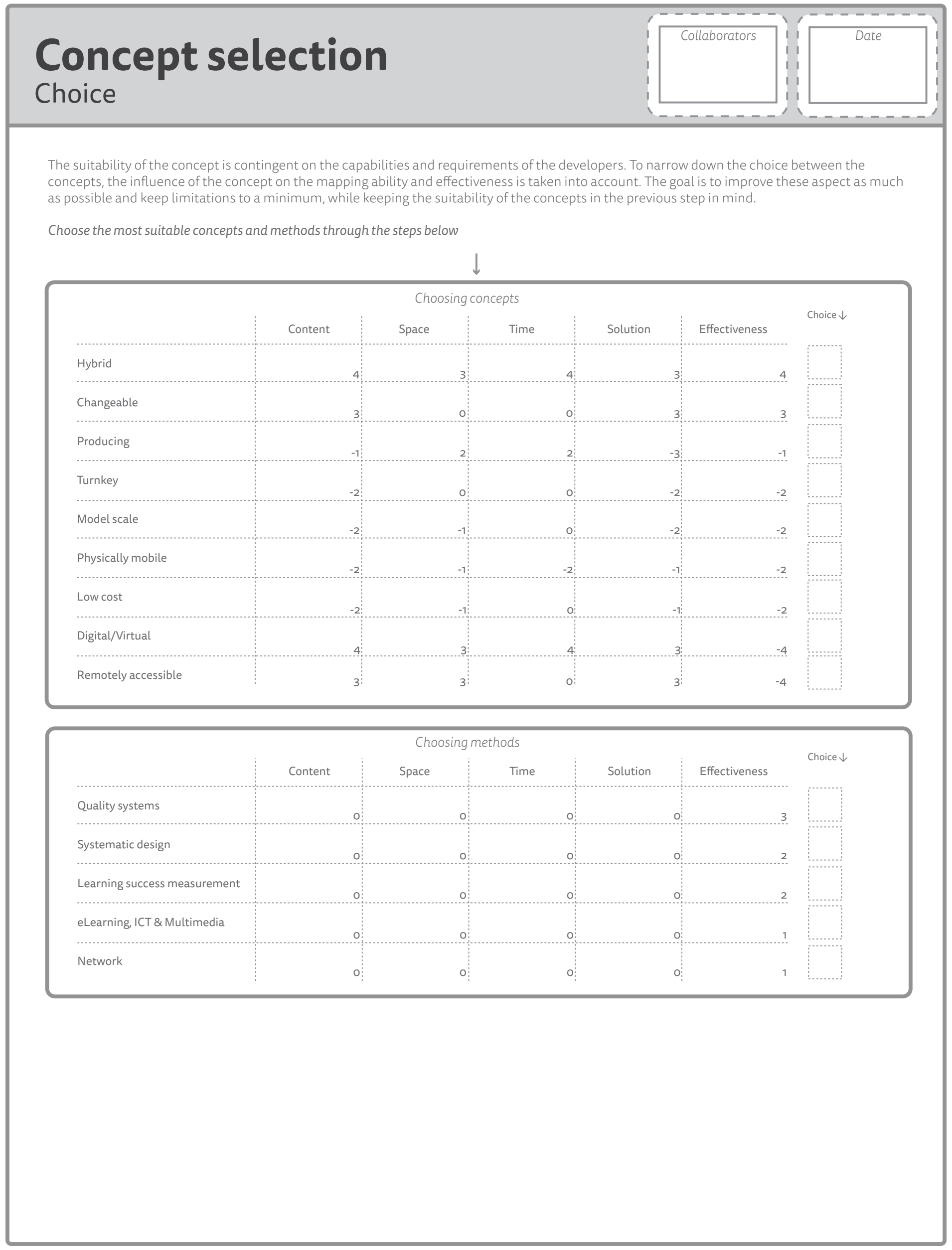
Capabilities / interests

	-4	-3	-2	-1	0	1	2	3	4	Range (>) ↓
Financial resources	no resources		low		medium		high		no limit	
Personal resources (effort)	no resources		low		medium		high		no limit	
Spacial resources	no resources		low		medium		high		no limit	
Scalability requirements	no concern		low		medium		high		very scalable	
Mobility requirements	no mobility		low mobility		medium mobility		high mobility		fully mobile	

Suitability concepts

	Financial	Personal	Spacial	Scalability	Mobility	Suitability ↓
Model scale						
Physically mobile						
Low cost						
eLearning, ICT & Multimedia						
Producing						
Digital/Virtual/Hybrid						
Remotely accessible						
Systematic design						
Turnkey						
Learning success measurement						
Quality systems						
Network						
Changeability						

Figure E.1. Concept selection method



Concept selection
Choice

Collaborators

Date

The suitability of the concept is contingent on the capabilities and requirements of the developers. To narrow down the choice between the concepts, the influence of the concept on the mapping ability and effectiveness is taken into account. The goal is to improve these aspect as much as possible and keep limitations to a minimum, while keeping the suitability of the concepts in the previous step in mind.

Choose the most suitable concepts and methods through the steps below

↓

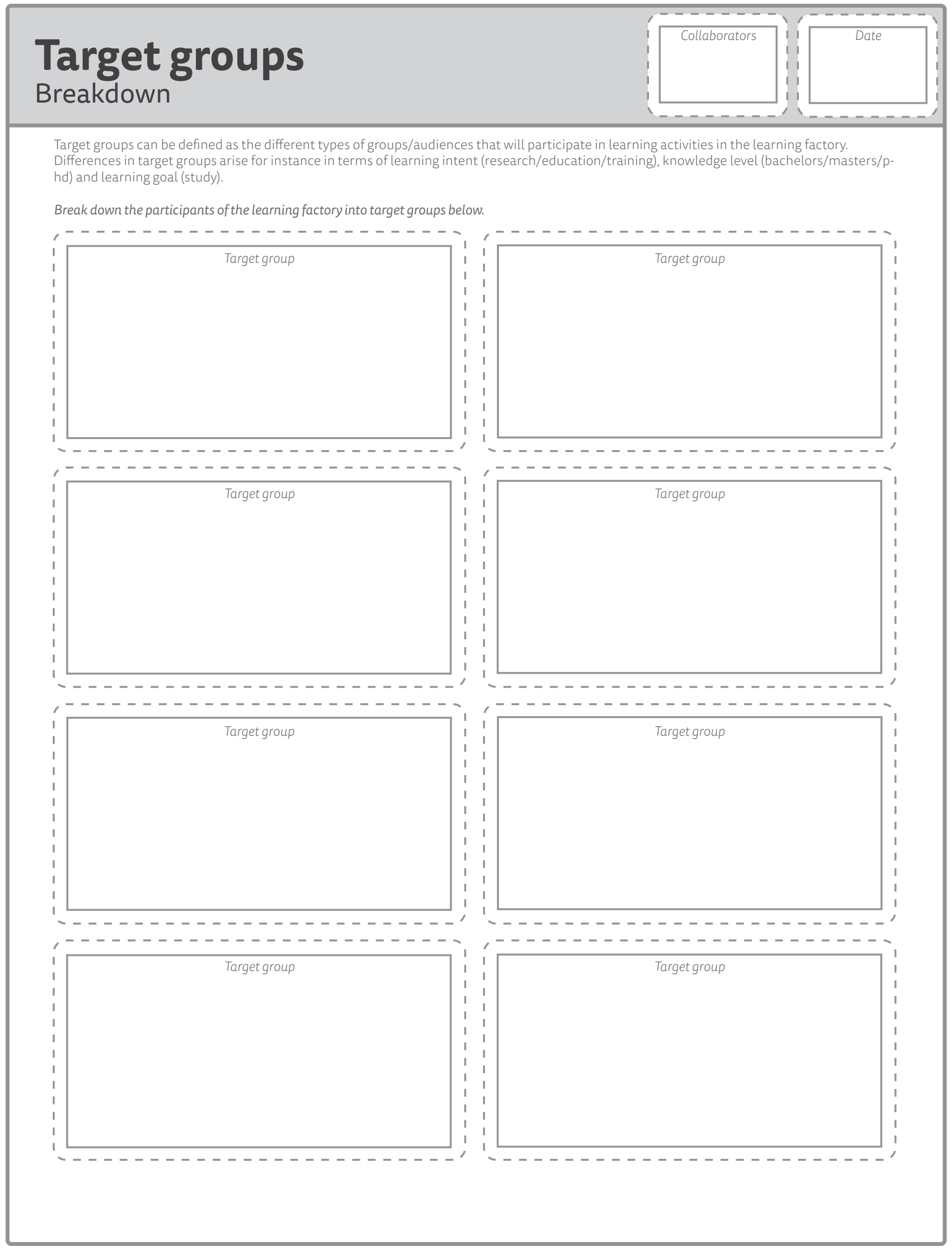
Choosing concepts

	Content	Space	Time	Solution	Effectiveness	Choice ↓
Hybrid	4	3	4	3	4	☐
Changeable	3	0	0	3	3	☐
Producing	-1	2	2	-3	-1	☐
Turnkey	-2	0	0	-2	-2	☐
Model scale	-2	-1	0	-2	-2	☐
Physically mobile	-2	-1	-2	-1	-2	☐
Low cost	-2	-1	0	-1	-2	☐
Digital/Virtual	4	3	4	3	-4	☐
Remotely accessible	3	3	0	3	-4	☐

Choosing methods

	Content	Space	Time	Solution	Effectiveness	Choice ↓
Quality systems	0	0	0	0	3	☐
Systematic design	0	0	0	0	2	☐
Learning success measurement	0	0	0	0	2	☐
eLearning, ICT & Multimedia	0	0	0	0	1	☐
Network	0	0	0	0	1	☐

Figure E.2. Concept choice method



Target groups
Breakdown

Collaborators

Date

Target groups can be defined as the different types of groups/audiences that will participate in learning activities in the learning factory. Differences in target groups arise for instance in terms of learning intent (research/education/training), knowledge level (bachelors/masters/p-hd) and learning goal (study).

Break down the participants of the learning factory into target groups below.

Target group

Target group

Target group

Target group

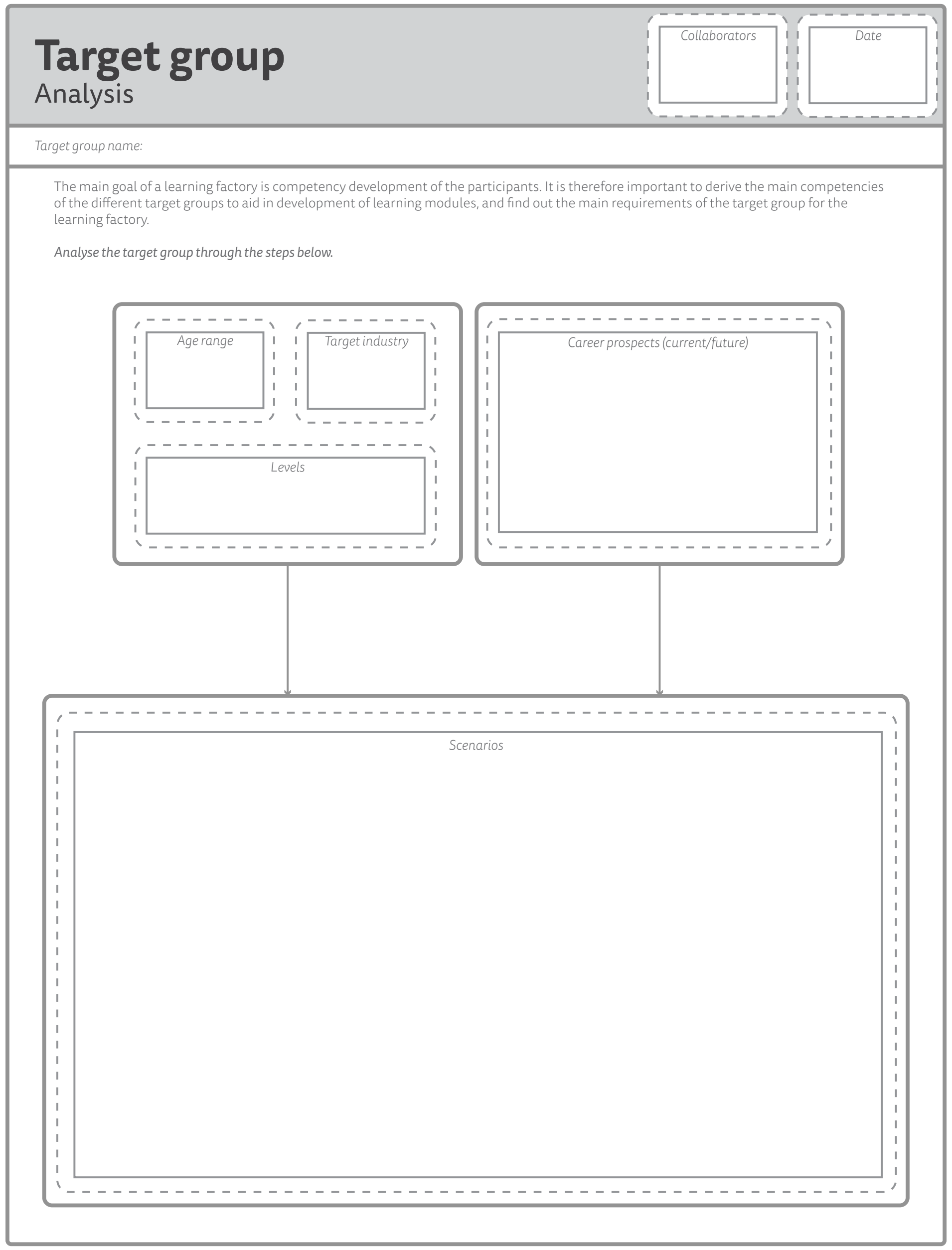
Target group

Target group

Target group

Target group

Figure E.3. Target group breakdown method



Target group
Analysis

Collaborators

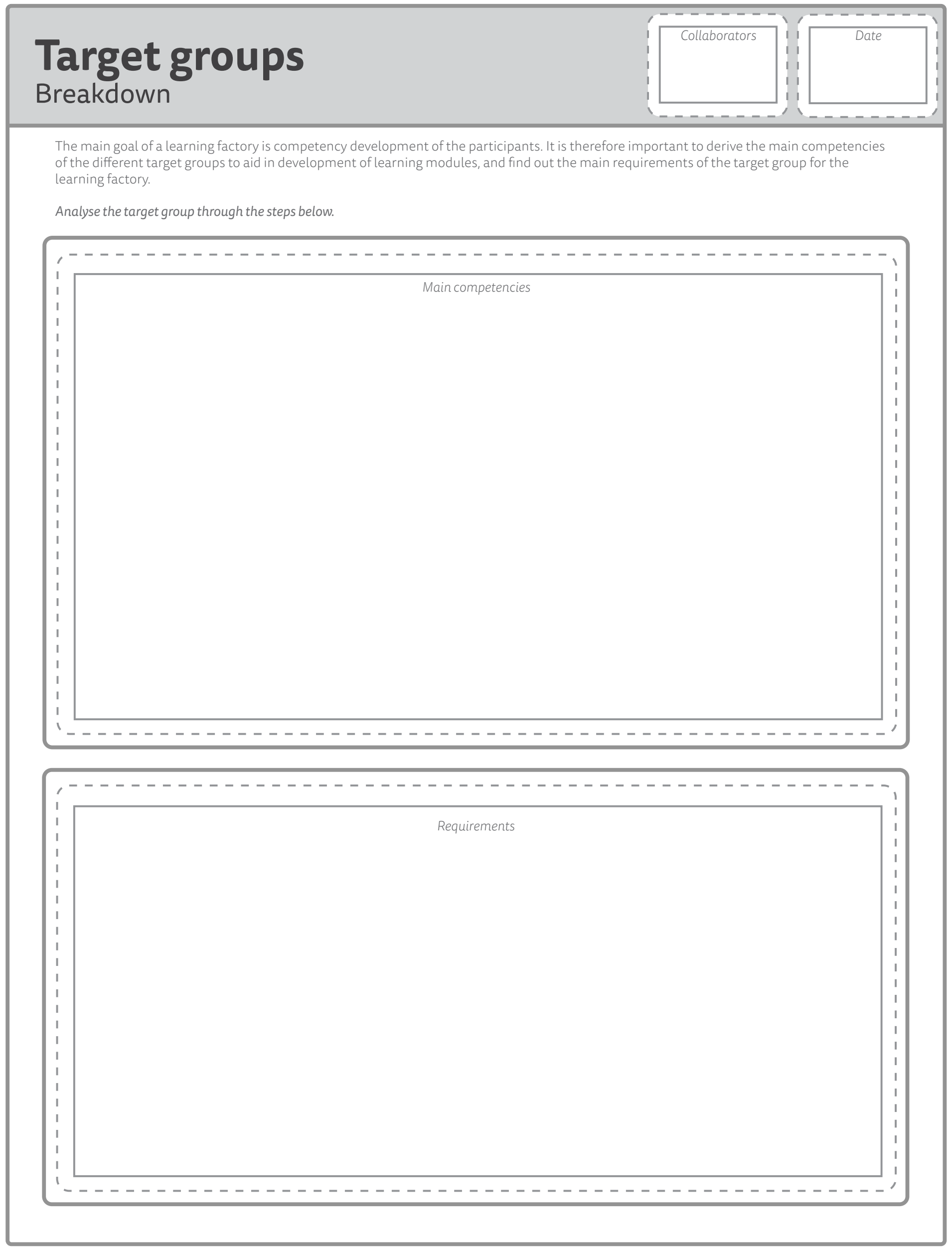
Date

Target group name:

The main goal of a learning factory is competency development of the participants. It is therefore important to derive the main competencies of the different target groups to aid in development of learning modules, and find out the main requirements of the target group for the learning factory.

Analyse the target group through the steps below.

Figure E.4. Target group analysis method part 1



Target groups
Breakdown

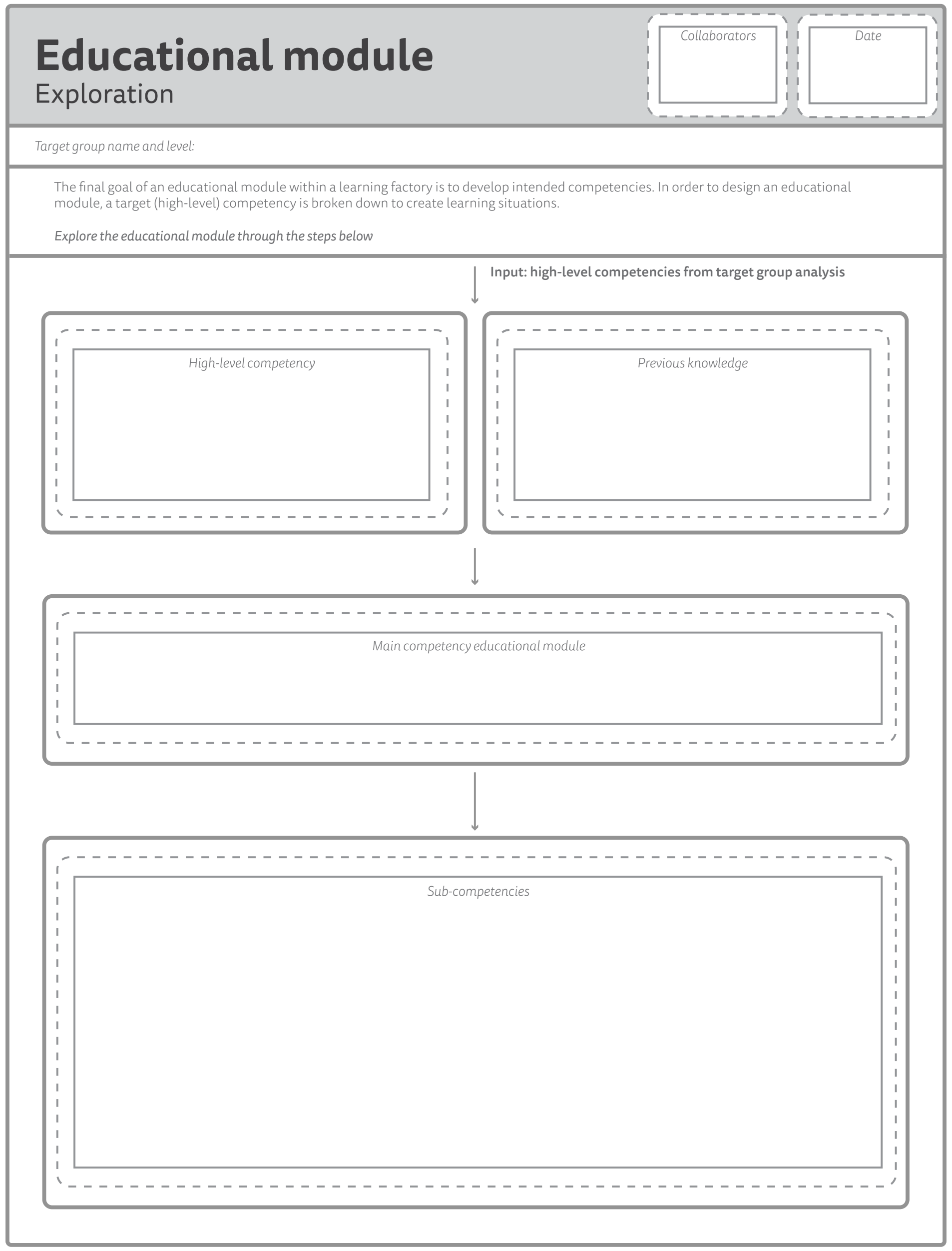
Collaborators

Date

The main goal of a learning factory is competency development of the participants. It is therefore important to derive the main competencies of the different target groups to aid in development of learning modules, and find out the main requirements of the target group for the learning factory.

Analyse the target group through the steps below.

Figure E.5. Target group analysis method part 2



Educational module
Exploration

Collaborators

Date

Target group name and level:

The final goal of an educational module within a learning factory is to develop intended competencies. In order to design an educational module, a target (high-level) competency is broken down to create learning situations.

Explore the educational module through the steps below

Input: high-level competencies from target group analysis

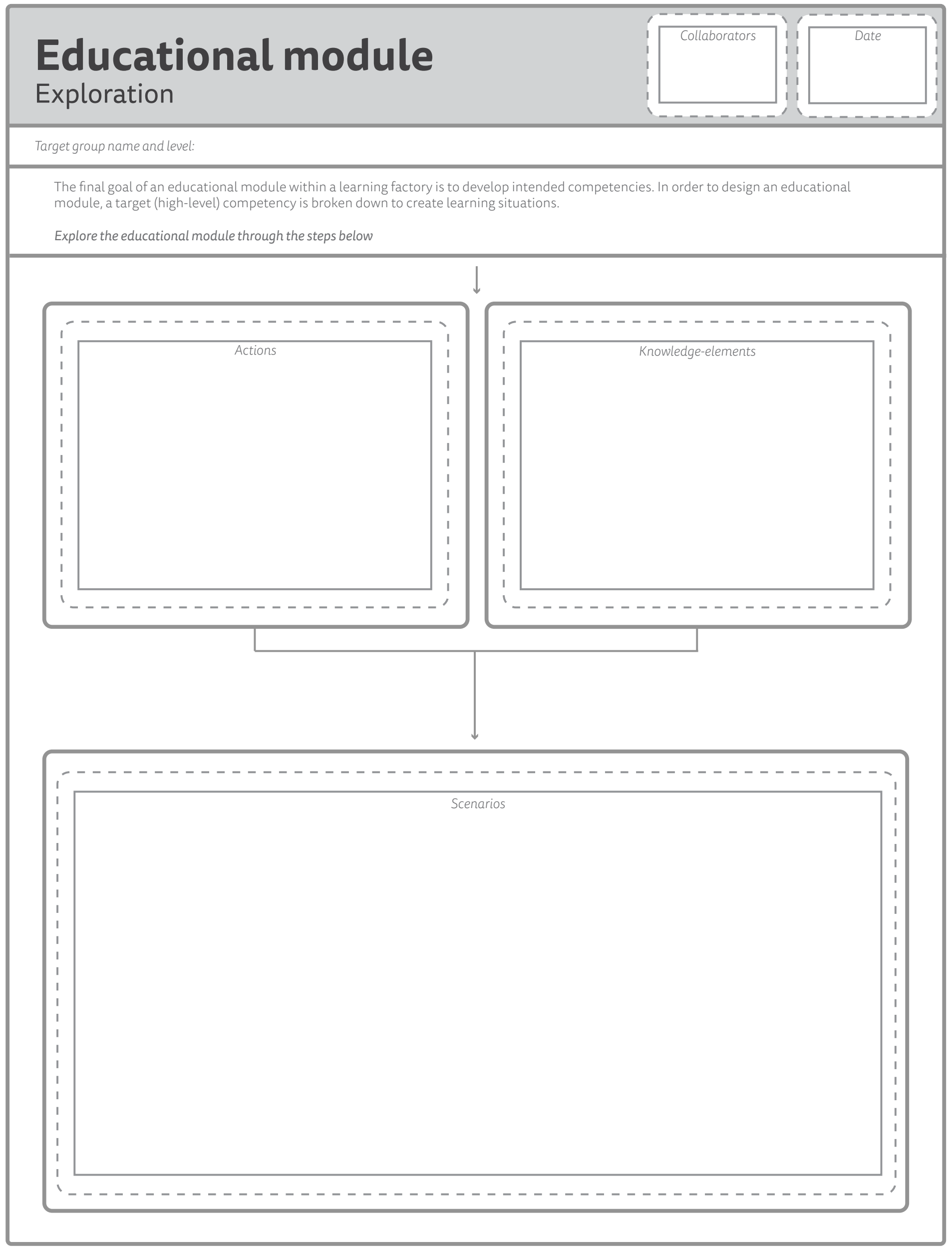
High-level competency

Previous knowledge

Main competency educational module

Sub-competencies

Figure E.6. Educational module exploration part 1



Educational module
Exploration

Collaborators

Date

Target group name and level:

The final goal of an educational module within a learning factory is to develop intended competencies. In order to design an educational module, a target (high-level) competency is broken down to create learning situations.

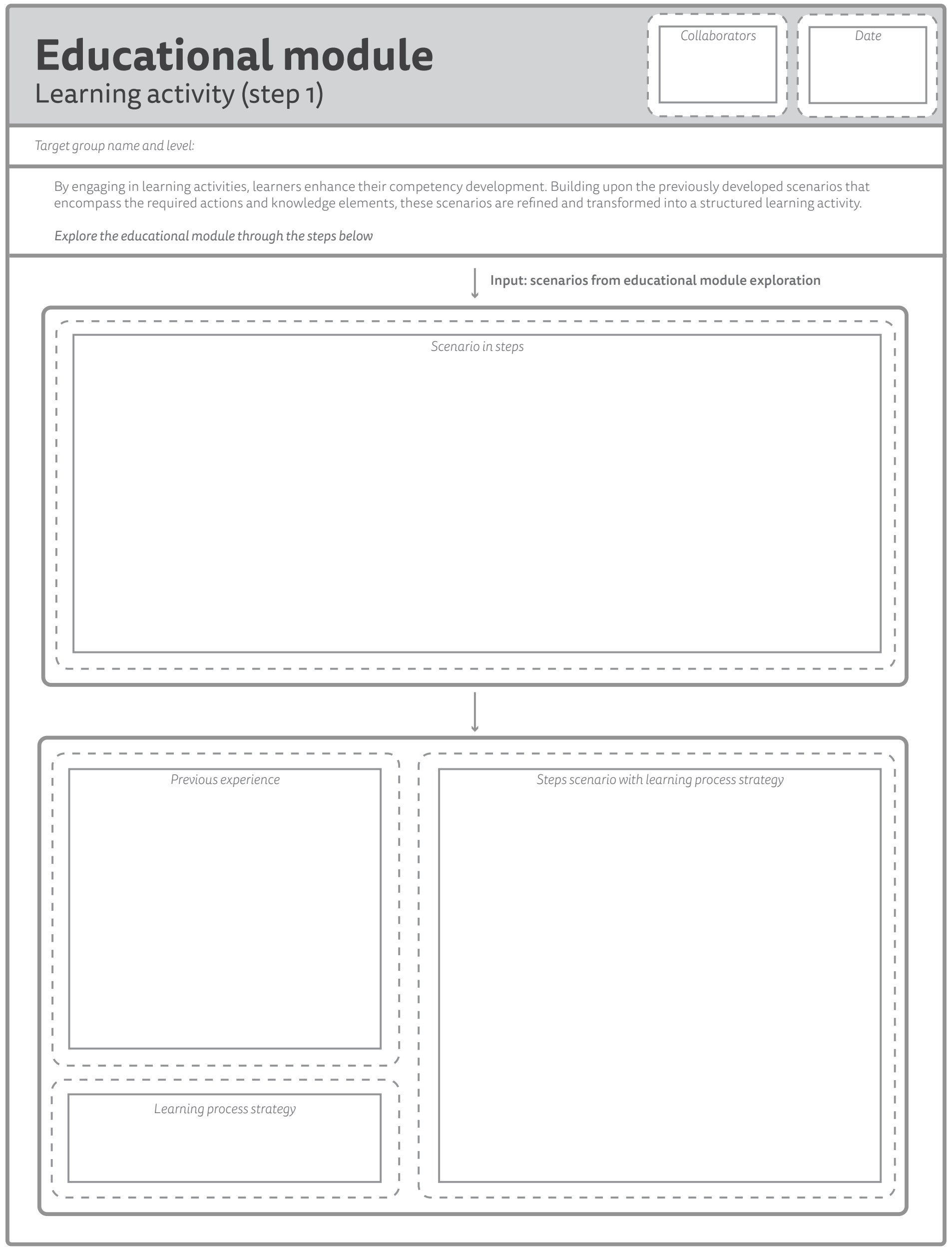
Explore the educational module through the steps below

Actions

Knowledge-elements

Scenarios

Figure E.7. Educational module exploration part 2



Educational module

Learning activity (step 1)

Collaborators

Date

Target group name and level:

By engaging in learning activities, learners enhance their competency development. Building upon the previously developed scenarios that encompass the required actions and knowledge elements, these scenarios are refined and transformed into a structured learning activity.

Explore the educational module through the steps below

Input: scenarios from educational module exploration

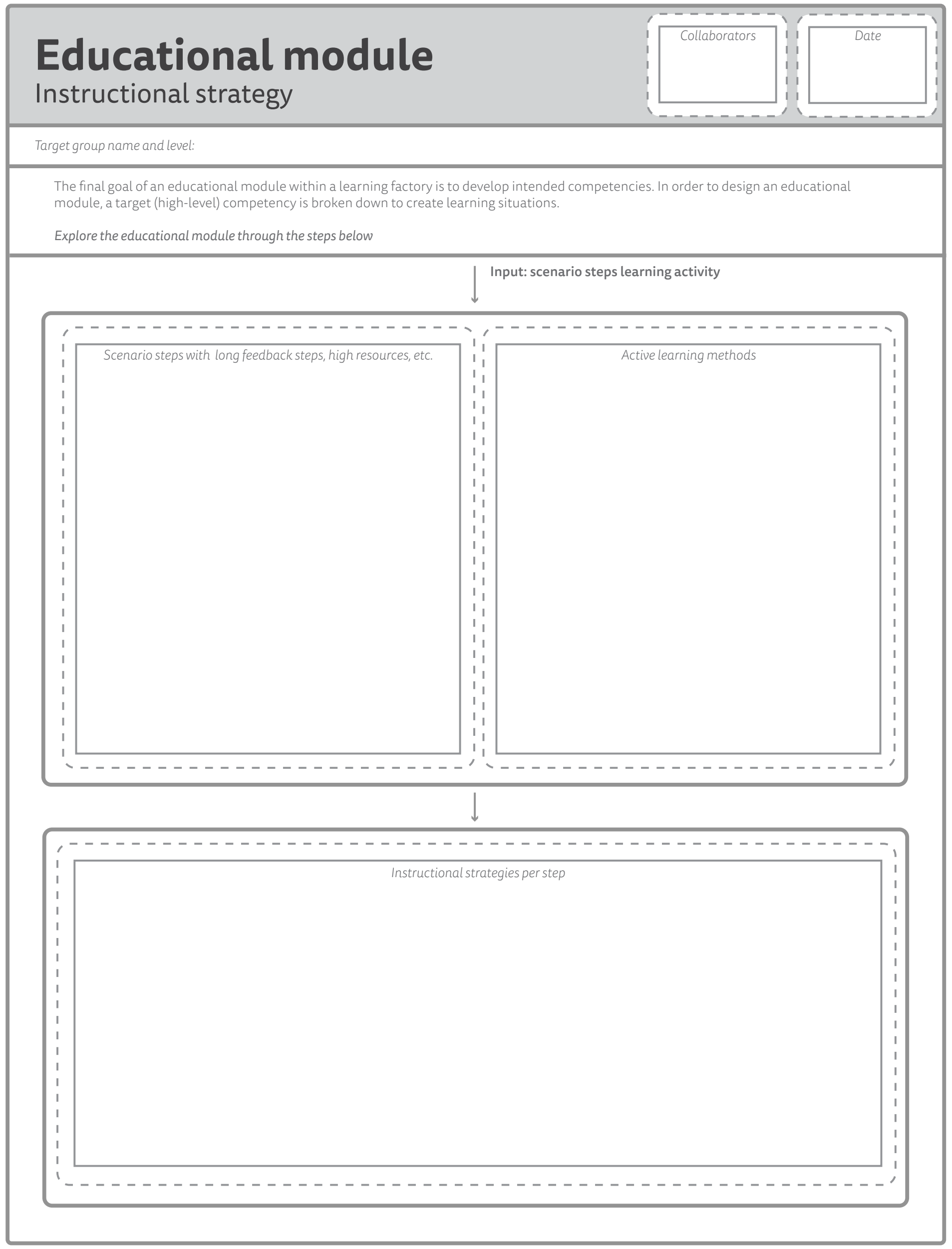
Scenario in steps

Previous experience

Learning process strategy

Steps scenario with learning process strategy

Figure E.8. Educational module learning activity method



Educational module

Instructional strategy

Collaborators

Date

Target group name and level:

The final goal of an educational module within a learning factory is to develop intended competencies. In order to design an educational module, a target (high-level) competency is broken down to create learning situations.

Explore the educational module through the steps below

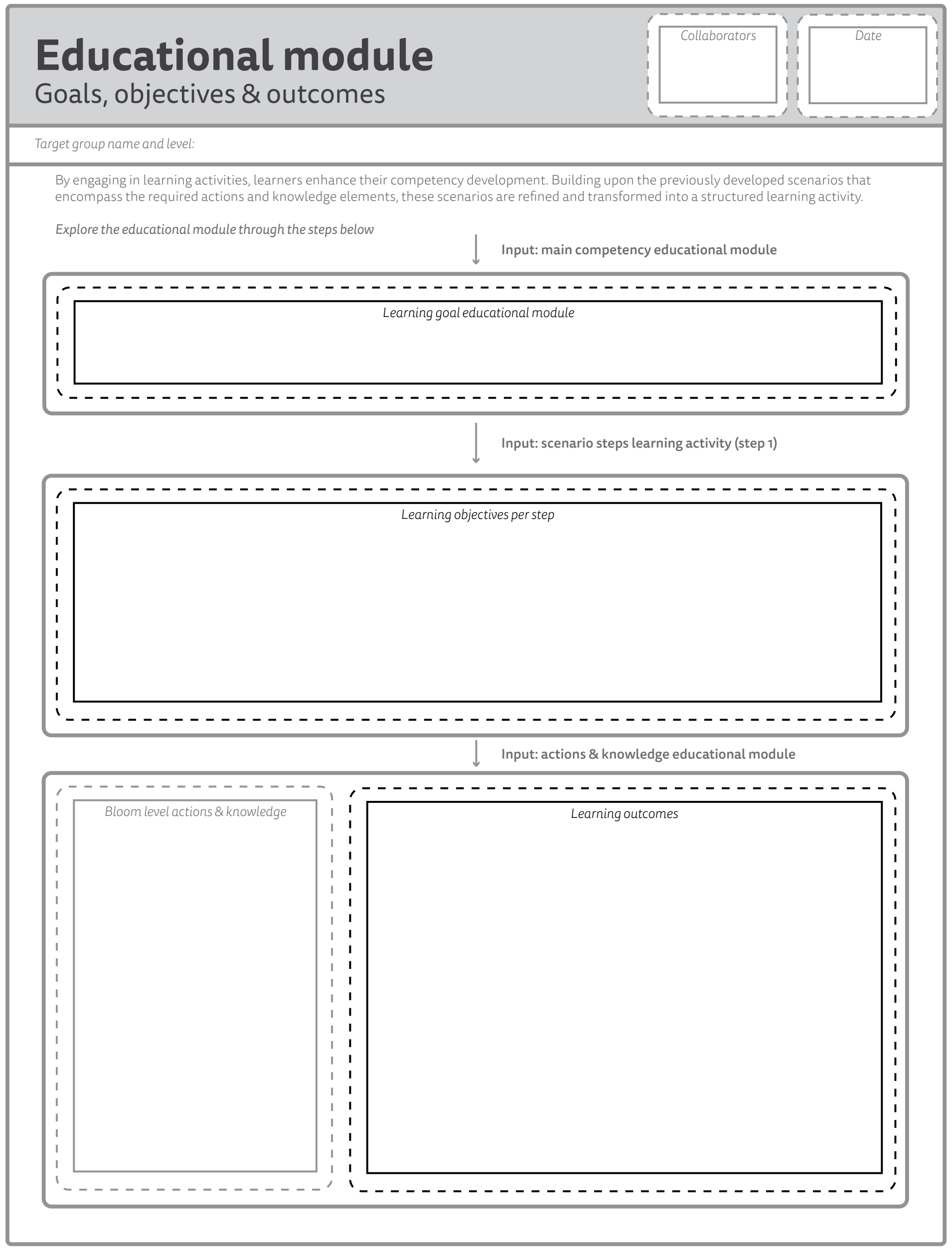
Input: scenario steps learning activity

Scenario steps with long feedback steps, high resources, etc.

Active learning methods

Instructional strategies per step

Figure E.9. Educational module instructional strategy method



Educational module
Goals, objectives & outcomes

Collaborators

Date

Target group name and level:

By engaging in learning activities, learners enhance their competency development. Building upon the previously developed scenarios that encompass the required actions and knowledge elements, these scenarios are refined and transformed into a structured learning activity.

Explore the educational module through the steps below

Input: main competency educational module

Learning goal educational module

Input: scenario steps learning activity (step 1)

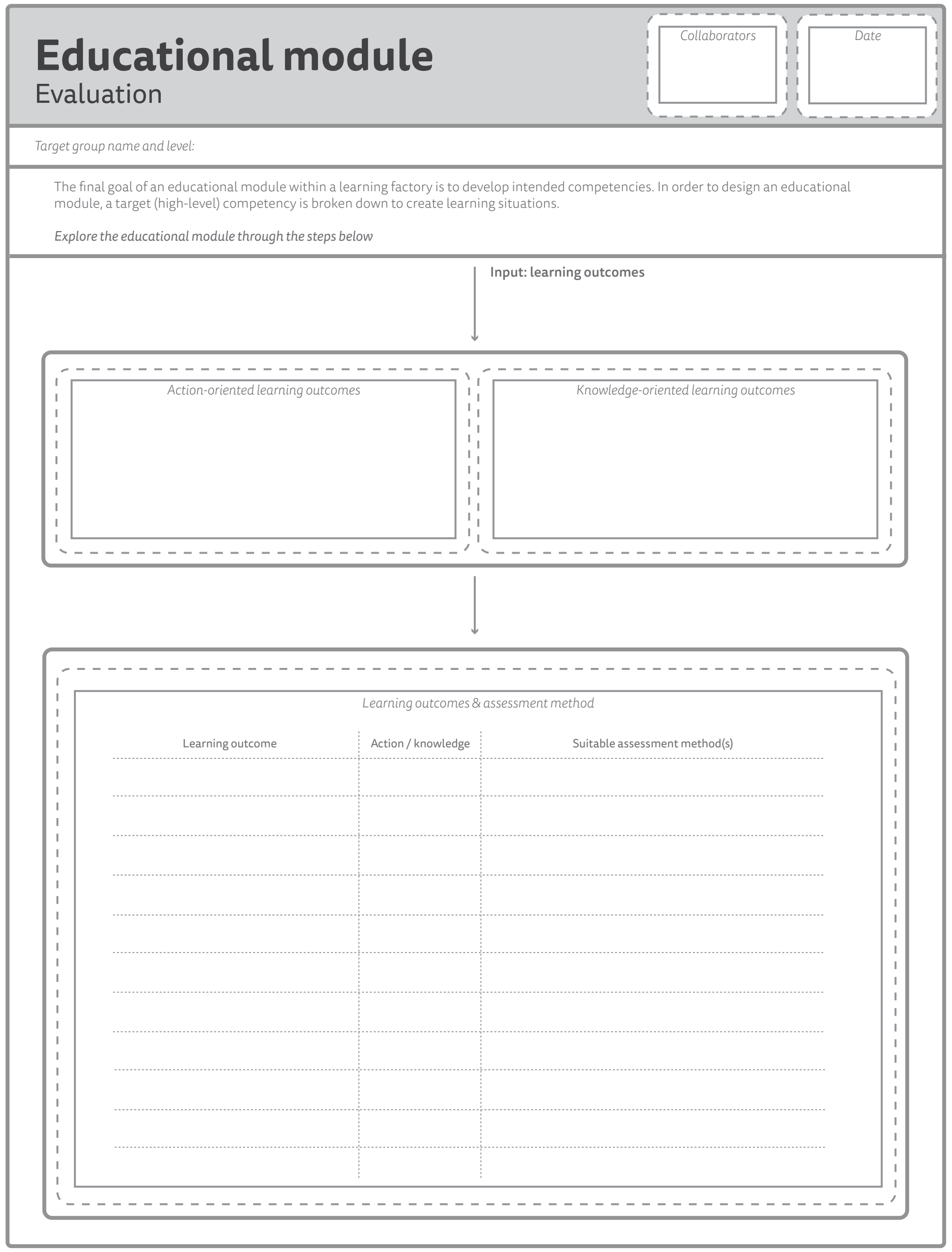
Learning objectives per step

Input: actions & knowledge educational module

Bloom level actions & knowledge

Learning outcomes

Figure E.10. Educational module goals, objectives & outcomes method



Educational module
Evaluation

Collaborators

Date

Target group name and level:

The final goal of an educational module within a learning factory is to develop intended competencies. In order to design an educational module, a target (high-level) competency is broken down to create learning situations.

Explore the educational module through the steps below

Input: learning outcomes

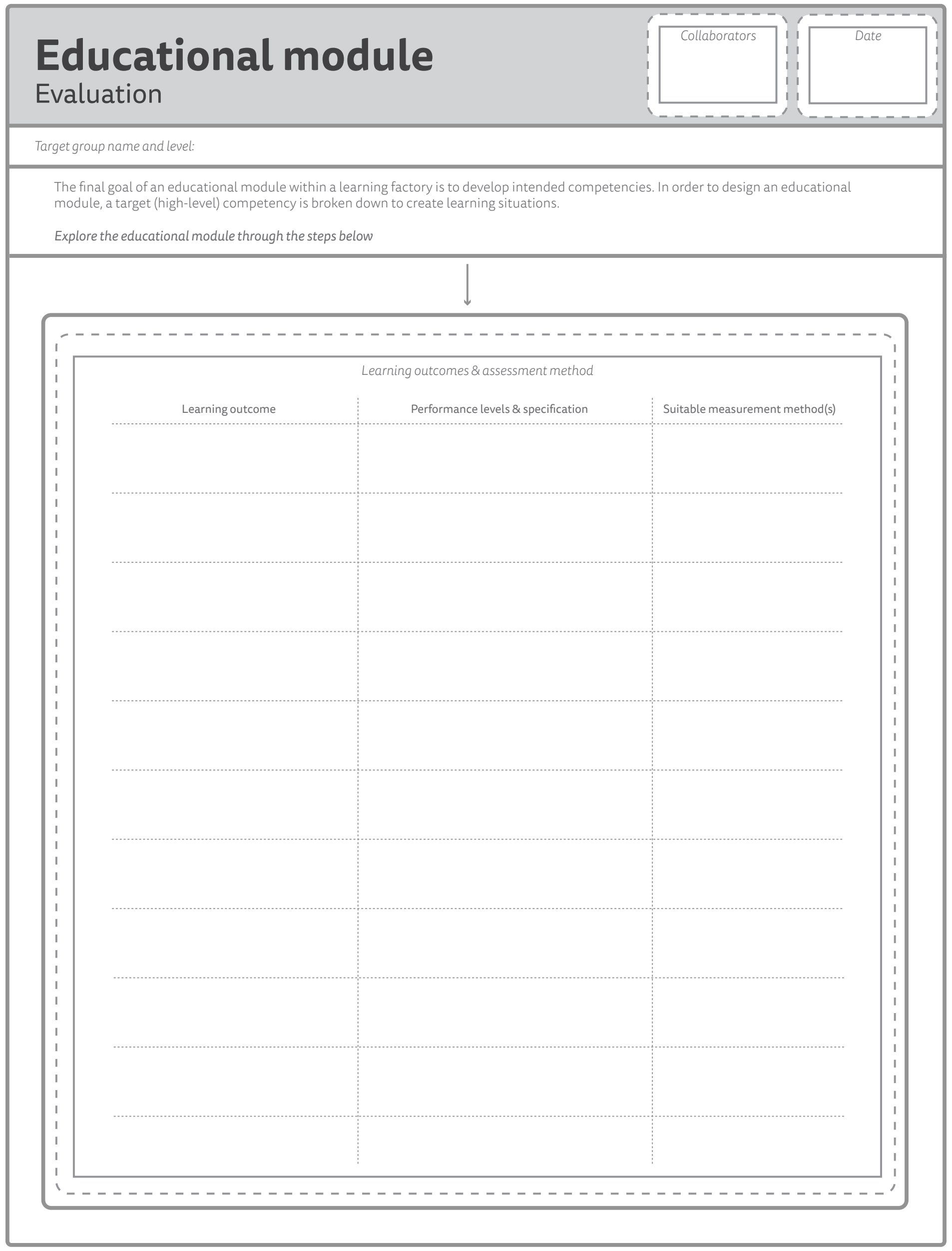
Action-oriented learning outcomes

Knowledge-oriented learning outcomes

Learning outcomes & assessment method

Learning outcome	Action / knowledge	Suitable assessment method(s)

Figure E.11. Educational module evaluation method part 1



Educational module
Evaluation

Collaborators

Date

Target group name and level:

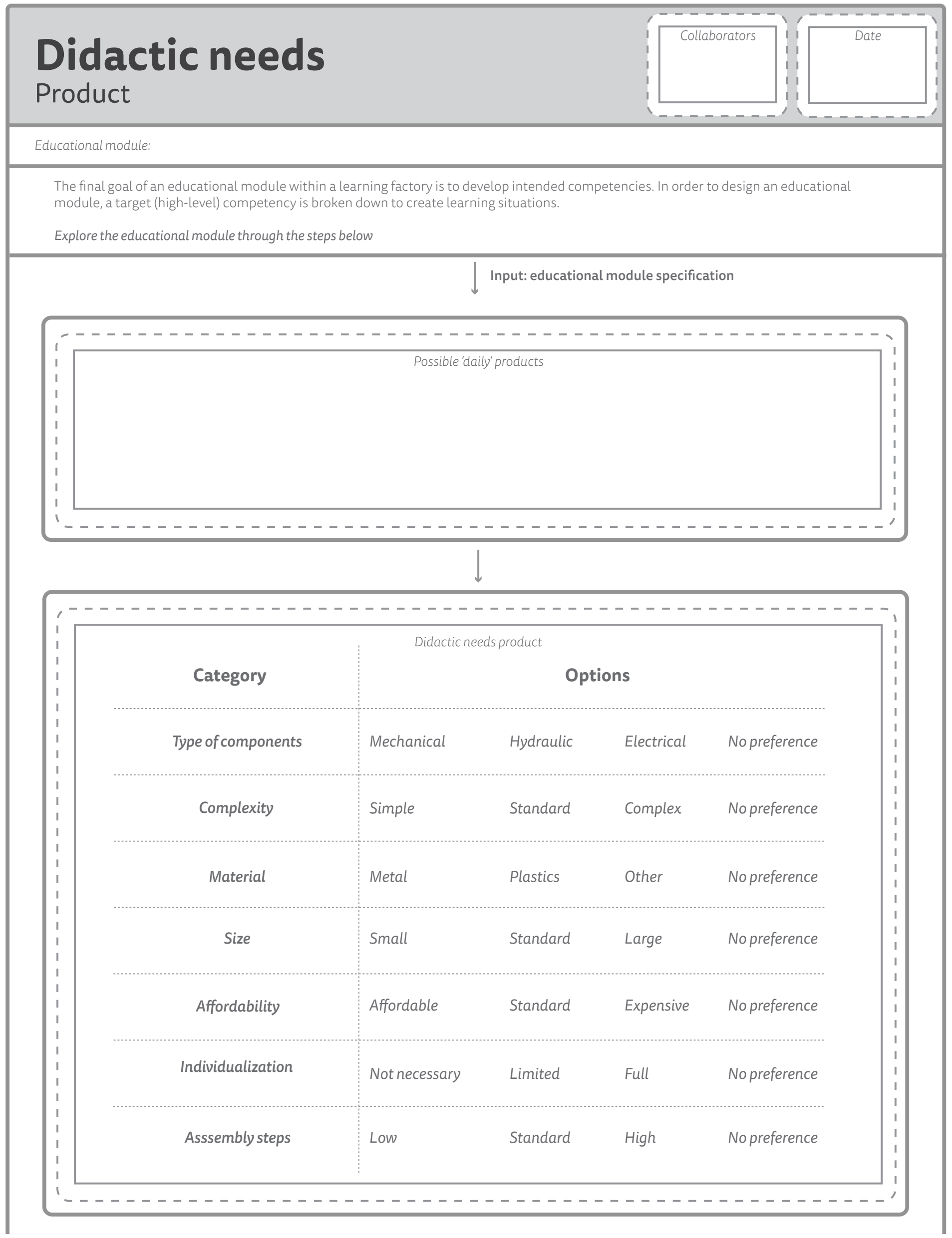
The final goal of an educational module within a learning factory is to develop intended competencies. In order to design an educational module, a target (high-level) competency is broken down to create learning situations.

Explore the educational module through the steps below

Learning outcomes & assessment method

Learning outcome	Performance levels & specification	Suitable measurement method(s)

Figure E.12. Educational module evaluation method part 2



Didactic needs
Product

Collaborators

Date

Educational module:

The final goal of an educational module within a learning factory is to develop intended competencies. In order to design an educational module, a target (high-level) competency is broken down to create learning situations.

Explore the educational module through the steps below

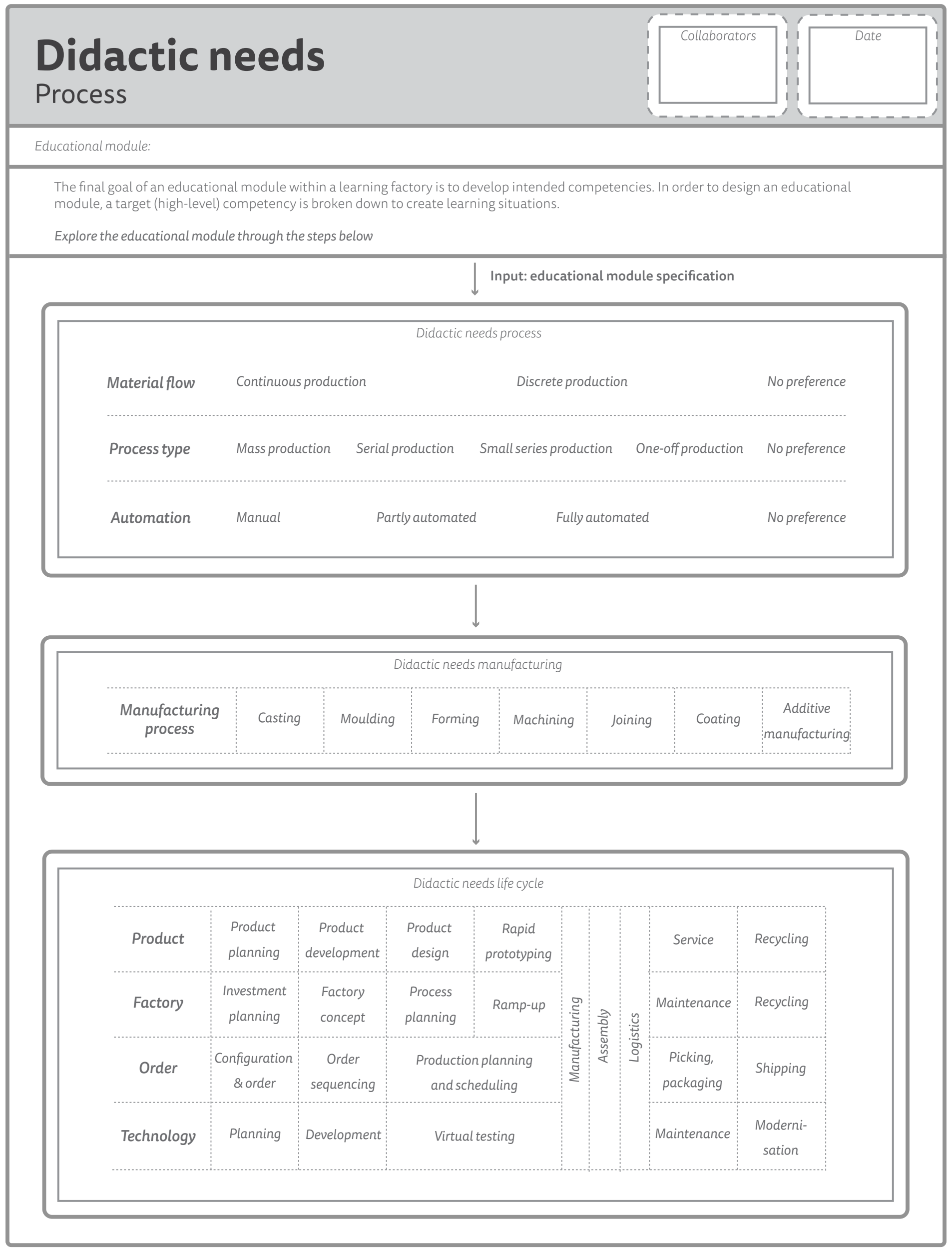
Input: educational module specification

Possible 'daily' products

Didactic needs product

Category	**Options**			
Type of components	*Mechanical*	*Hydraulic*	*Electrical*	*No preference*
Complexity	*Simple*	*Standard*	*Complex*	*No preference*
Material	*Metal*	*Plastics*	*Other*	*No preference*
Size	*Small*	*Standard*	*Large*	*No preference*
Affordability	*Affordable*	*Standard*	*Expensive*	*No preference*
Individualization	*Not necessary*	*Limited*	*Full*	*No preference*
Asssembly steps	*Low*	*Standard*	*High*	*No preference*

Figure E.13. Didactic neds product method



Didactic needs
Process

Collaborators

Date

Educational module:

The final goal of an educational module within a learning factory is to develop intended competencies. In order to design an educational module, a target (high-level) competency is broken down to create learning situations.

Explore the educational module through the steps below

Input: educational module specification

Didactic needs process

Material flow	Continuous production		Discrete production		No preference
Process type	Mass production	Serial production	Small series production	One-off production	No preference
Automation	Manual	Partly automated	Fully automated		No preference

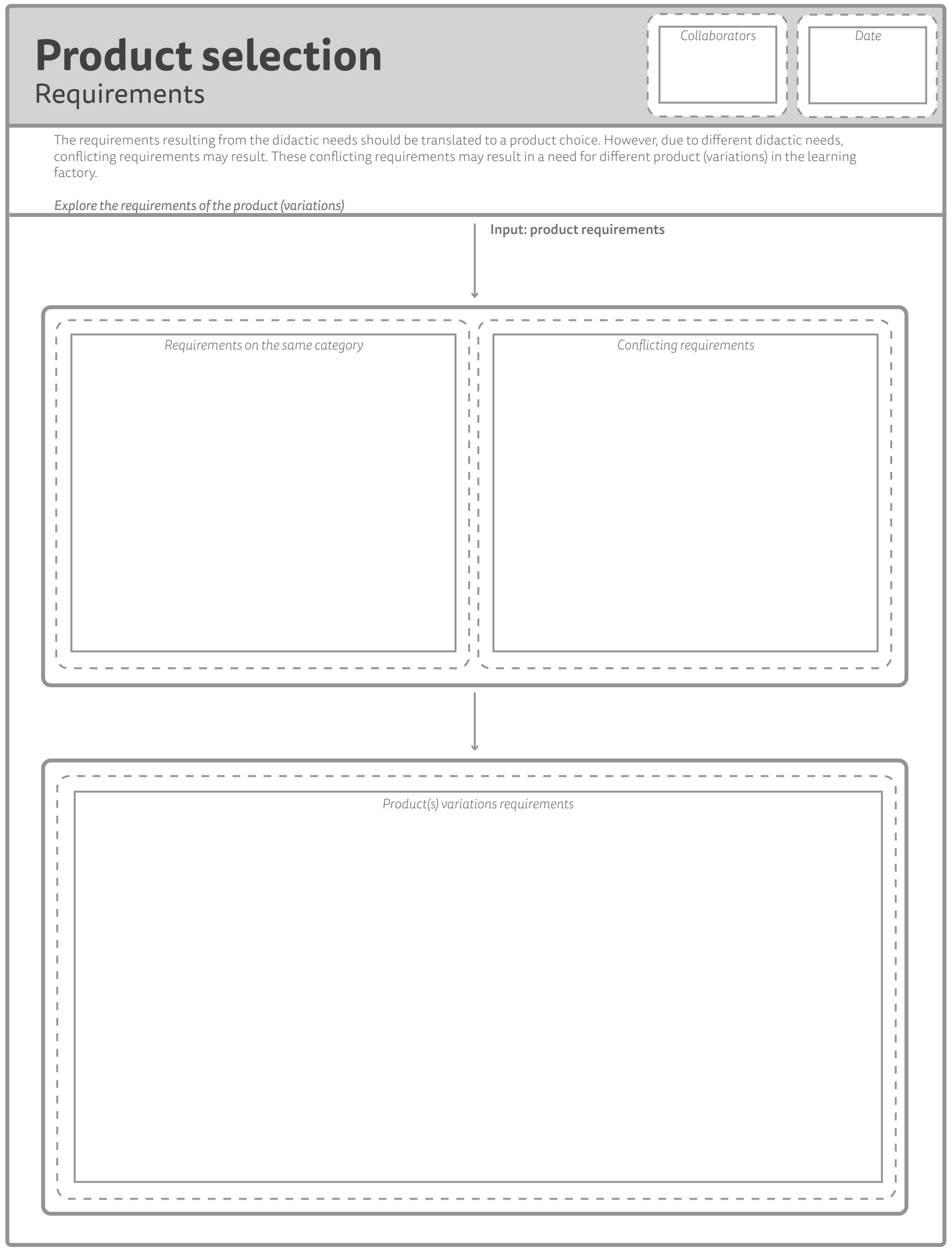
Didactic needs manufacturing

Manufacturing process	Casting	Moulding	Forming	Machining	Joining	Coating	Additive manufacturing

Didactic needs life cycle

Product	Product planning	Product development	Product design	Rapid prototyping	Manufacturing	Assembly	Logistics	Service	Recycling
Factory	Investment planning	Factory concept	Process planning	Ramp-up				Maintenance	Recycling
Order	Configuration & order	Order sequencing	Production planning and scheduling					Picking, packaging	Shipping
Technology	Planning	Development	Virtual testing					Maintenance	Moderni-sation

Figure E.14. Didactic neds process method



Product selection
Requirements

Collaborators

Date

The requirements resulting from the didactic needs should be translated to a product choice. However, due to different didactic needs, conflicting requirements may result. These conflicting requirements may result in a need for different product (variations) in the learning factory.

Explore the requirements of the product (variations)

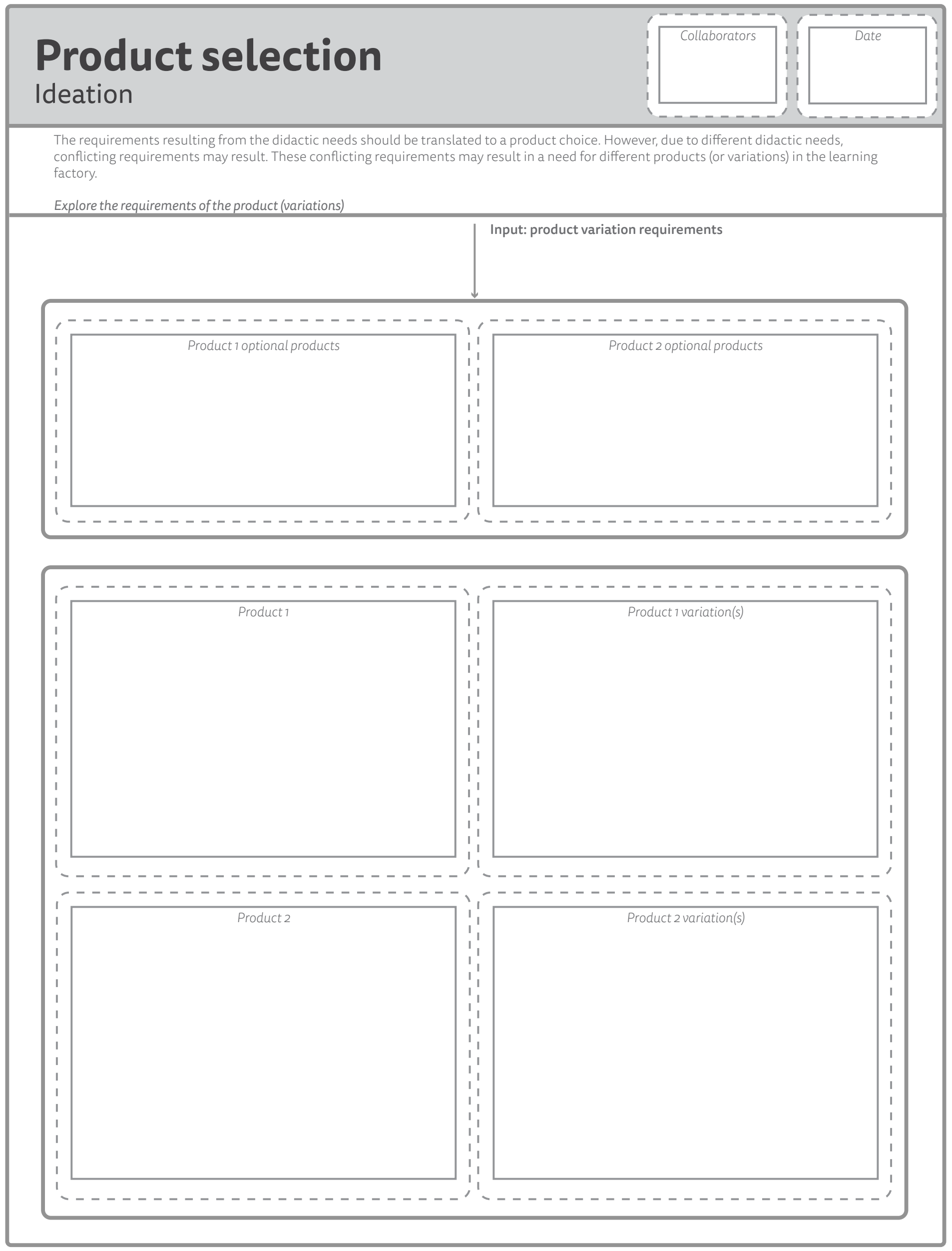
Input: product requirements

Requirements on the same category

Conflicting requirements

Product(s) variations requirements

Figure E.15. Product selection requirements method



Product selection

Ideation

Collaborators

Date

The requirements resulting from the didactic needs should be translated to a product choice. However, due to different didactic needs, conflicting requirements may result. These conflicting requirements may result in a need for different products (or variations) in the learning factory.

Explore the requirements of the product (variations)

Input: product variation requirements

Product 1 optional products

Product 2 optional products

Product 1

Product 1 variation(s)

Product 2

Product 2 variation(s)

Figure E.16. Product selection ideation method

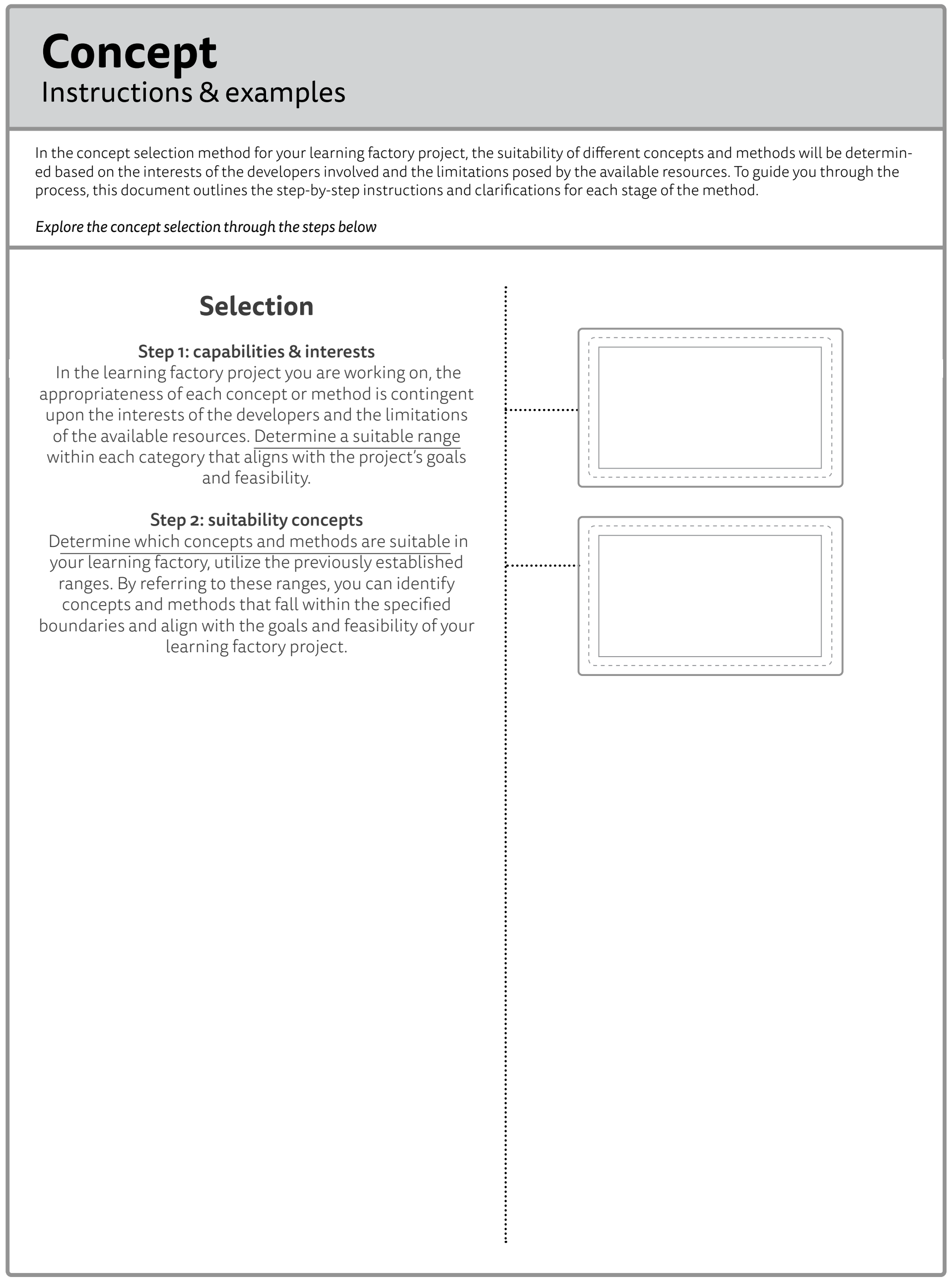
F

Other design guide components

Appendix F Other design guide components

F. Other design guide components

F.1 Method instructions & examples



Concept

Instructions & examples

In the concept selection method for your learning factory project, the suitability of different concepts and methods will be determined based on the interests of the developers involved and the limitations posed by the available resources. To guide you through the process, this document outlines the step-by-step instructions and clarifications for each stage of the method.

Explore the concept selection through the steps below

Selection

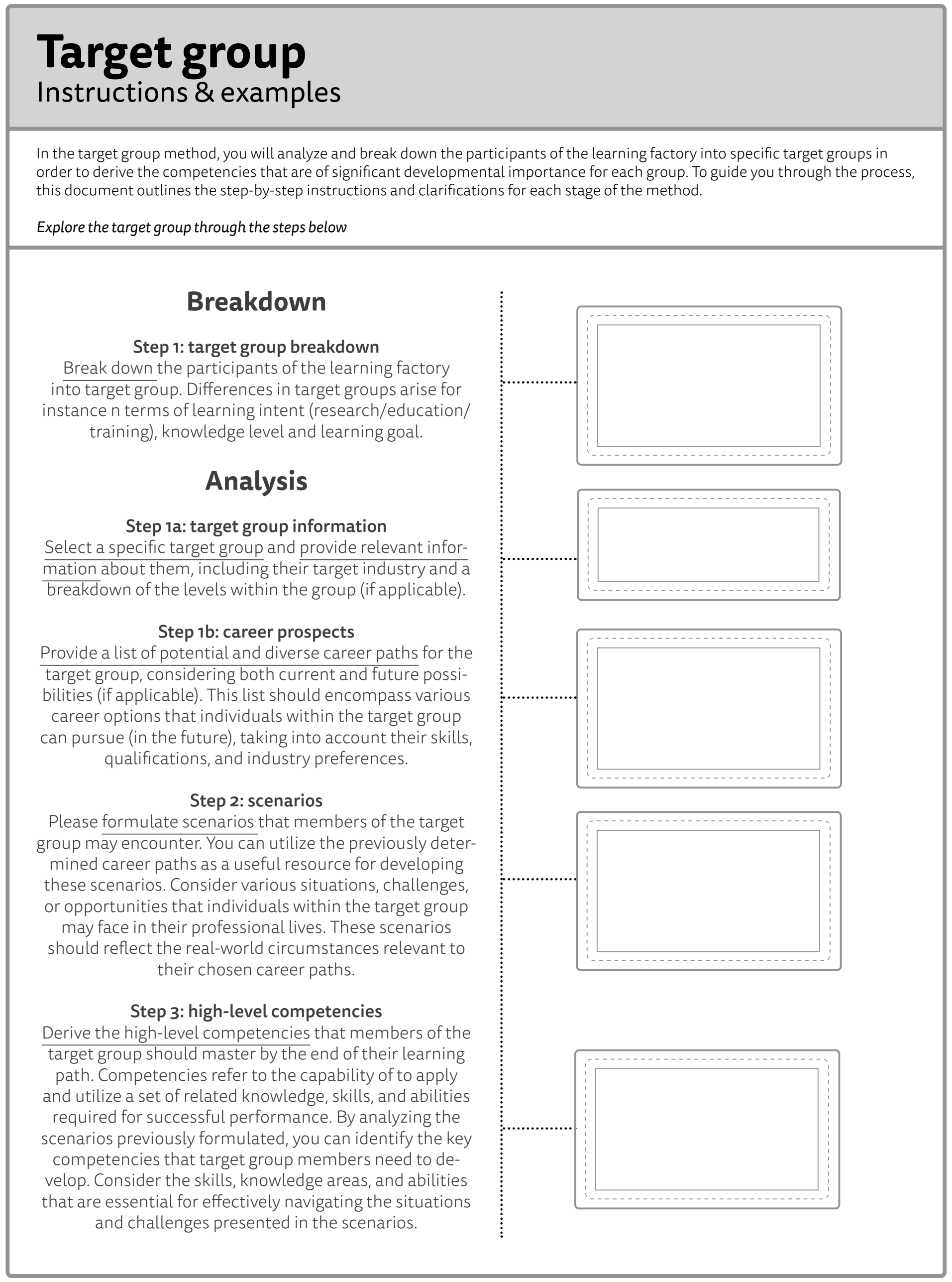
Step 1: capabilities & interests

In the learning factory project you are working on, the appropriateness of each concept or method is contingent upon the interests of the developers and the limitations of the available resources. Determine a suitable range within each category that aligns with the project's goals and feasibility.

Step 2: suitability concepts

Determine which concepts and methods are suitable in your learning factory, utilize the previously established ranges. By referring to these ranges, you can identify concepts and methods that fall within the specified boundaries and align with the goals and feasibility of your learning factory project.

Figure F.1. Concept instructions and examples



Target group

Instructions & examples

In the target group method, you will analyze and break down the participants of the learning factory into specific target groups in order to derive the competencies that are of significant developmental importance for each group. To guide you through the process, this document outlines the step-by-step instructions and clarifications for each stage of the method.

Explore the target group through the steps below

Breakdown

Step 1: target group breakdown
Break down the participants of the learning factory into target group. Differences in target groups arise for instance n terms of learning intent (research/education/training), knowledge level and learning goal.

Analysis

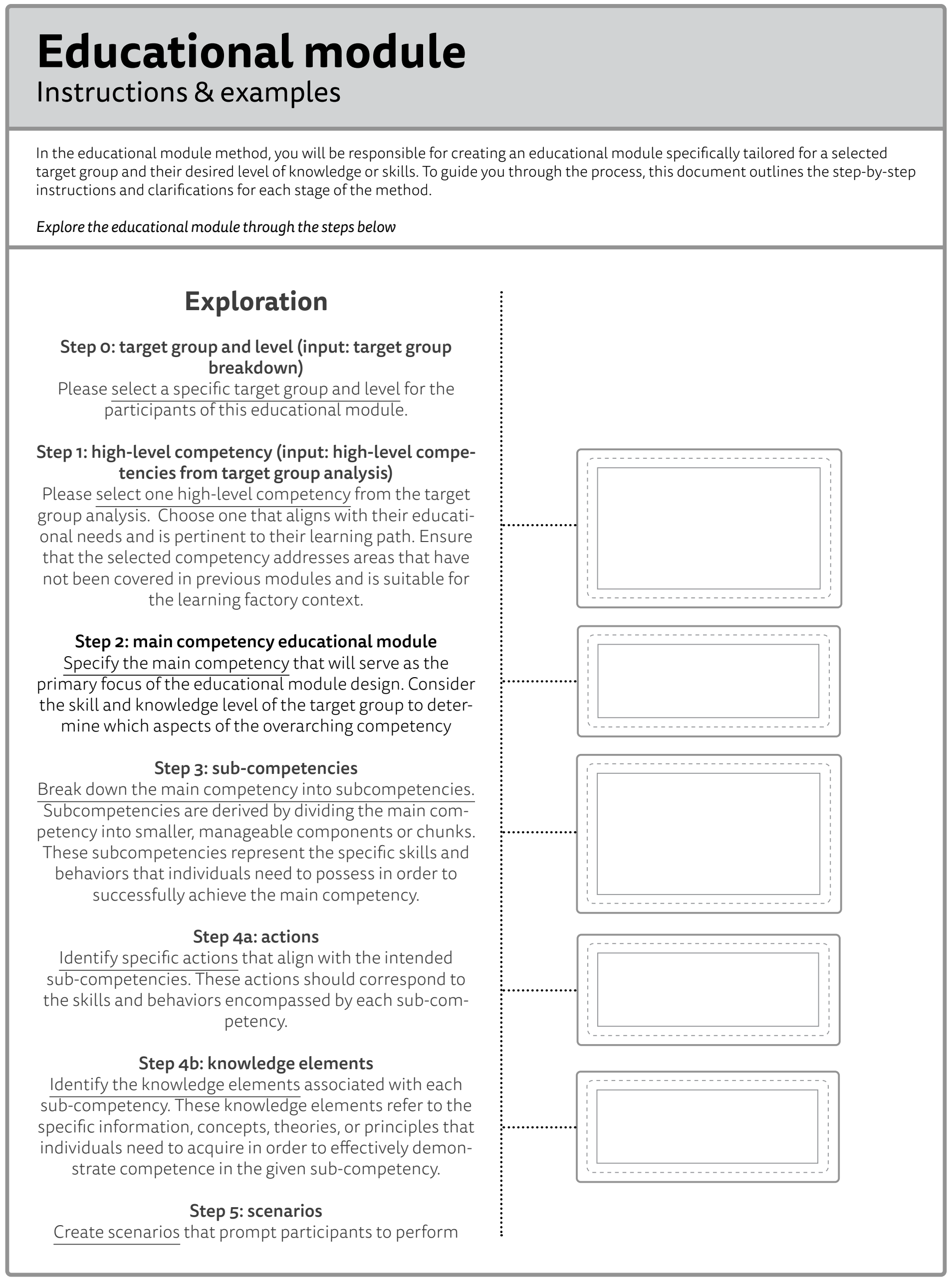
Step 1a: target group information
Select a specific target group and provide relevant information about them, including their target industry and a breakdown of the levels within the group (if applicable).

Step 1b: career prospects
Provide a list of potential and diverse career paths for the target group, considering both current and future possibilities (if applicable). This list should encompass various career options that individuals within the target group can pursue (in the future), taking into account their skills, qualifications, and industry preferences.

Step 2: scenarios
Please formulate scenarios that members of the target group may encounter. You can utilize the previously determined career paths as a useful resource for developing these scenarios. Consider various situations, challenges, or opportunities that individuals within the target group may face in their professional lives. These scenarios should reflect the real-world circumstances relevant to their chosen career paths.

Step 3: high-level competencies
Derive the high-level competencies that members of the target group should master by the end of their learning path. Competencies refer to the capability of to apply and utilize a set of related knowledge, skills, and abilities required for successful performance. By analyzing the scenarios previously formulated, you can identify the key competencies that target group members need to develop. Consider the skills, knowledge areas, and abilities that are essential for effectively navigating the situations and challenges presented in the scenarios.

Figure F.2. Target group instructions and examples



Educational module

Instructions & examples

In the educational module method, you will be responsible for creating an educational module specifically tailored for a selected target group and their desired level of knowledge or skills. To guide you through the process, this document outlines the step-by-step instructions and clarifications for each stage of the method.

Explore the educational module through the steps below

Exploration

Step 0: target group and level (input: target group breakdown)
Please select a specific target group and level for the participants of this educational module.

Step 1: high-level competency (input: high-level competencies from target group analysis)
Please select one high-level competency from the target group analysis. Choose one that aligns with their educational needs and is pertinent to their learning path. Ensure that the selected competency addresses areas that have not been covered in previous modules and is suitable for the learning factory context.

Step 2: main competency educational module
Specify the main competency that will serve as the primary focus of the educational module design. Consider the skill and knowledge level of the target group to determine which aspects of the overarching competency

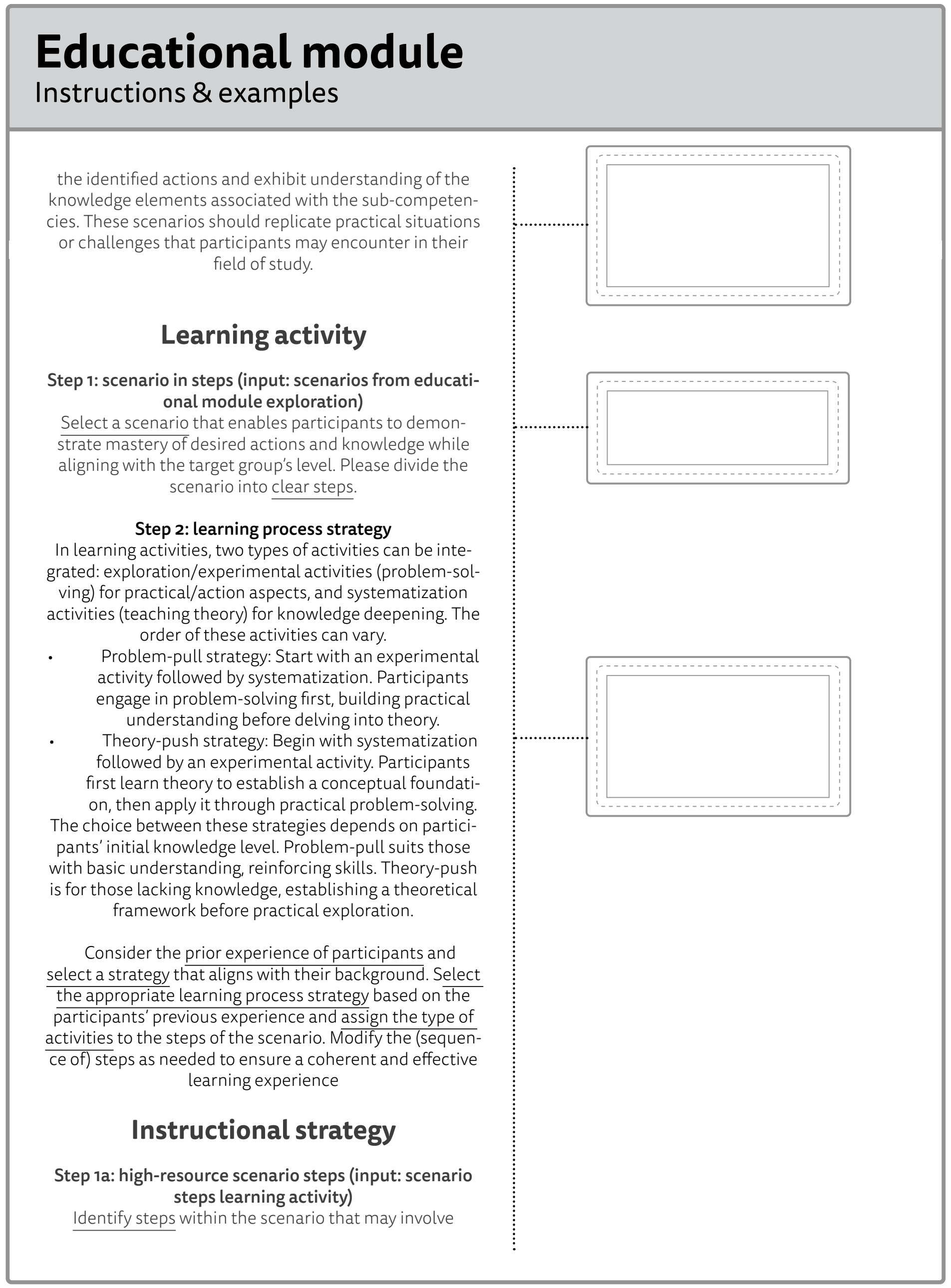
Step 3: sub-competencies
Break down the main competency into subcompetencies. Subcompetencies are derived by dividing the main competency into smaller, manageable components or chunks. These subcompetencies represent the specific skills and behaviors that individuals need to possess in order to successfully achieve the main competency.

Step 4a: actions
Identify specific actions that align with the intended sub-competencies. These actions should correspond to the skills and behaviors encompassed by each sub-competency.

Step 4b: knowledge elements
Identify the knowledge elements associated with each sub-competency. These knowledge elements refer to the specific information, concepts, theories, or principles that individuals need to acquire in order to effectively demonstrate competence in the given sub-competency.

Step 5: scenarios
Create scenarios that prompt participants to perform

Figure F.3. Educational module instructions and examples part 1



Educational module
Instructions & examples

the identified actions and exhibit understanding of the knowledge elements associated with the sub-competencies. These scenarios should replicate practical situations or challenges that participants may encounter in their field of study.

Learning activity

Step 1: scenario in steps (input: scenarios from educational module exploration)
Select a scenario that enables participants to demonstrate mastery of desired actions and knowledge while aligning with the target group's level. Please divide the scenario into clear steps.

Step 2: learning process strategy
In learning activities, two types of activities can be integrated: exploration/experimental activities (problem-solving) for practical/action aspects, and systematization activities (teaching theory) for knowledge deepening. The order of these activities can vary.

- Problem-pull strategy: Start with an experimental activity followed by systematization. Participants engage in problem-solving first, building practical understanding before delving into theory.
- Theory-push strategy: Begin with systematization followed by an experimental activity. Participants first learn theory to establish a conceptual foundation, then apply it through practical problem-solving.

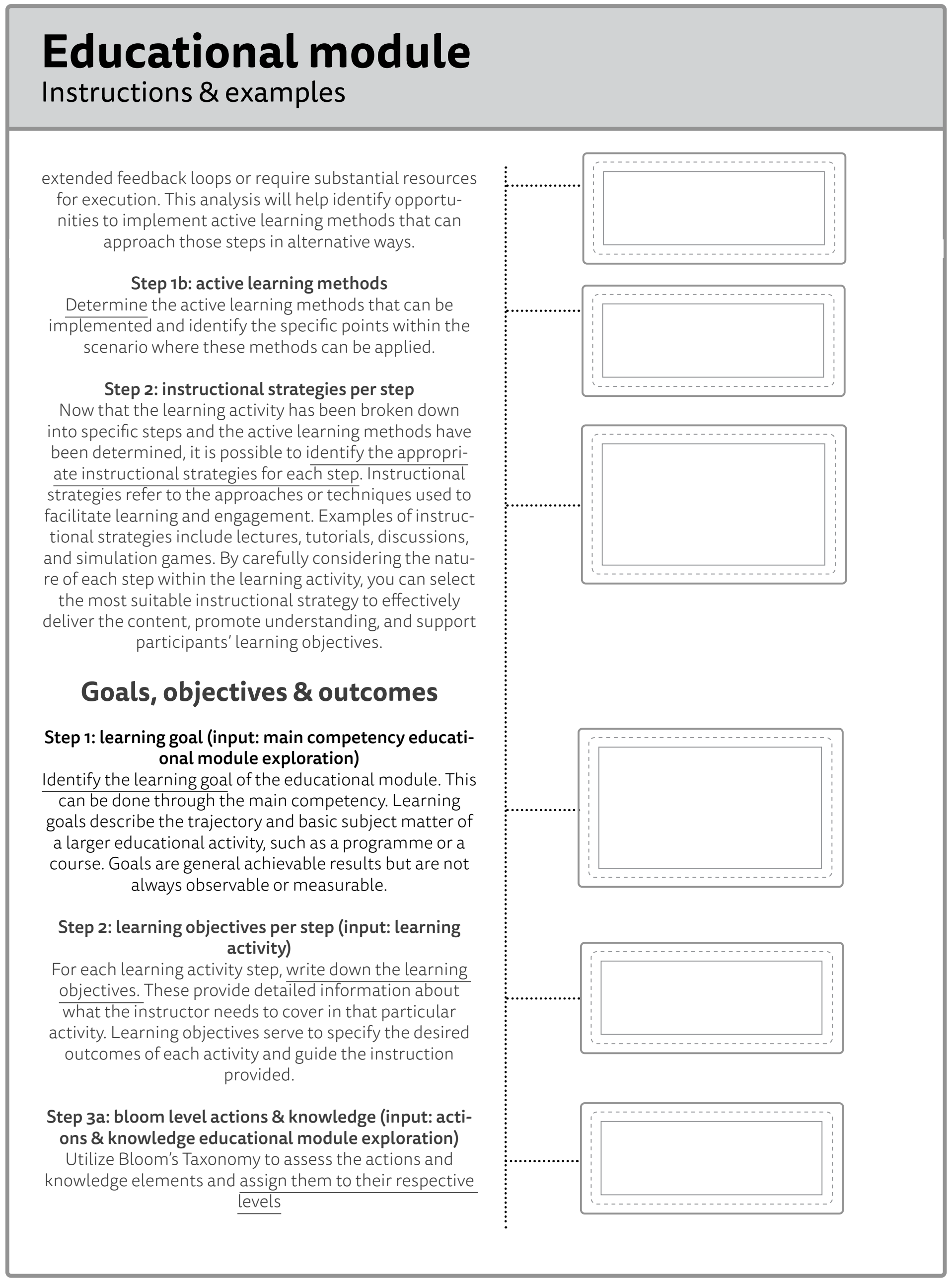
The choice between these strategies depends on participants' initial knowledge level. Problem-pull suits those with basic understanding, reinforcing skills. Theory-push is for those lacking knowledge, establishing a theoretical framework before practical exploration.

Consider the prior experience of participants and select a strategy that aligns with their background. Select the appropriate learning process strategy based on the participants' previous experience and assign the type of activities to the steps of the scenario. Modify the (sequence of) steps as needed to ensure a coherent and effective learning experience

Instructional strategy

Step 1a: high-resource scenario steps (input: scenario steps learning activity)
Identify steps within the scenario that may involve

Figure F.4. Educational module instructions and examples part 2



Educational module
Instructions & examples

extended feedback loops or require substantial resources for execution. This analysis will help identify opportunities to implement active learning methods that can approach those steps in alternative ways.

Step 1b: active learning methods
Determine the active learning methods that can be implemented and identify the specific points within the scenario where these methods can be applied.

Step 2: instructional strategies per step
Now that the learning activity has been broken down into specific steps and the active learning methods have been determined, it is possible to identify the appropriate instructional strategies for each step. Instructional strategies refer to the approaches or techniques used to facilitate learning and engagement. Examples of instructional strategies include lectures, tutorials, discussions, and simulation games. By carefully considering the nature of each step within the learning activity, you can select the most suitable instructional strategy to effectively deliver the content, promote understanding, and support participants' learning objectives.

Goals, objectives & outcomes

Step 1: learning goal (input: main competency educational module exploration)
Identify the learning goal of the educational module. This can be done through the main competency. Learning goals describe the trajectory and basic subject matter of a larger educational activity, such as a programme or a course. Goals are general achievable results but are not always observable or measurable.

Step 2: learning objectives per step (input: learning activity)
For each learning activity step, write down the learning objectives. These provide detailed information about what the instructor needs to cover in that particular activity. Learning objectives serve to specify the desired outcomes of each activity and guide the instruction provided.

Step 3a: bloom level actions & knowledge (input: actions & knowledge educational module exploration)
Utilize Bloom's Taxonomy to assess the actions and knowledge elements and assign them to their respective levels

Figure F.5. Educational module instructions and examples part 3

Educational module
Instructions & examples

Step 3b: numbered learning outcomes
Formulate and number the desired learning outcomes. These outcomes serve as specific statements that specify achievable behaviors or actions students should be able to demonstrate by the end of a learning activity. To enhance their effectiveness, learning outcomes should be student-centered, measurable, and observable. To facilitate the selection of appropriate words, Bloom's Taxonomy can be leveraged. Each level of the taxonomy offers a framework for choosing clear and precise verbs that align with the desired depth of understanding and application.

Evaluation

Step 1: action & knowledge learning outcomes (input: learning outcomes)
When it comes to assessing learning outcomes, it's important to use different methods depending on whether the focus is on action-oriented skills or knowledge-oriented understanding. Categorize and seperate the learning outcomes accordingly.

Step 2: learning outcomes & assessment methods
For each learning outcome, determine the suitable assessment method based on its action- or knowledge-oriented nature. For action-oriented learning outcomes, assessment methods that emphasize practical application and performance are often more suitable (such as performance-based assessment, project-based assessments or portfolios). On the other hand, for knowledge-oriented learning outcomes, assessment methods that focus on measuring understanding and comprehension are more suitable (such as written assessments, oral presentations, or research papers).

Step 3a: Performance levels & measurement
When assessing learning outcomes, it is essential to establish clear criteria for determining the level of success and the extent to which a performance meets those criteria. Define distinct performance levels for each learning outcome, outlining what needs to be done to reach each level. For instance, performance levels could be categorized as basic, proficient, and advanced, with corresponding descriptions of the required skills, knowledge, and abilities at each level. Additionally, specify suitable measurement method(s) on how to collect data for assessment.

Figure F.5. Educational module instructions and examples part 4

Didactic needs
Instructions & examples

The didactic needs method involves identifying requirements for each educational module on the product and process in the learning factory. To guide you through the process, this document outlines the step-by-step instructions and clarifications for each stage of the method.

Explore the didactic needs through the steps below

Product

Step 1: possible 'daily' products (input: educational module specification)
Provide a list of everyday products that you believe would be suitable for use in the educational modules created for the learning factory. This list will help you identify some of the didactic needs in the later stages of the method.

Step 2: didactic needs product
Please go through each category and circle the option that corresponds to the didactic needs for the product of the educational module. If a particular category is not important or does not have a specific preference in the educational module, please select the "No Preference" option.

Process

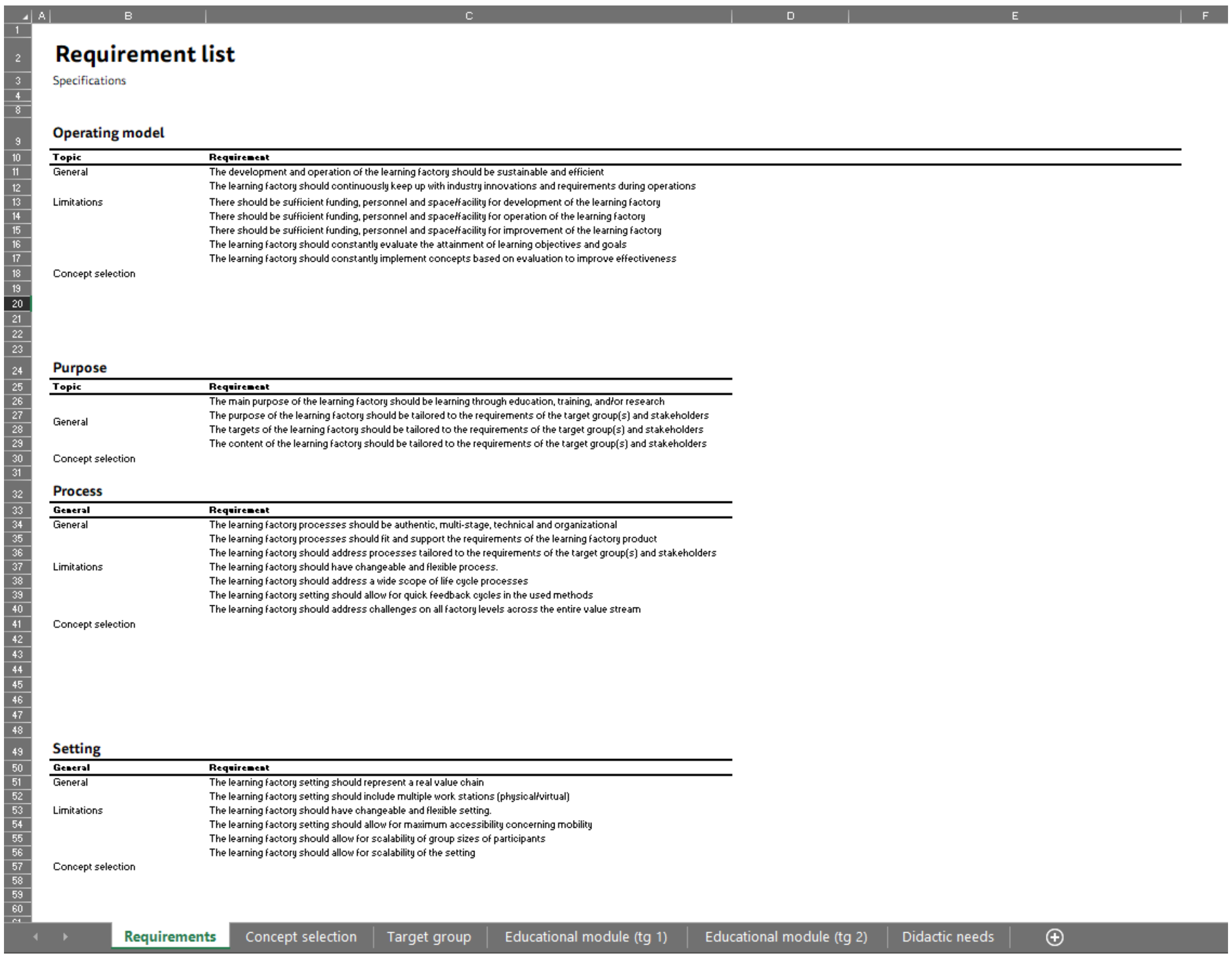
Step 1: didactic needs process
Please review each category and indicate the option that corresponds to the didactic needs specific to the process for the educational module. If a particular category is not important or does not hold a specific preference in the educational module, please select the "No Preference" option.

Step 2: didactic needs manufacturing
Please identify and highlight the manufacturing processes that are crucial to incorporate in the educational module.

Step 3: didactic needs life cycle
Please identify and highlight the life cycle stages that are crucial to incorporate in the educational module.

Figure F.4. Didactic needs instructions and examples

F.2 Impressions of requirements/specifications spreadsheet



Requirement list

Specifications

Operating model

Topic	**Requirement**
General	The development and operation of the learning factory should be sustainable and efficient
	The learning factory should continuously keep up with industry innovations and requirements during operations
Limitations	There should be sufficient funding, personnel and space/facility for development of the learning factory
	There should be sufficient funding, personnel and space/facility for operation of the learning factory
	There should be sufficient funding, personnel and space/facility for improvement of the learning factory
	The learning factory should constantly evaluate the attainment of learning objectives and goals
	The learning factory should constantly implement concepts based on evaluation to improve effectiveness
Concept selection	

Purpose

Topic	**Requirement**
	The main purpose of the learning factory should be learning through education, training, and/or research
General	The purpose of the learning factory should be tailored to the requirements of the target group(s) and stakeholders
	The targets of the learning factory should be tailored to the requirements of the target group(s) and stakeholders
	The content of the learning factory should be tailored to the requirements of the target group(s) and stakeholders
Concept selection	

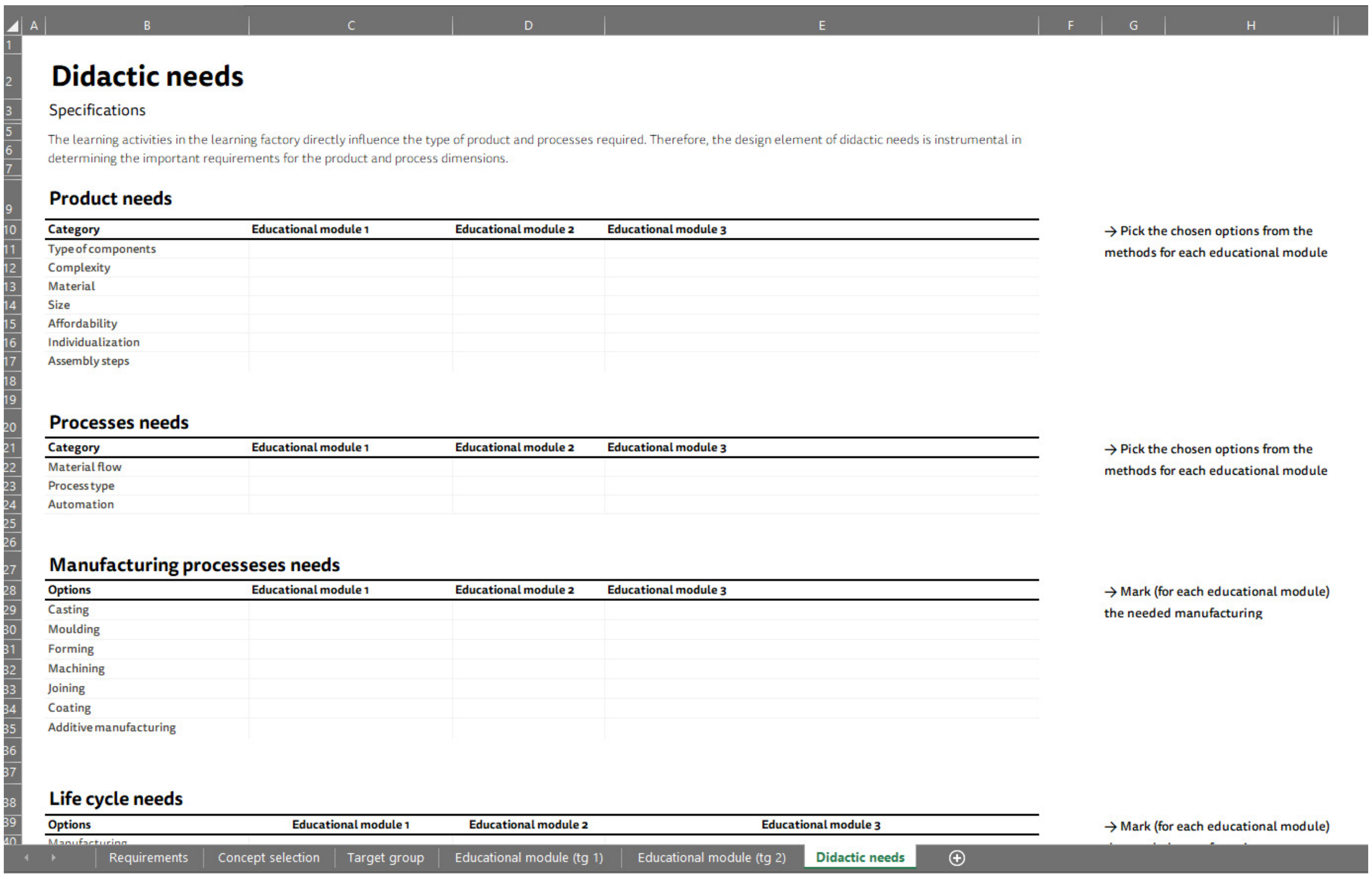
Process

General	**Requirement**
General	The learning factory processes should be authentic, multi-stage, technical and organizational
	The learning factory processes should fit and support the requirements of the learning factory product
	The learning factory should address processes tailored to the requirements of the target group(s) and stakeholders
Limitations	The learning factory should have changeable and flexible process.
	The learning factory should address a wide scope of life cycle processes
	The learning factory setting should allow for quick feedback cycles in the used methods
	The learning factory should address challenges on all factory levels across the entire value stream
Concept selection	

Setting

General	**Requirement**
General	The learning factory setting should represent a real value chain
	The learning factory setting should include multiple work stations (physical/virtual)
Limitations	The learning factory should have changeable and flexible setting.
	The learning factory setting should allow for maximum accessibility concerning mobility
	The learning factory should allow for scalability of group sizes of participants
	The learning factory should allow for scalability of the setting
Concept selection	

Figure F.5. Impression of requirements in the spreadsheet



Didactic needs

Specifications

The learning activities in the learning factory directly influence the type of product and processes required. Therefore, the design element of didactic needs is instrumental in determining the important requirements for the product and process dimensions.

Product needs

Category	**Educational module 1**	**Educational module 2**	**Educational module 3**
Type of components			
Complexity			
Material			
Size			
Affordability			
Individualization			
Assembly steps			

→ Pick the chosen options from the methods for each educational module

Processes needs

Category	**Educational module 1**	**Educational module 2**	**Educational module 3**
Material flow			
Process type			
Automation			

→ Pick the chosen options from the methods for each educational module

Manufacturing processeses needs

Options	**Educational module 1**	**Educational module 2**	**Educational module 3**
Casting			
Moulding			
Forming			
Machining			
Joining			
Coating			
Additive manufacturing			

→ Mark (for each educational module) the needed manufacturing

Life cycle needs

Options	**Educational module 1**	**Educational module 2**	**Educational module 3**

→ Mark (for each educational module)

Figure F.6. Impression of specifications in the spreadsheet

G

Case study

Appendix G Case study

G. Case study

G.1 Case study methods

Concept
Suitability

Collaborators

Date

Different variations of learning factories, incorporating diverse concepts and methods, have the potential to overcome limitations and optimize outcomes. The appropriateness of each concept or method is contingent upon the interests and capabilities of the developer or those involved in the process.

Explore the suitability of the concepts through the steps below

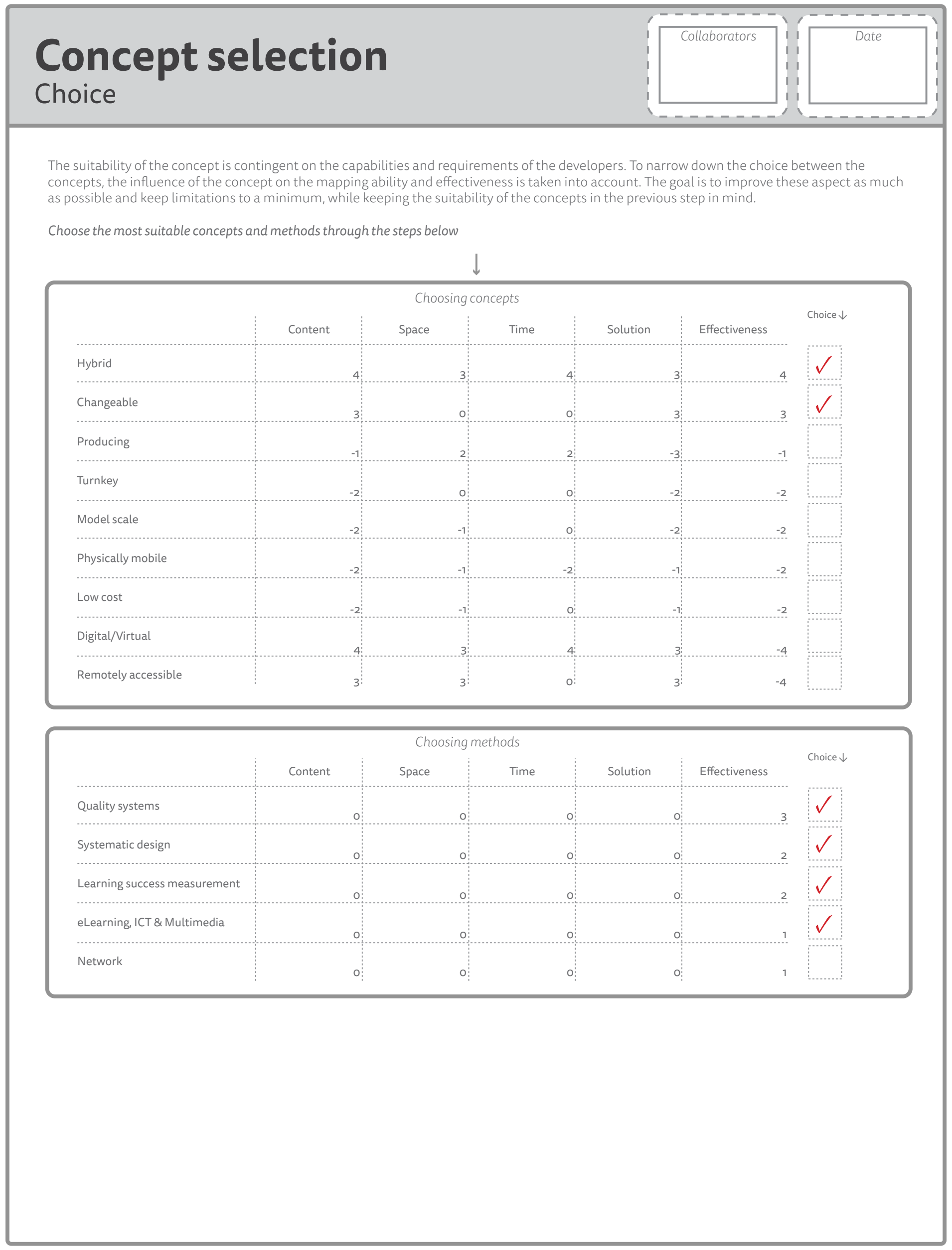
Capabilities / interests

	-4	-3	-2	-1	0	1	2	3	4	Range (>) ↓
Financial resources	no concern	X	high		medium		low		no resources	> -3
Personal resources (effort)	no concern X		high		medium		low		no resources	> -4
Spacial resources	no concern		high X		medium		low		no resources	> -2
Scalability requirements	no concern		low		medium X		high		very scalable	> 0
Mobility requirements	no concern X		low		medium		high		fully mobile	> -4

Suitability concepts

	Financial	Personal	Spacial	Scalability	Mobility	Suitability ↓
Model scale	3	3	3	-2	0	☐
Physically mobile	1	0	4	1	4	✓
Low cost	4	3	0	0	0	✓
Producing	2	0	0	0	-4	✓
Digital/Virtual	2	0	3	3	4	✓
Hybrid	-3	-3	0	2	1	✓
Remotely accessible	3	2	4	4	4	✓
Changeability	-3	-3	0	2	0	✓
Turnkey	2	3	0	0	0	✓
eLearning, ICT & Multimedia	-1	-1	0	1	0	✓
Systematic design	0	2	0	0	0	✓
Learning success measurement	0	-1	0	0	0	✓
Quality systems	-1	-1	0	0	0	✓
Network	1	1	0	0	0	✓

Figure G.1. Case study concept selection



Concept selection
Choice

Collaborators

Date

The suitability of the concept is contingent on the capabilities and requirements of the developers. To narrow down the choice between the concepts, the influence of the concept on the mapping ability and effectiveness is taken into account. The goal is to improve these aspect as much as possible and keep limitations to a minimum, while keeping the suitability of the concepts in the previous step in mind.

Choose the most suitable concepts and methods through the steps below

↓

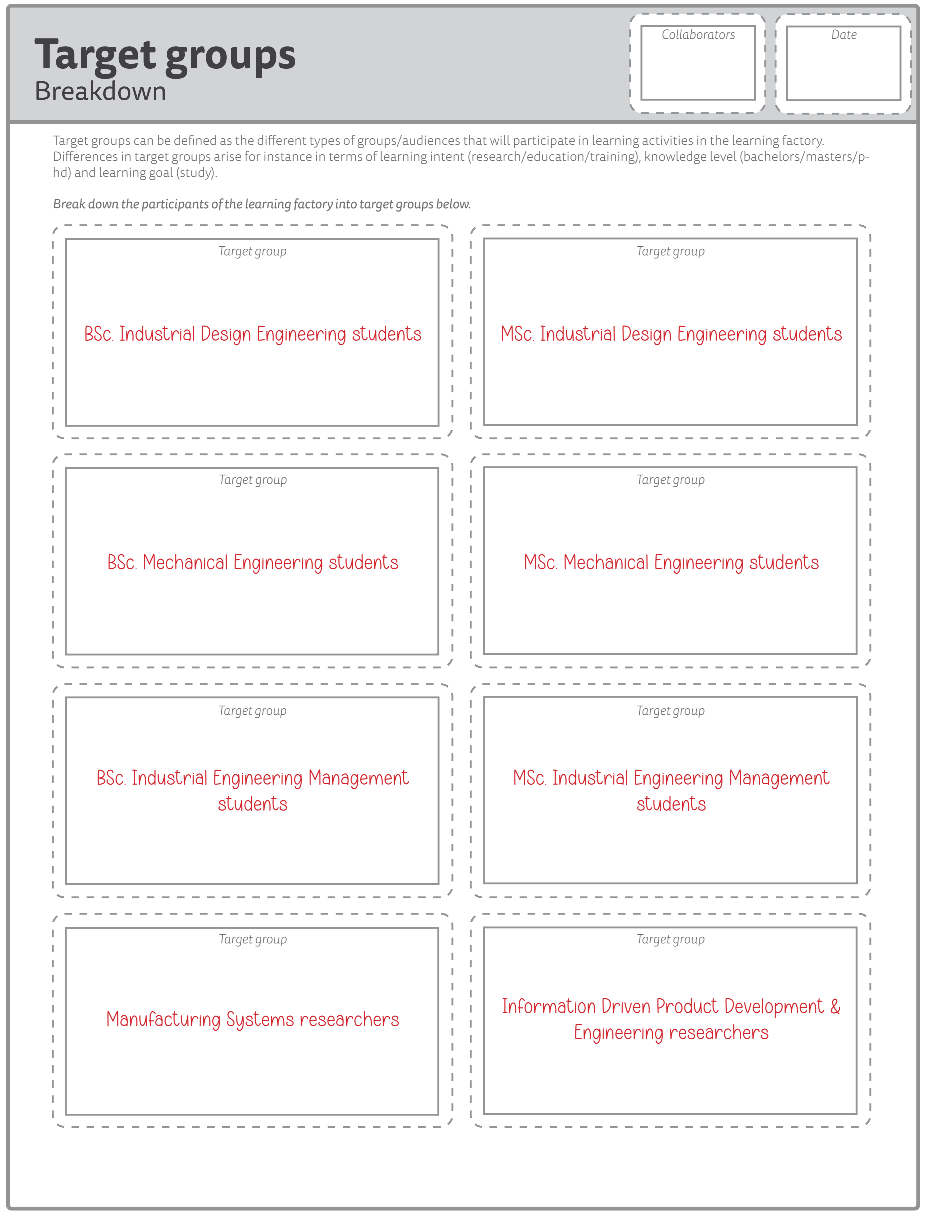
Choosing concepts

	Content	Space	Time	Solution	Effectiveness	Choice ↓
Hybrid	4	3	4	3	4	☑
Changeable	3	0	0	3	3	☑
Producing	-1	2	2	-3	-1	☐
Turnkey	-2	0	0	-2	-2	☐
Model scale	-2	-1	0	-2	-2	☐
Physically mobile	-2	-1	-2	-1	-2	☐
Low cost	-2	-1	0	-1	-2	☐
Digital/Virtual	4	3	4	3	-4	☐
Remotely accessible	3	3	0	3	-4	☐

Choosing methods

	Content	Space	Time	Solution	Effectiveness	Choice ↓
Quality systems	0	0	0	0	3	☑
Systematic design	0	0	0	0	2	☑
Learning success measurement	0	0	0	0	2	☑
eLearning, ICT & Multimedia	0	0	0	0	1	☑
Network	0	0	0	0	1	☐

Figure G.2. Case study concept choice



Target groups
Breakdown

Collaborators

Date

Target groups can be defined as the different types of groups/audiences that will participate in learning activities in the learning factory. Differences in target groups arise for instance in terms of learning intent (research/education/training), knowledge level (bachelors/masters/p-hd) and learning goal (study).

Break down the participants of the learning factory into target groups below.

Target group
BSc. Industrial Design Engineering students

Target group
MSc. Industrial Design Engineering students

Target group
BSc. Mechanical Engineering students

Target group
MSc. Mechanical Engineering students

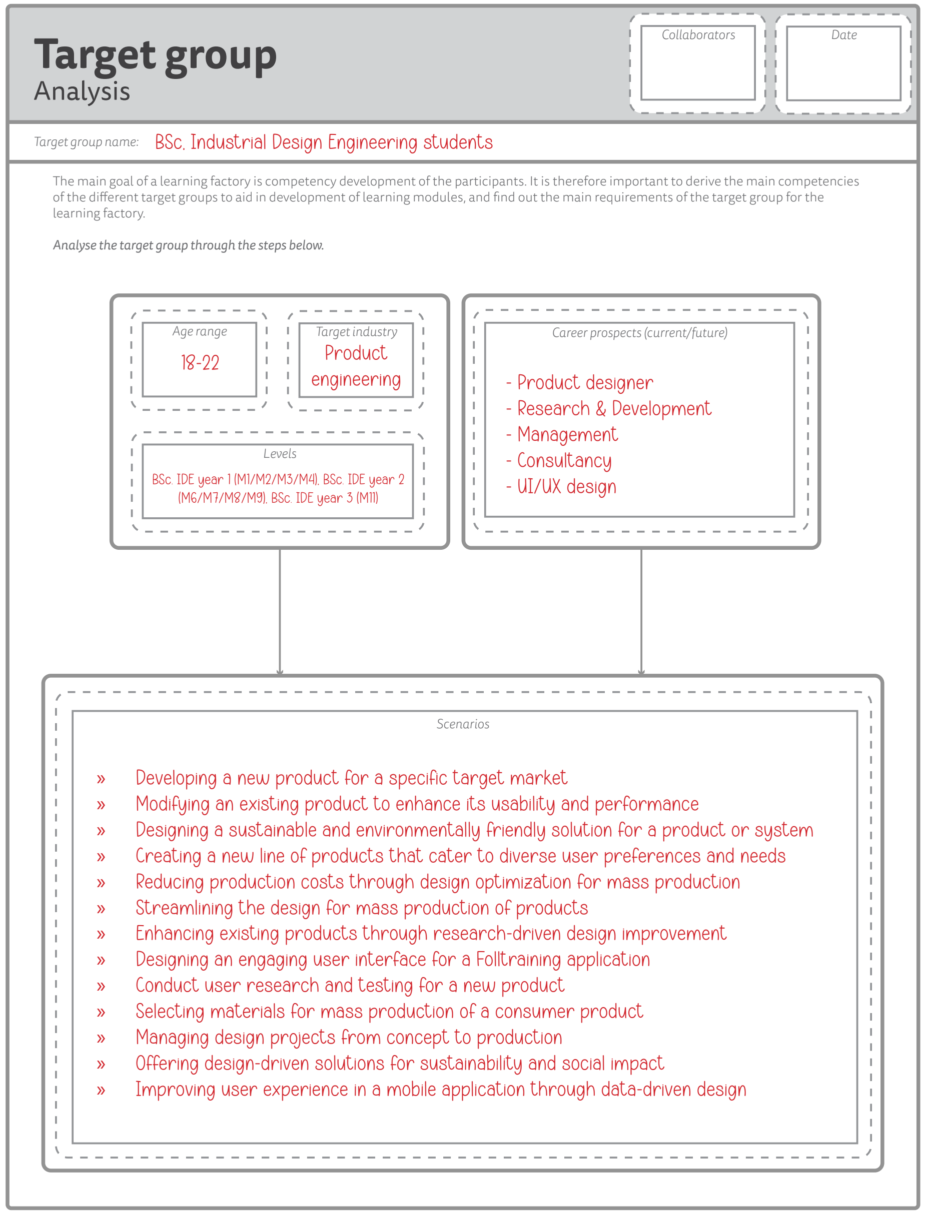
Target group
BSc. Industrial Engineering Management students

Target group
MSc. Industrial Engineering Management students

Target group
Manufacturing Systems researchers

Target group
Information Driven Product Development & Engineering researchers

Figure G.3. Case study target group breakdown



Target group
Analysis

Collaborators

Date

Target group name: BSc. Industrial Design Engineering students

The main goal of a learning factory is competency development of the participants. It is therefore important to derive the main competencies of the different target groups to aid in development of learning modules, and find out the main requirements of the target group for the learning factory.

Analyse the target group through the steps below.

Age range
18-22

Target industry
Product engineering

Levels
BSc. IDE year 1 (M1/M2/M3/M4), BSc. IDE year 2 (M6/M7/M8/M9), BSc. IDE year 3 (M11)

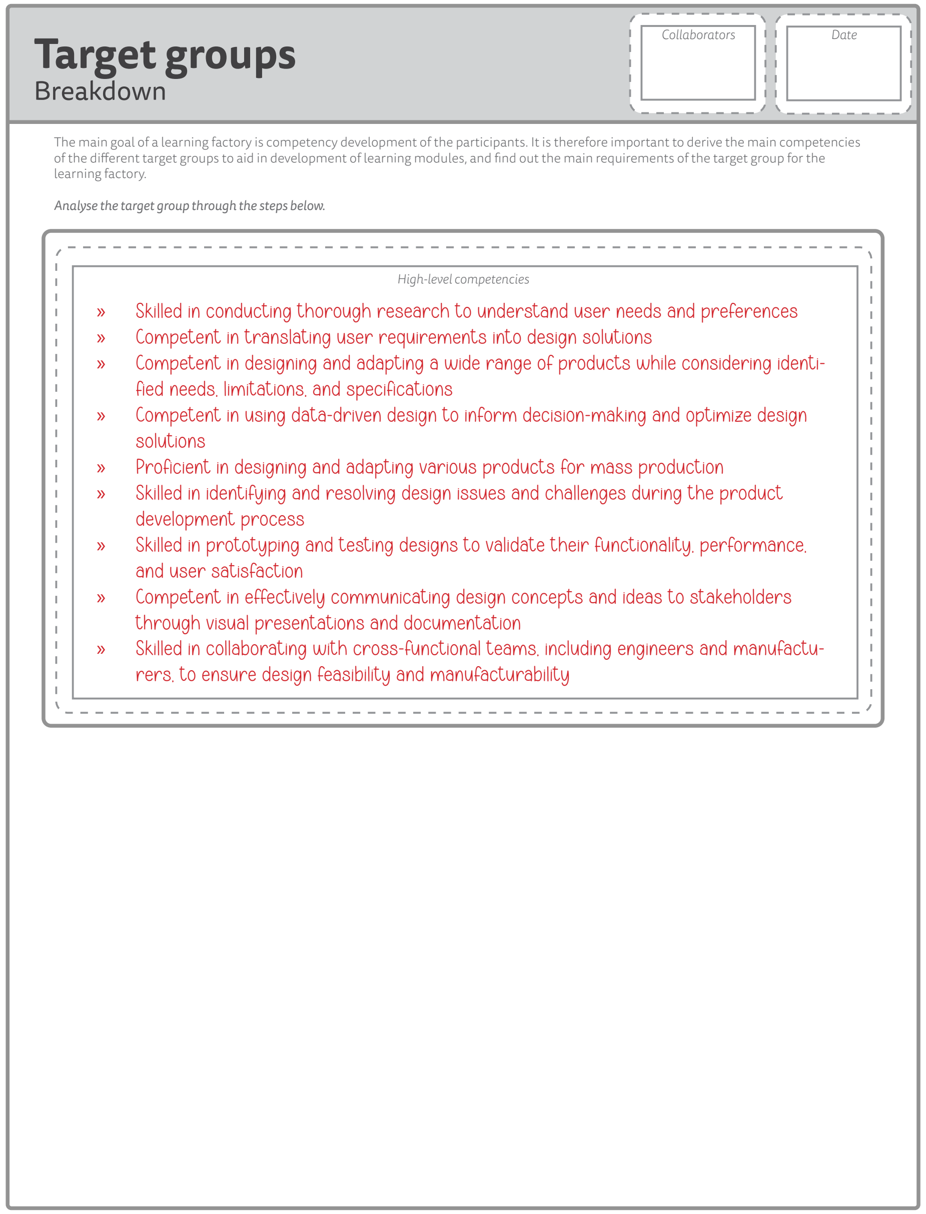
Career prospects (current/future)

- Product designer
- Research & Development
- Management
- Consultancy
- UI/UX design

Scenarios

» Developing a new product for a specific target market
» Modifying an existing product to enhance its usability and performance
» Designing a sustainable and environmentally friendly solution for a product or system
» Creating a new line of products that cater to diverse user preferences and needs
» Reducing production costs through design optimization for mass production
» Streamlining the design for mass production of products
» Enhancing existing products through research-driven design improvement
» Designing an engaging user interface for a Folltraining application
» Conduct user research and testing for a new product
» Selecting materials for mass production of a consumer product
» Managing design projects from concept to production
» Offering design-driven solutions for sustainability and social impact
» Improving user experience in a mobile application through data-driven design

Figure G.4. Case study target group analysis part 1



Target groups
Breakdown

Collaborators

Date

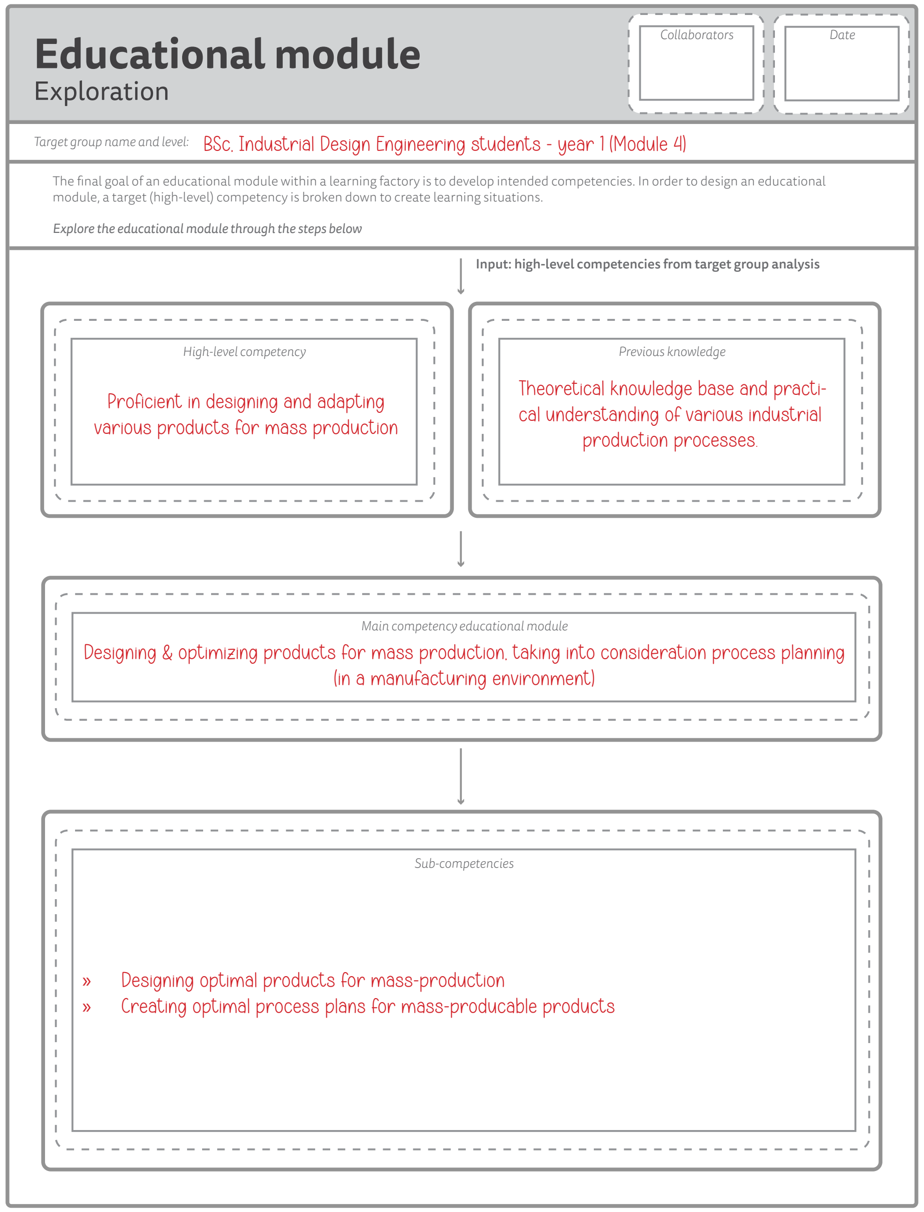
The main goal of a learning factory is competency development of the participants. It is therefore important to derive the main competencies of the different target groups to aid in development of learning modules, and find out the main requirements of the target group for the learning factory.

Analyse the target group through the steps below.

High-level competencies

» Skilled in conducting thorough research to understand user needs and preferences
» Competent in translating user requirements into design solutions
» Competent in designing and adapting a wide range of products while considering identified needs, limitations, and specifications
» Competent in using data-driven design to inform decision-making and optimize design solutions
» Proficient in designing and adapting various products for mass production
» Skilled in identifying and resolving design issues and challenges during the product development process
» Skilled in prototyping and testing designs to validate their functionality, performance, and user satisfaction
» Competent in effectively communicating design concepts and ideas to stakeholders through visual presentations and documentation
» Skilled in collaborating with cross-functional teams, including engineers and manufacturers, to ensure design feasibility and manufacturability

Figure G.5. Case study target group analysis part 2



Educational module

Exploration

Collaborators

Date

Target group name and level: BSc. Industrial Design Engineering students - year 1 (Module 4)

The final goal of an educational module within a learning factory is to develop intended competencies. In order to design an educational module, a target (high-level) competency is broken down to create learning situations.

Explore the educational module through the steps below

Input: high-level competencies from target group analysis

High-level competency

Proficient in designing and adapting various products for mass production

Previous knowledge

Theoretical knowledge base and practical understanding of various industrial production processes.

Main competency educational module

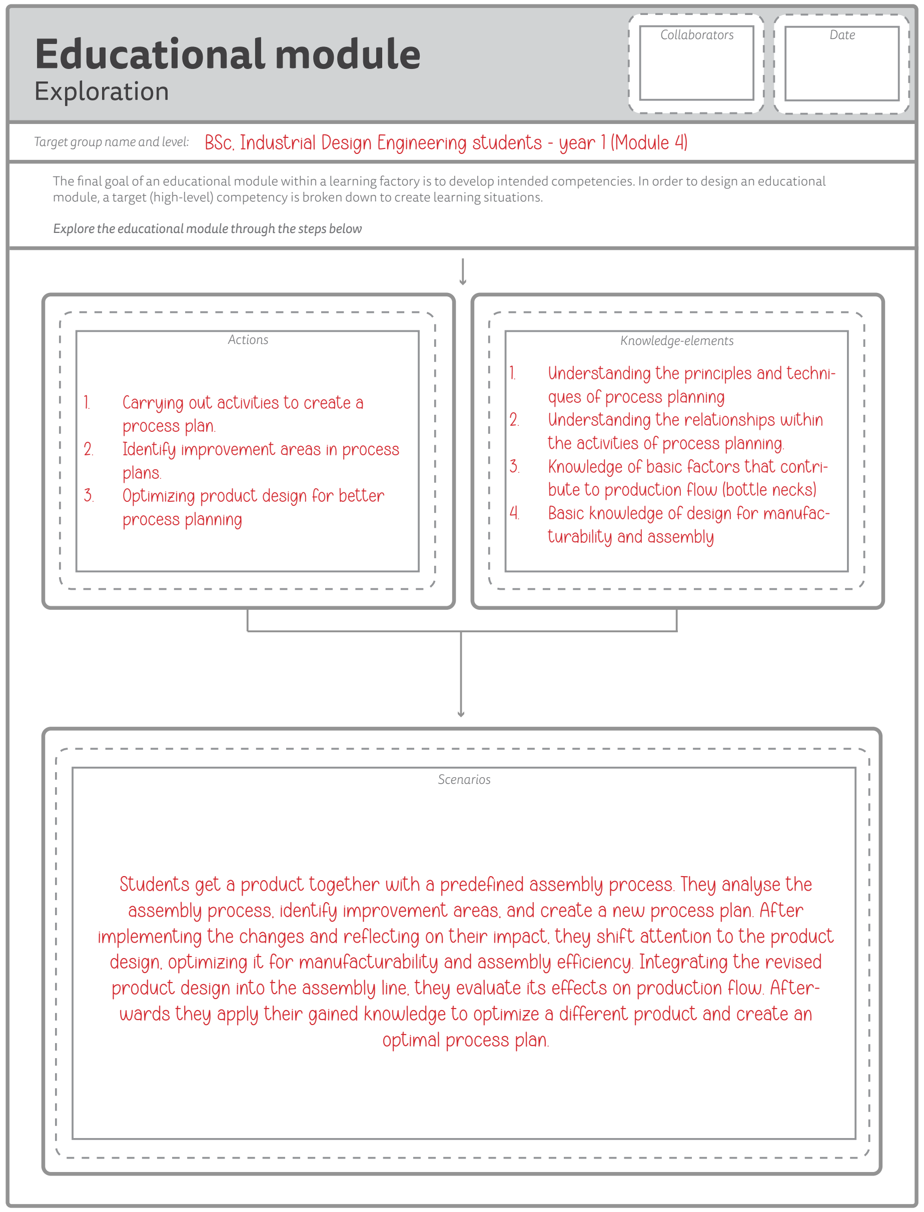
Designing & optimizing products for mass production, taking into consideration process planning (in a manufacturing environment)

Sub-competencies

» Designing optimal products for mass-production

» Creating optimal process plans for mass-producable products

Figure G.6. Case study educational module exploration part 1 MOD4



Educational module

Exploration

Collaborators

Date

Target group name and level: BSc. Industrial Design Engineering students - year 1 (Module 4)

The final goal of an educational module within a learning factory is to develop intended competencies. In order to design an educational module, a target (high-level) competency is broken down to create learning situations.

Explore the educational module through the steps below

Actions

1. Carrying out activities to create a process plan.
2. Identify improvement areas in process plans.
3. Optimizing product design for better process planning

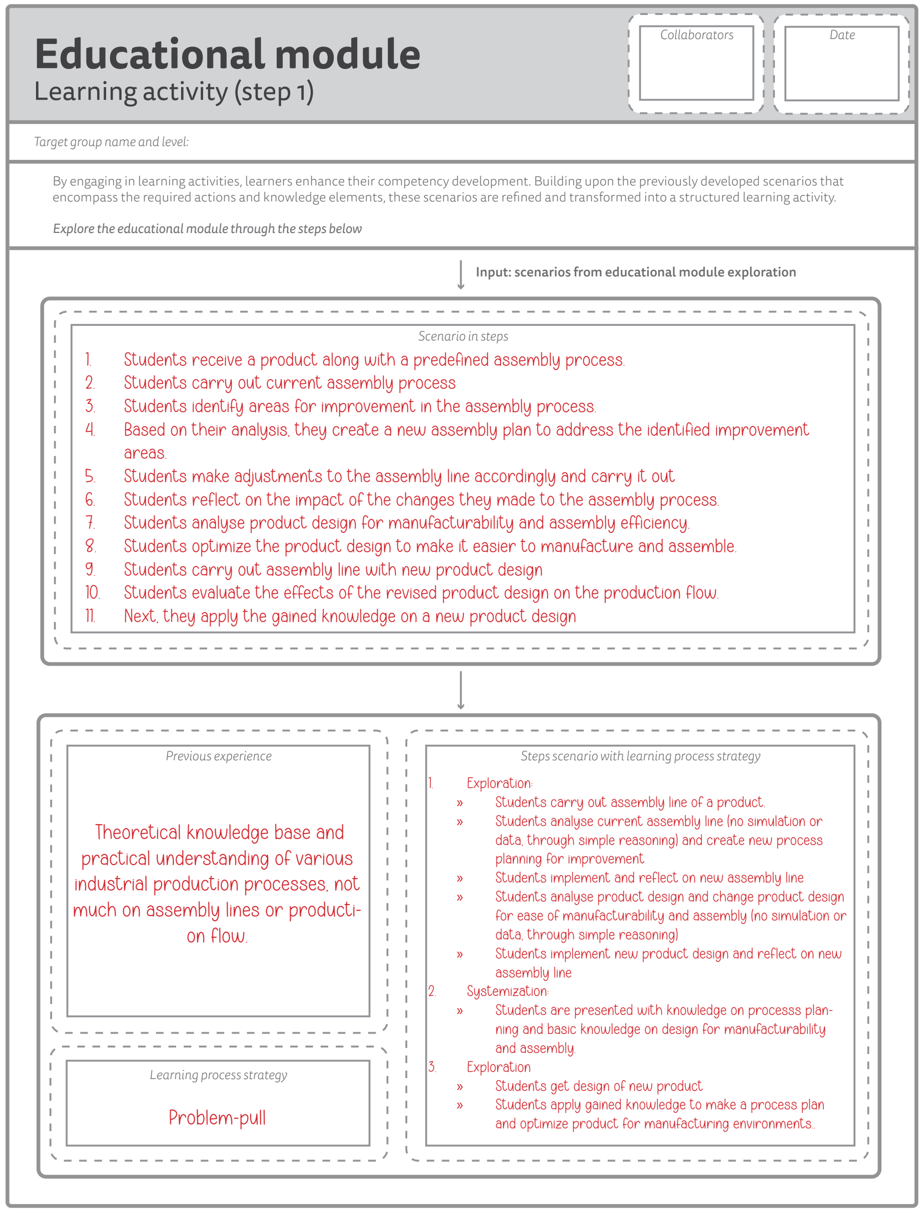
Knowledge-elements

1. Understanding the principles and techniques of process planning
2. Understanding the relationships within the activities of process planning.
3. Knowledge of basic factors that contribute to production flow (bottle necks)
4. Basic knowledge of design for manufacturability and assembly

Scenarios

Students get a product together with a predefined assembly process. They analyse the assembly process, identify improvement areas, and create a new process plan. After implementing the changes and reflecting on their impact, they shift attention to the product design, optimizing it for manufacturability and assembly efficiency. Integrating the revised product design into the assembly line, they evaluate its effects on production flow. Afterwards they apply their gained knowledge to optimize a different product and create an optimal process plan.

Figure G.7. Case study educational module exploration part 2 MOD4



Educational module

Learning activity (step 1)

Collaborators

Date

Target group name and level:

By engaging in learning activities, learners enhance their competency development. Building upon the previously developed scenarios that encompass the required actions and knowledge elements, these scenarios are refined and transformed into a structured learning activity.

Explore the educational module through the steps below

Input: scenarios from educational module exploration

Scenario in steps

1. Students receive a product along with a predefined assembly process.
2. Students carry out current assembly process
3. Students identify areas for improvement in the assembly process.
4. Based on their analysis, they create a new assembly plan to address the identified improvement areas.
5. Students make adjustments to the assembly line accordingly and carry it out
6. Students reflect on the impact of the changes they made to the assembly process.
7. Students analyse product design for manufacturability and assembly efficiency
8. Students optimize the product design to make it easier to manufacture and assemble.
9. Students carry out assembly line with new product design
10. Students evaluate the effects of the revised product design on the production flow.
11. Next, they apply the gained knowledge on a new product design

Previous experience

Theoretical knowledge base and practical understanding of various industrial production processes, not much on assembly lines or producti-on flow.

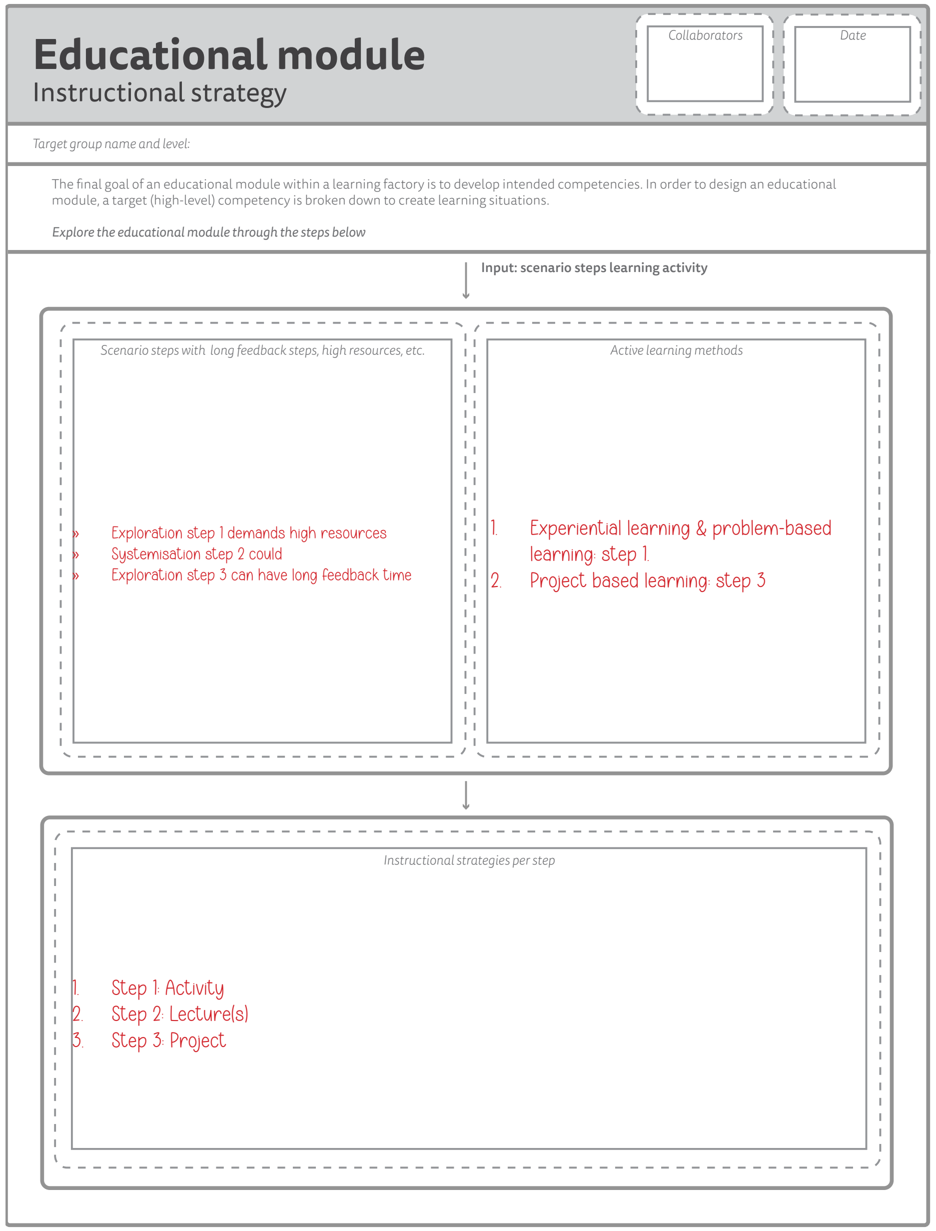
Learning process strategy

Problem-pull

Steps scenario with learning process strategy

1. Exploration:
   - Students carry out assembly line of a product.
   - Students analyse current assembly line (no simulation or data, through simple reasoning) and create new process planning for improvement
   - Students implement and reflect on new assembly line
   - Students analyse product design and change product design for ease of manufacturability and assembly (no simulation or data, through simple reasoning)
   - Students implement new product design and reflect on new assembly line
2. Systemization:
   - Students are presented with knowledge on processs planning and basic knowledge on design for manufacturability and assembly.
3. Exploration
   - Students get design of new product
   - Students apply gained knowledge to make a process plan and optimize product for manufacturing environments..

Figure G.8. Case study educational module learning activity MOD4



Educational module

Instructional strategy

Collaborators

Date

Target group name and level:

The final goal of an educational module within a learning factory is to develop intended competencies. In order to design an educational module, a target (high-level) competency is broken down to create learning situations.

Explore the educational module through the steps below

Input: scenario steps learning activity

Scenario steps with long feedback steps, high resources, etc.

- Exploration step 1 demands high resources
- Systemisation step 2 could
- Exploration step 3 can have long feedback time

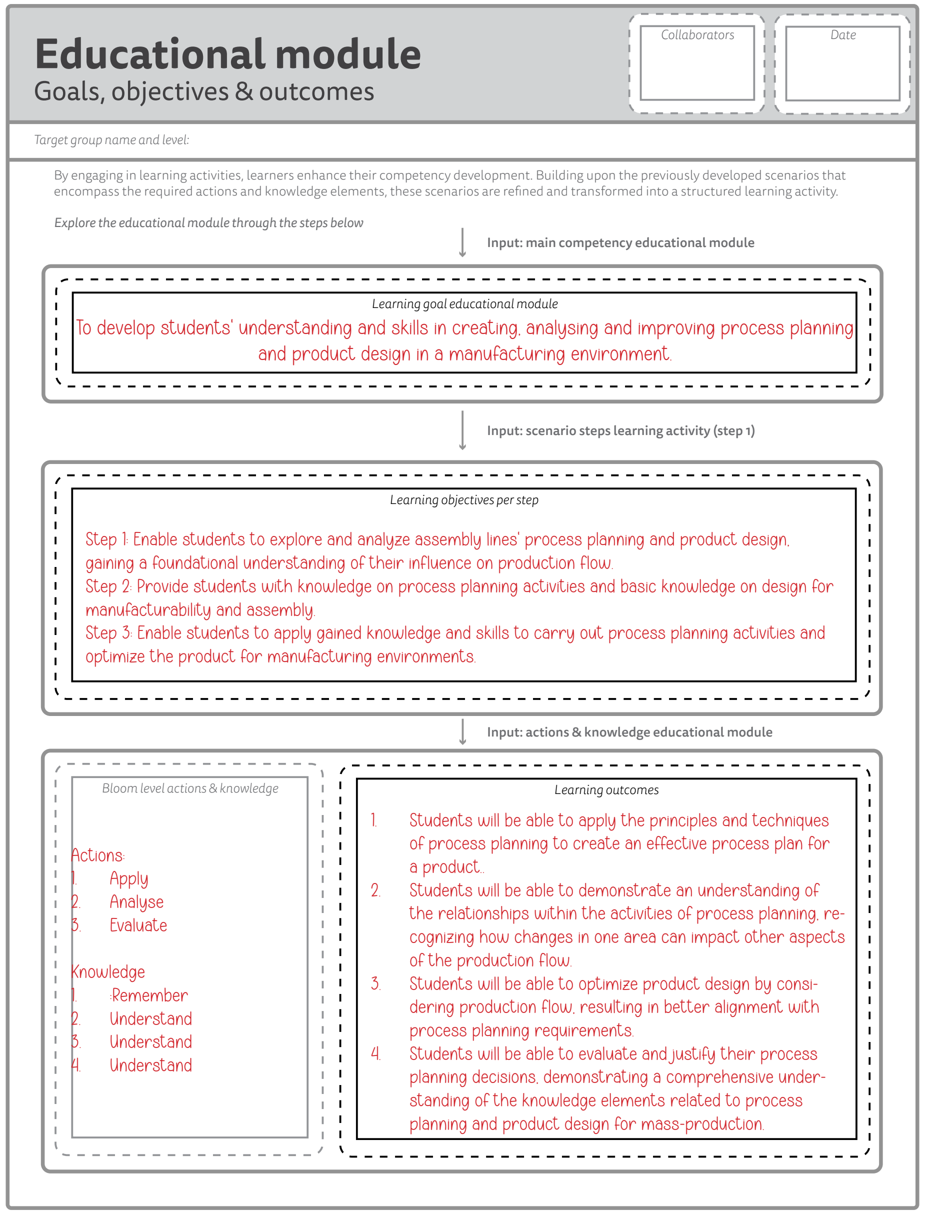
Active learning methods

1. Experiential learning & problem-based learning: step 1.
2. Project based learning: step 3

Instructional strategies per step

1. Step 1: Activity
2. Step 2: Lecture(s)
3. Step 3: Project

Figure G.9. Case study educational module instructional strategy MOD4



Educational module

Goals, objectives & outcomes

Collaborators

Date

Target group name and level:

By engaging in learning activities, learners enhance their competency development. Building upon the previously developed scenarios that encompass the required actions and knowledge elements, these scenarios are refined and transformed into a structured learning activity.

Explore the educational module through the steps below

Input: main competency educational module

Learning goal educational module

To develop students' understanding and skills in creating, analysing and improving process planning and product design in a manufacturing environment.

Input: scenario steps learning activity (step 1)

Learning objectives per step

Step 1: Enable students to explore and analyze assembly lines' process planning and product design, gaining a foundational understanding of their influence on production flow.
Step 2: Provide students with knowledge on process planning activities and basic knowledge on design for manufacturability and assembly.
Step 3: Enable students to apply gained knowledge and skills to carry out process planning activities and optimize the product for manufacturing environments.

Input: actions & knowledge educational module

Bloom level actions & knowledge

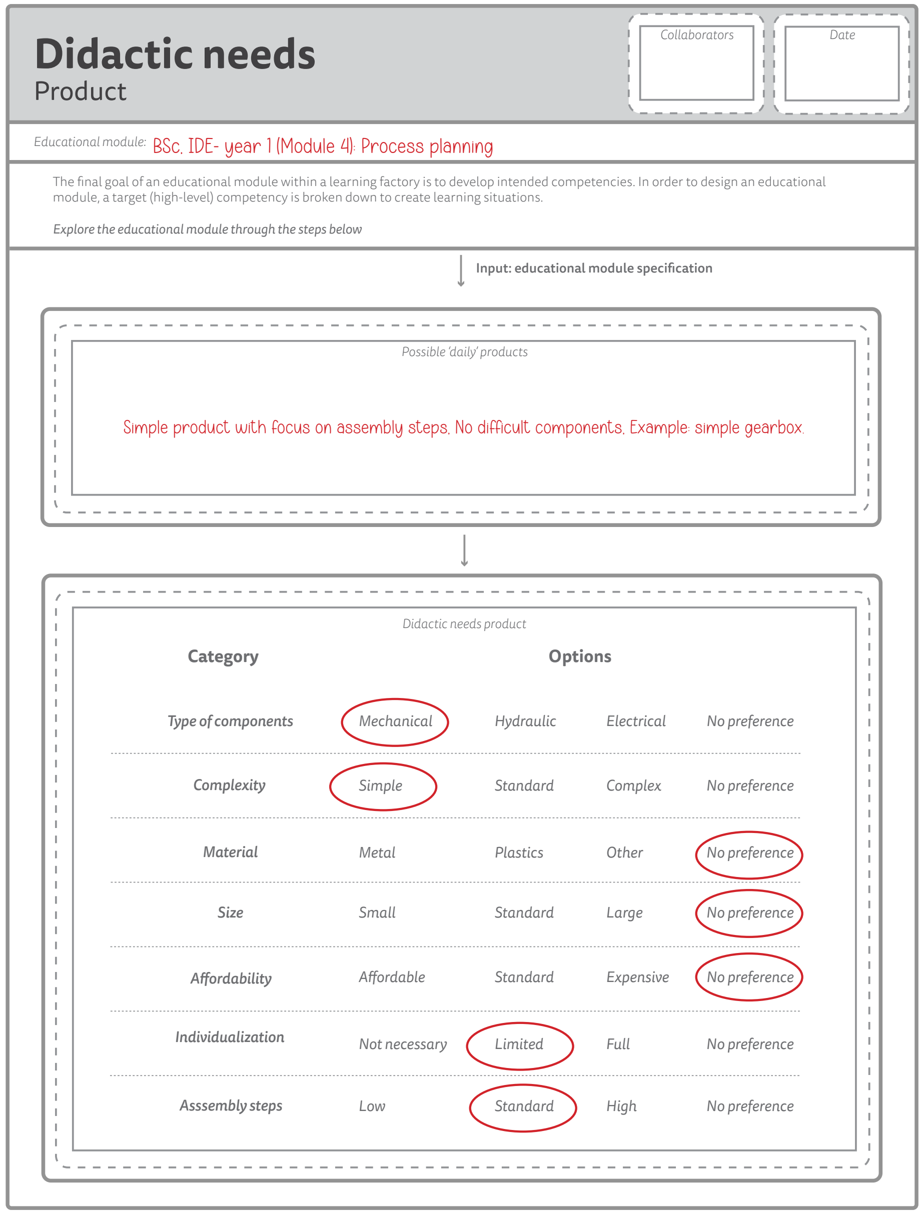
Actions:
1. Apply
2. Analyse
3. Evaluate

Knowledge
1. :Remember
2. Understand
3. Understand
4. Understand

Learning outcomes

1. Students will be able to apply the principles and techniques of process planning to create an effective process plan for a product..
2. Students will be able to demonstrate an understanding of the relationships within the activities of process planning, recognizing how changes in one area can impact other aspects of the production flow.
3. Students will be able to optimize product design by considering production flow, resulting in better alignment with process planning requirements.
4. Students will be able to evaluate and justify their process planning decisions, demonstrating a comprehensive understanding of the knowledge elements related to process planning and product design for mass-production.

Figure G.10. Case study educational module goals, objectives & outcomes MOD4



Didactic needs

Product

Collaborators

Date

Educational module: BSc. IDE- year 1 (Module 4): Process planning

The final goal of an educational module within a learning factory is to develop intended competencies. In order to design an educational module, a target (high-level) competency is broken down to create learning situations.

Explore the educational module through the steps below

Input: educational module specification

Possible 'daily' products

Simple product with focus on assembly steps. No difficult components. Example: simple gearbox

Didactic needs product

Category	**Options**			
Type of components	[✓ *Mechanical*]	*Hydraulic*	*Electrical*	*No preference*
Complexity	[✓ *Simple*]	*Standard*	*Complex*	*No preference*
Material	*Metal*	*Plastics*	*Other*	[✓ *No preference*]
Size	*Small*	*Standard*	*Large*	[✓ *No preference*]
Affordability	*Affordable*	*Standard*	*Expensive*	[✓ *No preference*]
Individualization	*Not necessary*	[✓ *Limited*]	*Full*	*No preference*
Asssembly steps	*Low*	[✓ *Standard*]	*High*	*No preference*

Figure G.11. Case study didactic needs product MOD4

Didactic needs

Process

Collaborators

Date

Educational module: BSc. IDE- year 1 (Module 4): Process planning

The final goal of an educational module within a learning factory is to develop intended competencies. In order to design an educational module, a target (high-level) competency is broken down to create learning situations.

Explore the educational module through the steps below

Input: educational module specification

Didactic needs process

Material flow: Continuous production | Discrete production | [✓ No preference]

Process type: [✓ Mass production] | Serial production | Small series production | One-off production | No preference

Automation: [✓ Manual] | Partly automated | Fully automated | No preference

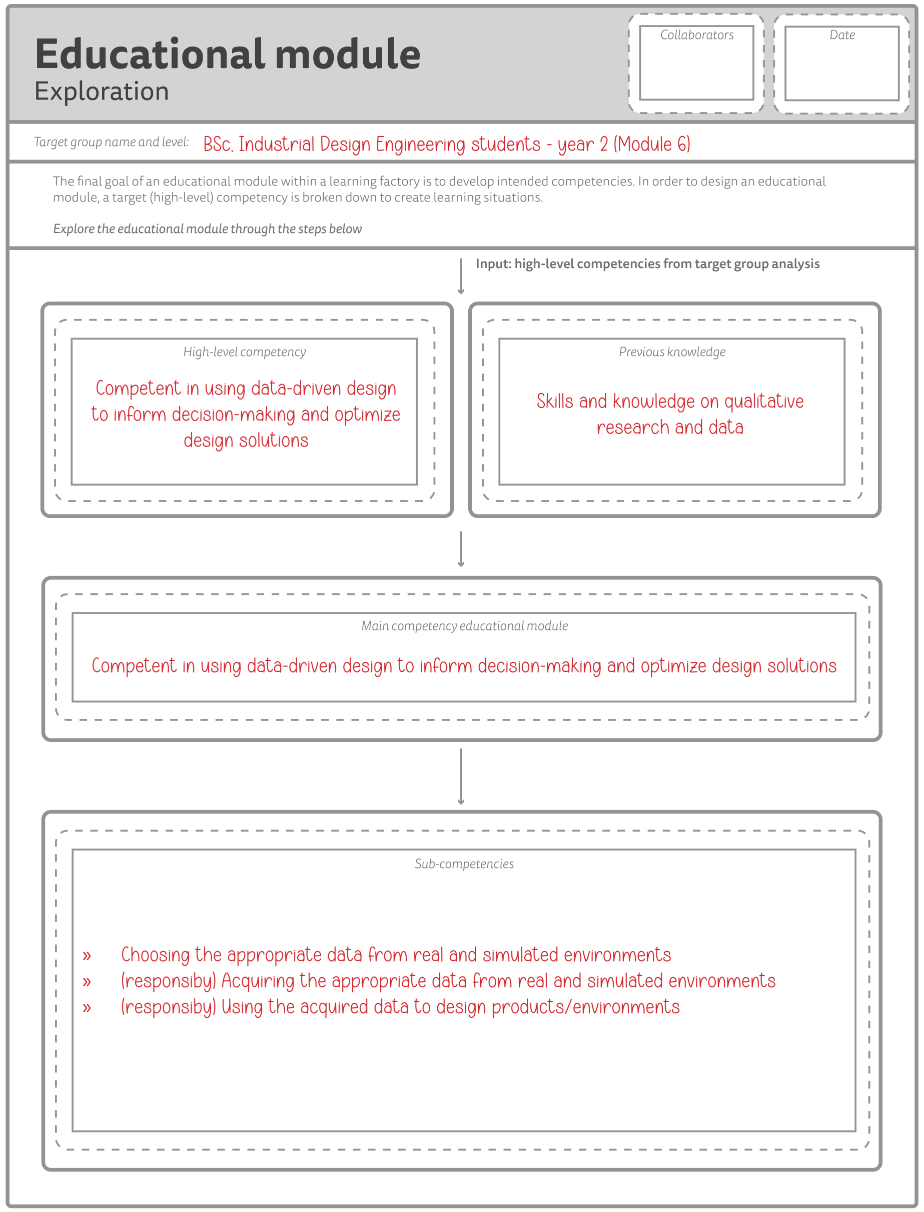
Didactic needs manufacturing

Manufacturing process	Casting	Moulding	Forming	Machining	Joining	Coating	Additive manufacturing

Didactic needs life cycle

Product	Product planning	Product development	Product design	Rapid prototyping	Manufacturing	Assembly	Logistics	Service	Recycling
Factory	Investment planning	Factory concept	Process planning	Ramp-up				Maintenance	Recycling
Order	Configuration & order	Order sequencing	Production planning and scheduling					Picking, packaging	Shipping
Technology	Planning	Development	Virtual testing					Maintenance	Moderni-sation

Figure G.12. Case study didactic needs process MOD4



Educational module

Exploration

Collaborators

Date

Target group name and level: BSc. Industrial Design Engineering students - year 2 (Module 6)

The final goal of an educational module within a learning factory is to develop intended competencies. In order to design an educational module, a target (high-level) competency is broken down to create learning situations.

Explore the educational module through the steps below

Input: high-level competencies from target group analysis

High-level competency

Competent in using data-driven design to inform decision-making and optimize design solutions

Previous knowledge

Skills and knowledge on qualitative research and data

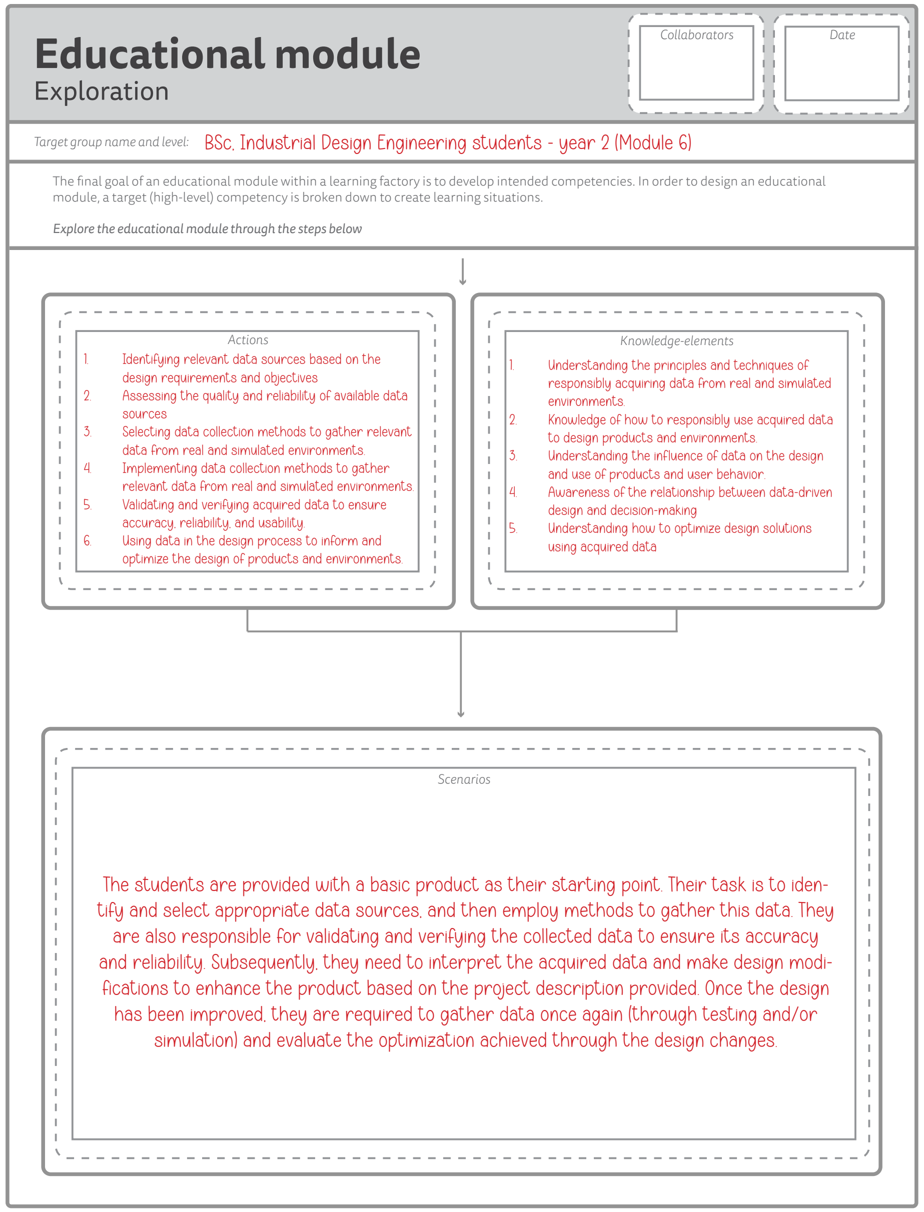
Main competency educational module

Competent in using data-driven design to inform decision-making and optimize design solutions

Sub-competencies

» Choosing the appropriate data from real and simulated environments
» (responsibly) Acquiring the appropriate data from real and simulated environments
» (responsiby) Using the acquired data to design products/environments

Figure G.13. Case study educational module exploration part 1 MOD5



Educational module

Exploration

Target group name and level: BSc. Industrial Design Engineering students - year 2 (Module 6)

The final goal of an educational module within a learning factory is to develop intended competencies. In order to design an educational module, a target (high-level) competency is broken down to create learning situations.

Explore the educational module through the steps below

Actions

1. Identifying relevant data sources based on the design requirements and objectives
2. Assessing the quality and reliability of available data sources
3. Selecting data collection methods to gather relevant data from real and simulated environments.
4. Implementing data collection methods to gather relevant data from real and simulated environments.
5. Validating and verifying acquired data to ensure accuracy, reliability, and usability.
6. Using data in the design process to inform and optimize the design of products and environments.

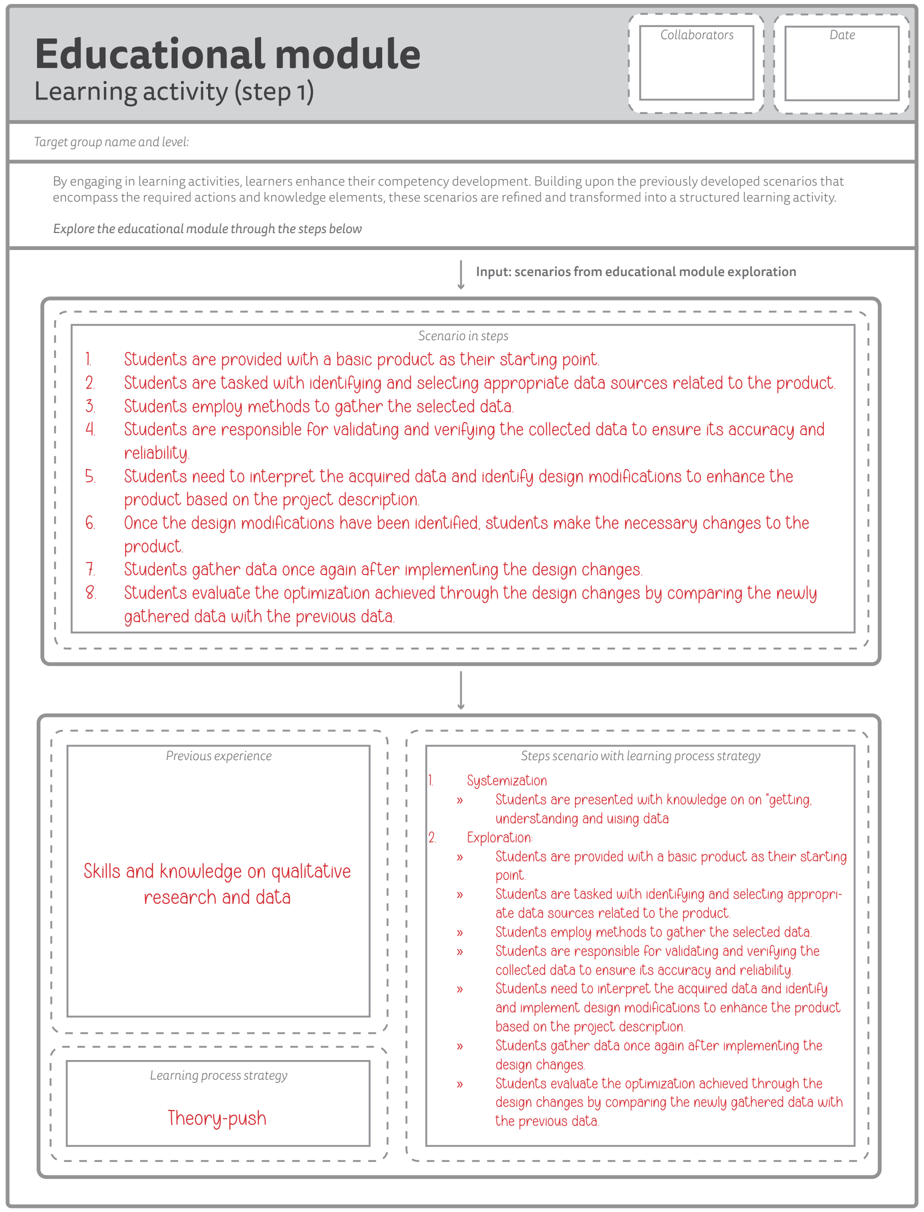
Knowledge-elements

1. Understanding the principles and techniques of responsibly acquiring data from real and simulated environments.
2. Knowledge of how to responsibly use acquired data to design products and environments.
3. Understanding the influence of data on the design and use of products and user behavior.
4. Awareness of the relationship between data-driven design and decision-making
5. Understanding how to optimize design solutions using acquired data

Scenarios

The students are provided with a basic product as their starting point. Their task is to identify and select appropriate data sources, and then employ methods to gather this data. They are also responsible for validating and verifying the collected data to ensure its accuracy and reliability. Subsequently, they need to interpret the acquired data and make design modifications to enhance the product based on the project description provided. Once the design has been improved, they are required to gather data once again (through testing and/or simulation) and evaluate the optimization achieved through the design changes.

Figure G.14. Case study educational module exploration part 2 MOD5



Educational module

Learning activity (step 1)

Target group name and level:

By engaging in learning activities, learners enhance their competency development. Building upon the previously developed scenarios that encompass the required actions and knowledge elements, these scenarios are refined and transformed into a structured learning activity.

Explore the educational module through the steps below

Input: scenarios from educational module exploration

Scenario in steps

1. Students are provided with a basic product as their starting point.
2. Students are tasked with identifying and selecting appropriate data sources related to the product.
3. Students employ methods to gather the selected data.
4. Students are responsible for validating and verifying the collected data to ensure its accuracy and reliability.
5. Students need to interpret the acquired data and identify design modifications to enhance the product based on the project description.
6. Once the design modifications have been identified, students make the necessary changes to the product.
7. Students gather data once again after implementing the design changes.
8. Students evaluate the optimization achieved through the design changes by comparing the newly gathered data with the previous data.

Previous experience

Skills and knowledge on qualitative research and data

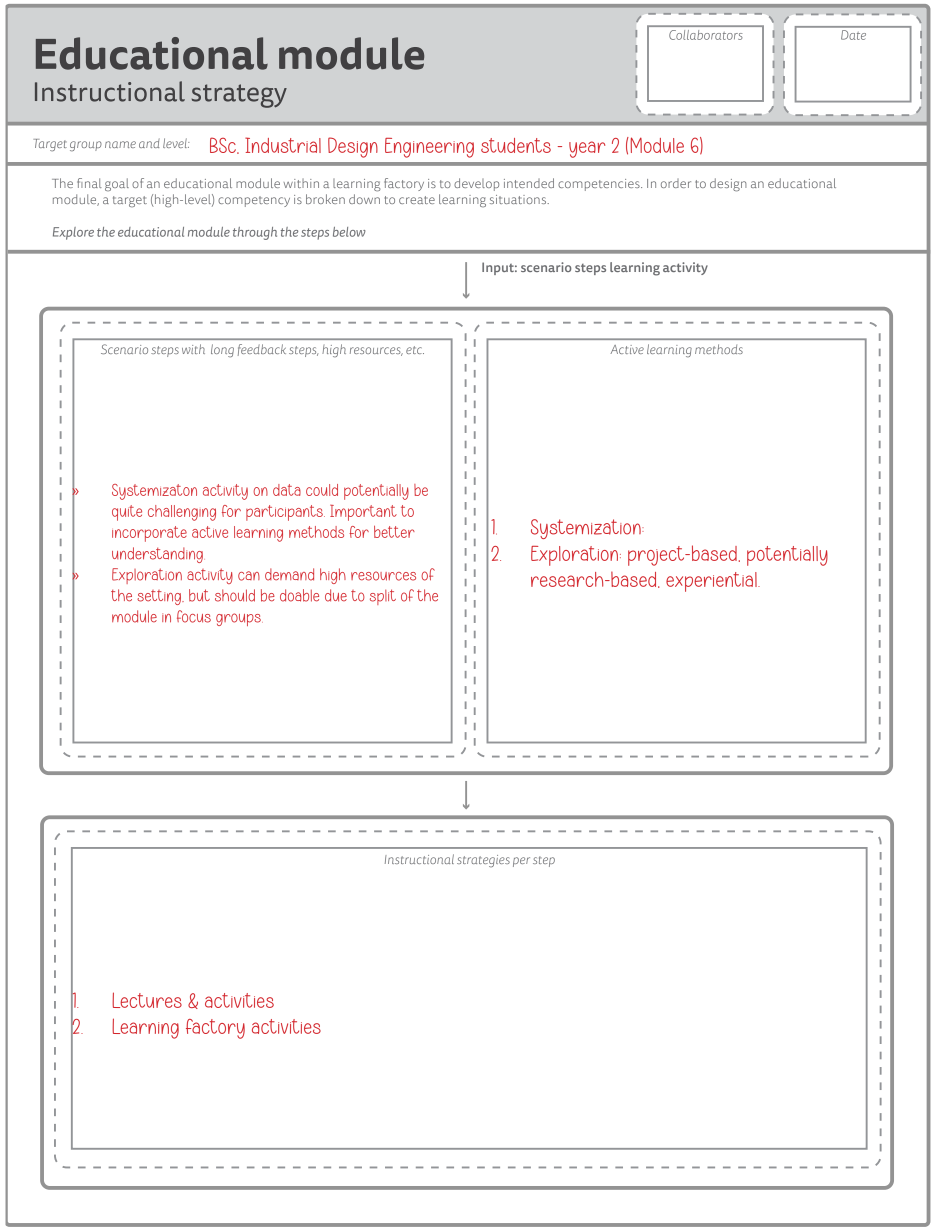
Learning process strategy

Theory-push

Steps scenario with learning process strategy

1. Systemization
   - » Students are presented with knowledge on on "getting, understanding and uising data
2. Exploration:
   - » Students are provided with a basic product as their starting point.
   - » Students are tasked with identifying and selecting appropriate data sources related to the product.
   - » Students employ methods to gather the selected data.
   - » Students are responsible for validating and verifying the collected data to ensure its accuracy and reliability.
   - » Students need to interpret the acquired data and identify and implement design modifications to enhance the product based on the project description.
   - » Students gather data once again after implementing the design changes.
   - » Students evaluate the optimization achieved through the design changes by comparing the newly gathered data with the previous data.

Figure G.15. Case study educational module learning activity MOD5



Educational module

Instructional strategy

Collaborators

Date

Target group name and level: BSc. Industrial Design Engineering students - year 2 (Module 6)

The final goal of an educational module within a learning factory is to develop intended competencies. In order to design an educational module, a target (high-level) competency is broken down to create learning situations.

Explore the educational module through the steps below

Input: scenario steps learning activity

Scenario steps with long feedback steps, high resources, etc.

» Systemizaton activity on data could potentially be quite challenging for participants. Important to incorporate active learning methods for better understanding.

» Exploration activity can demand high resources of the setting, but should be doable due to split of the module in focus groups.

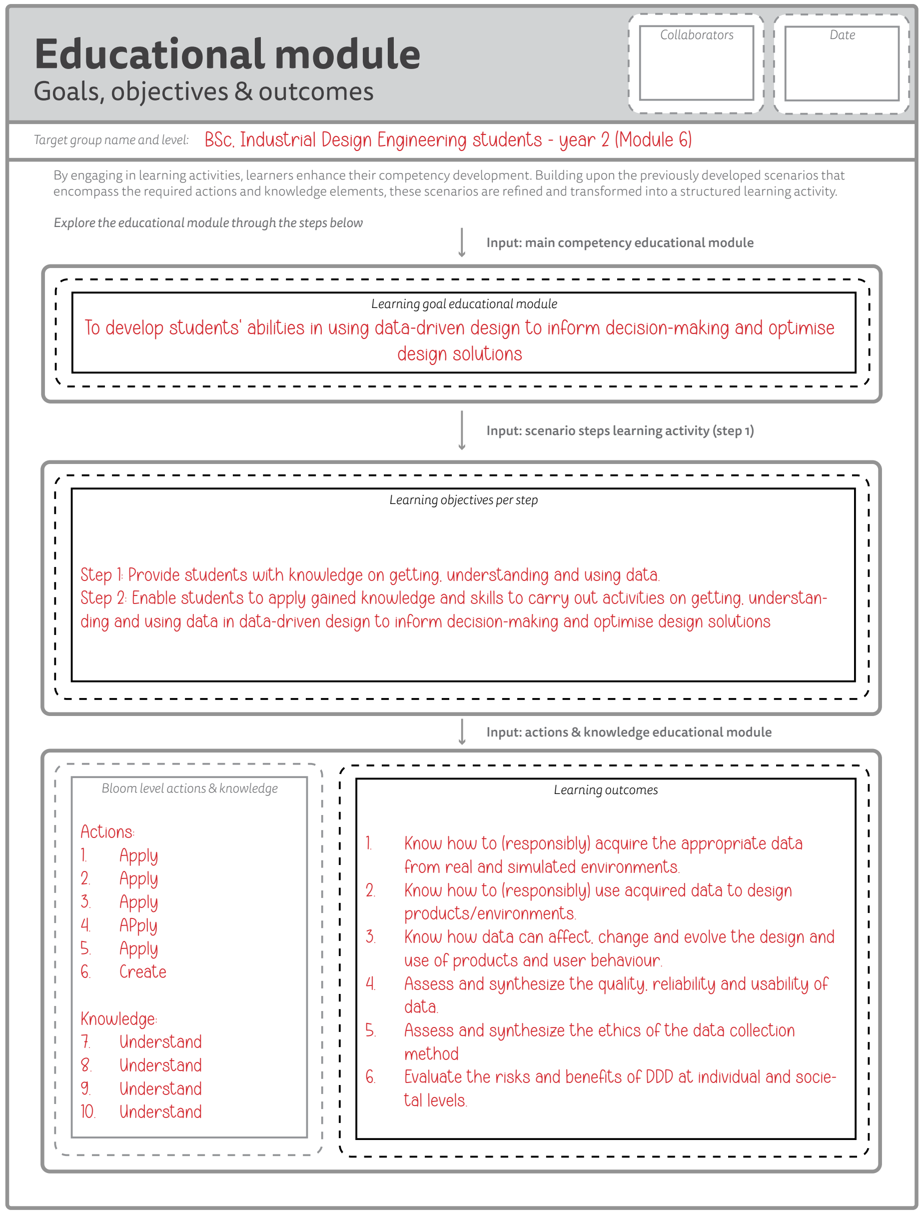
Active learning methods

1. Systemization:
2. Exploration: project-based, potentially research-based, experiential.

Instructional strategies per step

1. Lectures & activities
2. Learning factory activities

Figure G.16. Case study educational module instructional strategy MOD5



Educational module

Goals, objectives & outcomes

Collaborators

Date

Target group name and level: BSc. Industrial Design Engineering students - year 2 (Module 6)

By engaging in learning activities, learners enhance their competency development. Building upon the previously developed scenarios that encompass the required actions and knowledge elements, these scenarios are refined and transformed into a structured learning activity.

Explore the educational module through the steps below

Input: main competency educational module

Learning goal educational module

To develop students' abilities in using data-driven design to inform decision-making and optimise design solutions

Input: scenario steps learning activity (step 1)

Learning objectives per step

Step 1: Provide students with knowledge on getting, understanding and using data.

Step 2: Enable students to apply gained knowledge and skills to carry out activities on getting, understanding and using data in data-driven design to inform decision-making and optimise design solutions

Input: actions & knowledge educational module

Bloom level actions & knowledge

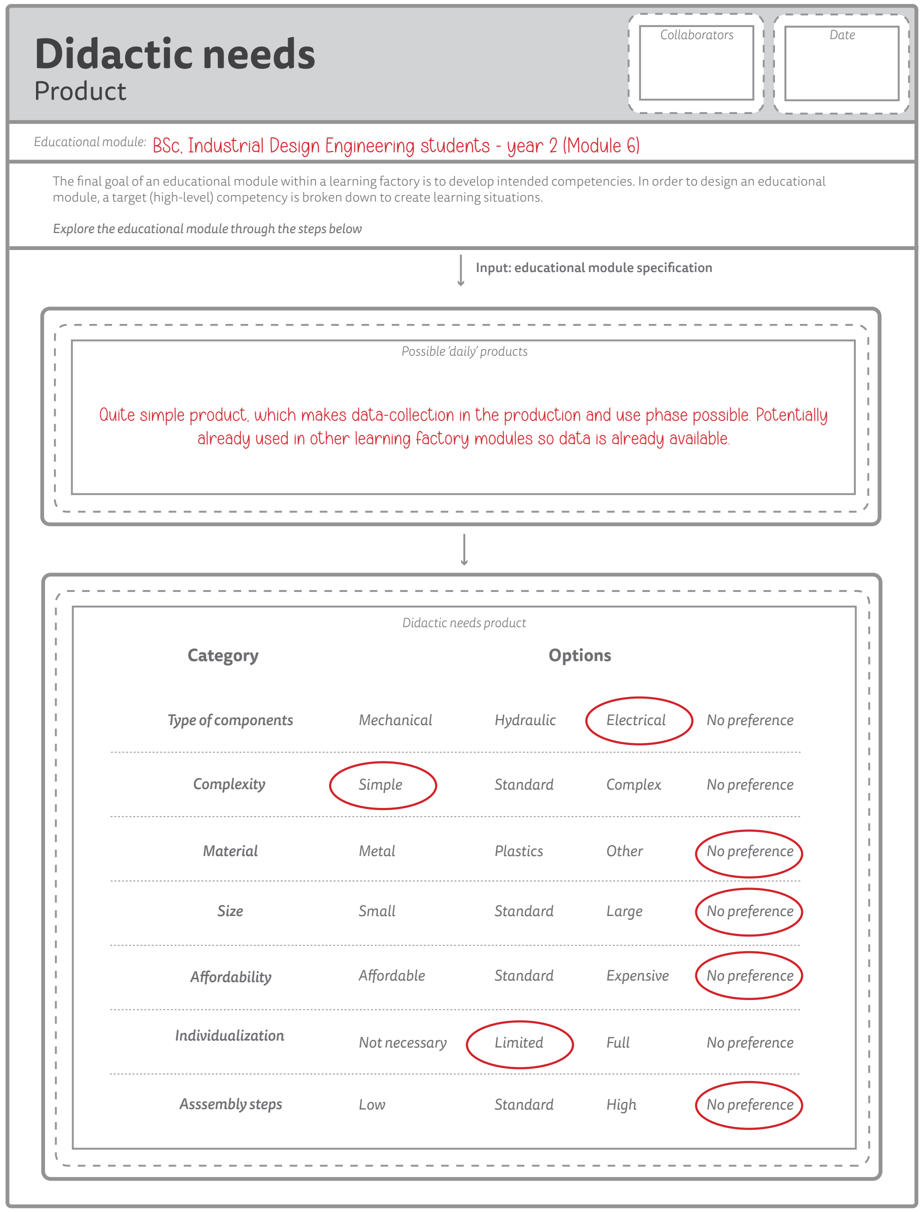
Actions:
1. Apply
2. Apply
3. Apply
4. APply
5. Apply
6. Create

Knowledge:
7. Understand
8. Understand
9. Understand
10. Understand

Learning outcomes

1. Know how to (responsibly) acquire the appropriate data from real and simulated environments.
2. Know how to (responsibly) use acquired data to design products/environments.
3. Know how data can affect, change and evolve the design and use of products and user behaviour.
4. Assess and synthesize the quality, reliability and usability of data.
5. Assess and synthesize the ethics of the data collection method.
6. Evaluate the risks and benefits of DDD at individual and societal levels.

Figure G.17. Case study educational module goals, objectives & outcomes MOD5



Didactic needs
Product

Collaborators

Date

Educational module: BSc. Industrial Design Engineering students - year 2 (Module 6)

The final goal of an educational module within a learning factory is to develop intended competencies. In order to design an educational module, a target (high-level) competency is broken down to create learning situations.

Explore the educational module through the steps below

Input: educational module specification

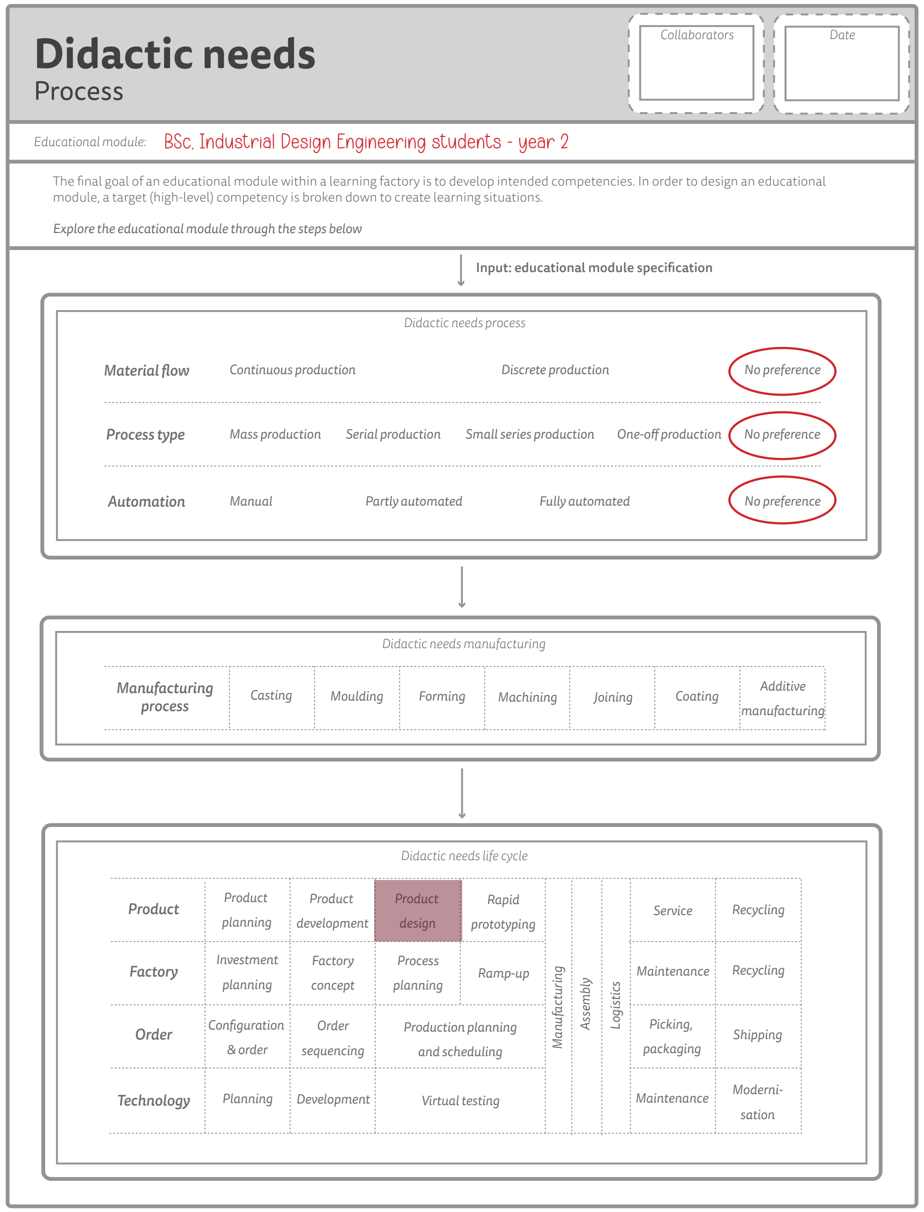
Possible 'daily' products

Quite simple product, which makes data-collection in the production and use phase possible. Potentially already used in other learning factory modules so data is already available.

Didactic needs product

Category	Options			
Type of components	*Mechanical*	*Hydraulic*	[✓ *Electrical*]	*No preference*
Complexity	[✓ *Simple*]	*Standard*	*Complex*	*No preference*
Material	*Metal*	*Plastics*	*Other*	[✓ *No preference*]
Size	*Small*	*Standard*	*Large*	[✓ *No preference*]
Affordability	*Affordable*	*Standard*	*Expensive*	[✓ *No preference*]
Individualization	*Not necessary*	[✓ *Limited*]	*Full*	*No preference*
Asssembly steps	*Low*	*Standard*	*High*	[✓ *No preference*]

Figure G.18. Case study didactic needs product MOD5



Didactic needs
Process

Collaborators

Date

Educational module: BSc. Industrial Design Engineering students - year 2

The final goal of an educational module within a learning factory is to develop intended competencies. In order to design an educational module, a target (high-level) competency is broken down to create learning situations.

Explore the educational module through the steps below

Input: educational module specification

Didactic needs process

Material flow	*Continuous production*		*Discrete production*		[✓ *No preference*]
Process type	*Mass production*	*Serial production*	*Small series production*	*One-off production*	[✓ *No preference*]
Automation	*Manual*	*Partly automated*	*Fully automated*		[✓ *No preference*]

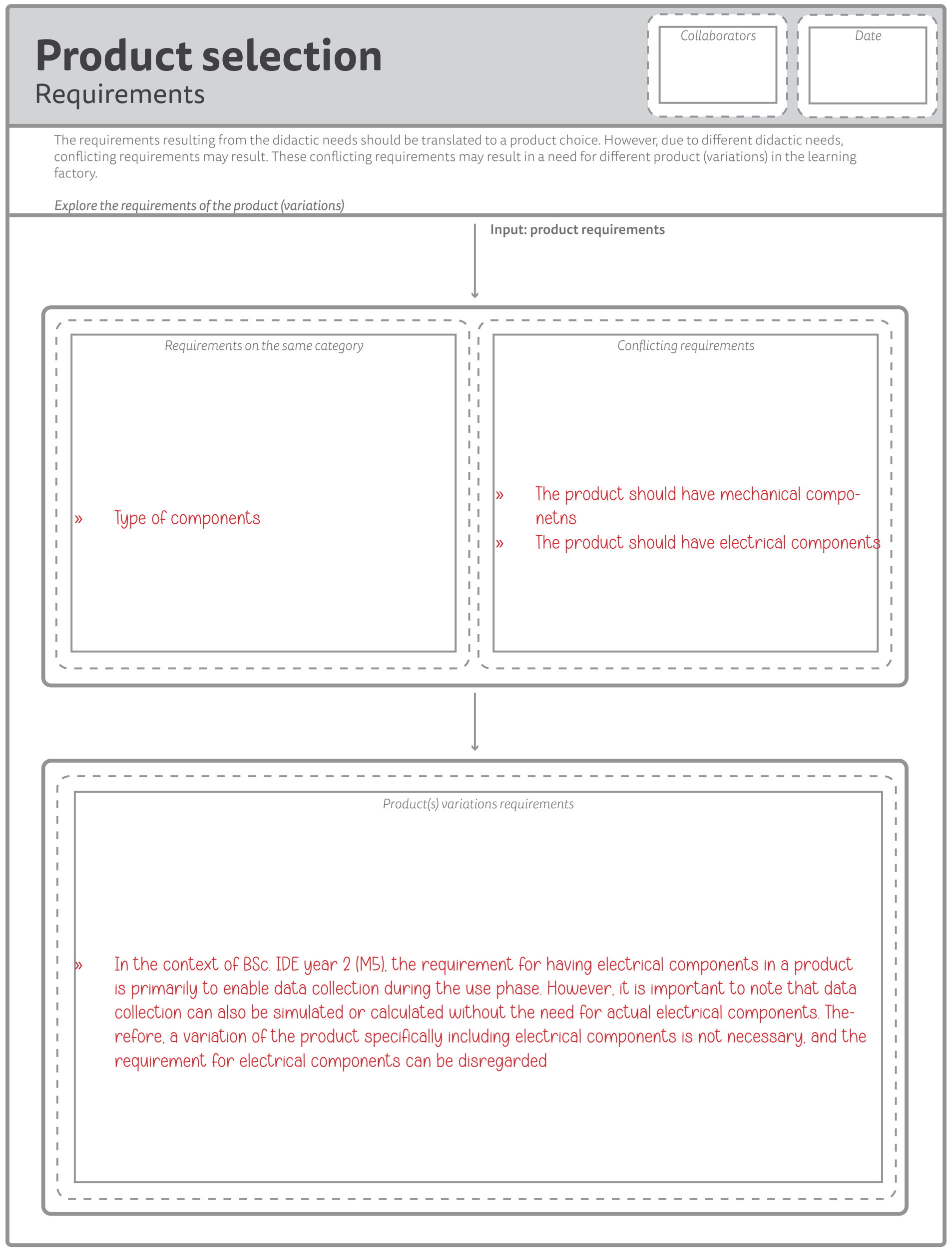
Didactic needs manufacturing

Manufacturing process	*Casting*	*Moulding*	*Forming*	*Machining*	*Joining*	*Coating*	*Additive manufacturing*

Didactic needs life cycle

Product	*Product planning*	*Product development*	[✓ *Product design*]	*Rapid prototyping*	*Manufacturing*	*Assembly*	*Logistics*	*Service*	*Recycling*
Factory	*Investment planning*	*Factory concept*	*Process planning*	*Ramp-up*				*Maintenance*	*Recycling*
Order	*Configuration & order*	*Order sequencing*	*Production planning and scheduling*					*Picking, packaging*	*Shipping*
Technology	*Planning*	*Development*	*Virtual testing*					*Maintenance*	*Moderni-sation*

Figure G.19. Case study didactic needs process MOD5



Product selection
Requirements

Collaborators

Date

The requirements resulting from the didactic needs should be translated to a product choice. However, due to different didactic needs, conflicting requirements may result. These conflicting requirements may result in a need for different product (variations) in the learning factory.

Explore the requirements of the product (variations)

Input: product requirements

Requirements on the same category

» Type of components

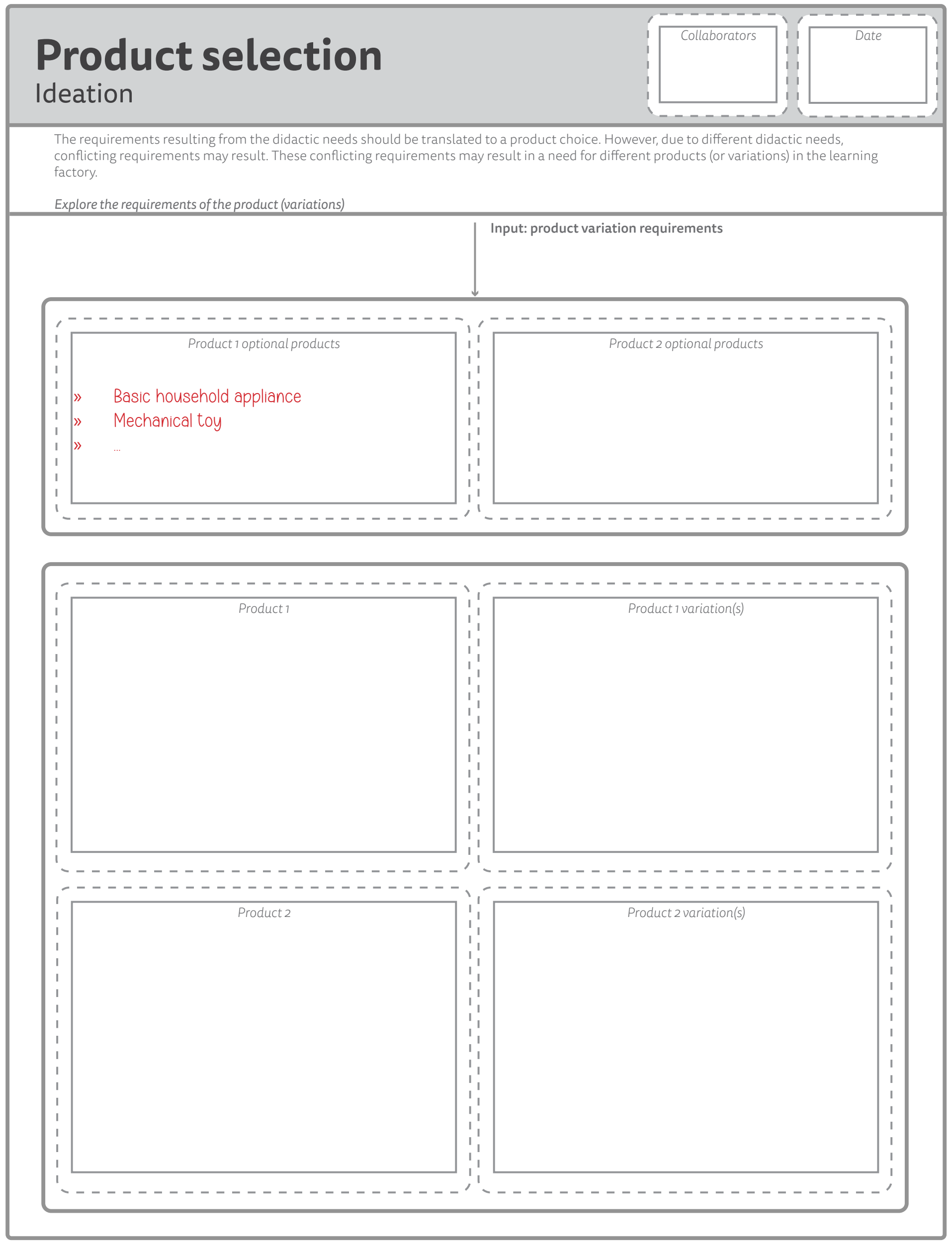
Conflicting requirements

» The product should have mechanical componetns
» The product should have electrical components

Product(s) variations requirements

» In the context of BSc. IDE year 2 (M5), the requirement for having electrical components in a product is primarily to enable data collection during the use phase. However, it is important to note that data collection can also be simulated or calculated without the need for actual electrical components. Therefore, a variation of the product specifically including electrical components is not necessary, and the requirement for electrical components can be disregarded

Figure G.20. Case study product selection requirements



Product selection
Ideation

Collaborators

Date

The requirements resulting from the didactic needs should be translated to a product choice. However, due to different didactic needs, conflicting requirements may result. These conflicting requirements may result in a need for different products (or variations) in the learning factory.

Explore the requirements of the product (variations)

Input: product variation requirements

Product 1 optional products

» Basic household appliance
» Mechanical toy
» ...

Product 2 optional products

Product 1

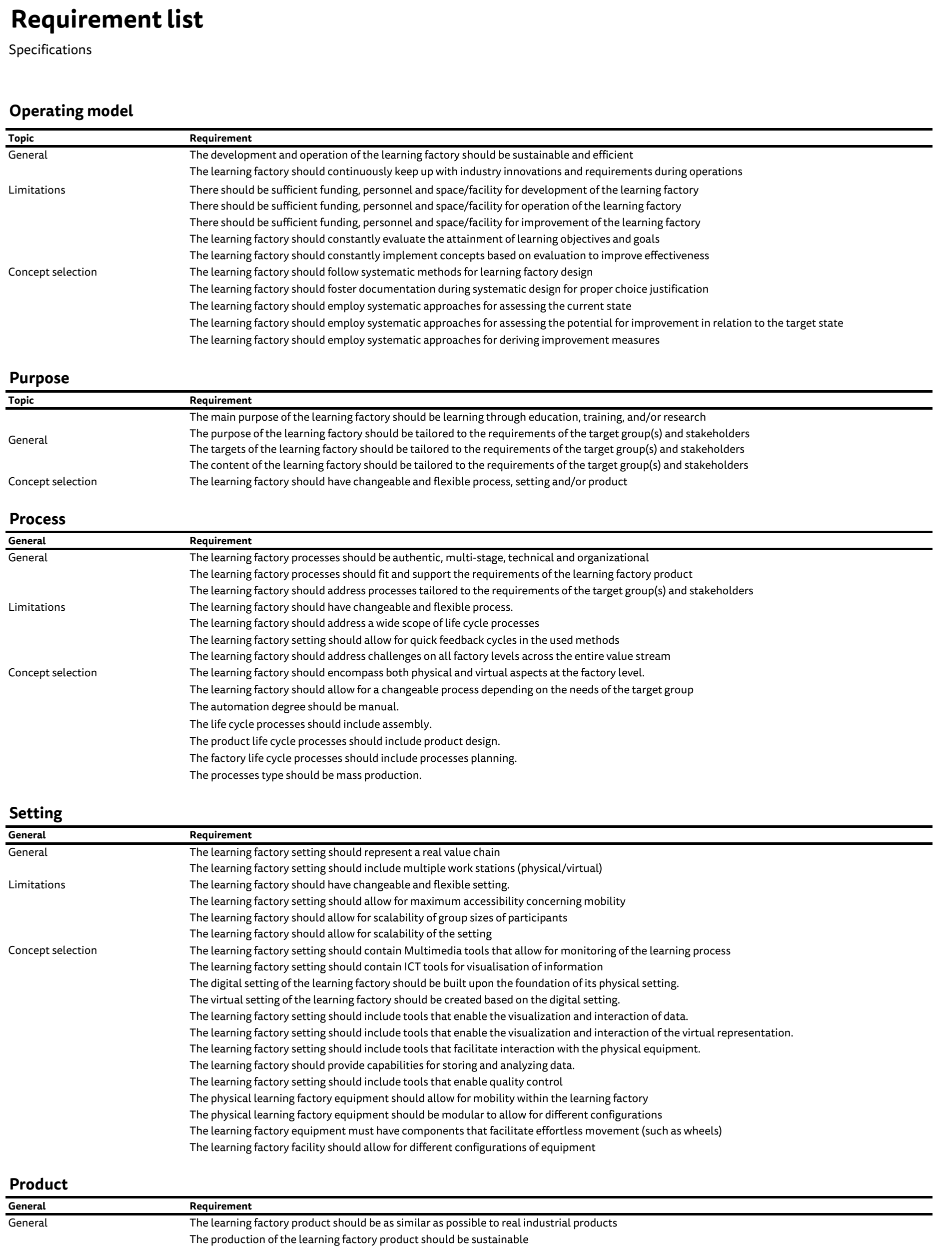
Product 1 variation(s)

Product 2

Product 2 variation(s)

Figure 1. Figure G.21. Case study product selection ideation

G.2 Case study requirements & specification lists



Requirement list

Specifications

Operating model

Topic	Requirement
General	The development and operation of the learning factory should be sustainable and efficient
	The learning factory should continuously keep up with industry innovations and requirements during operations
Limitations	There should be sufficient funding, personnel and space/facility for development of the learning factory
	There should be sufficient funding, personnel and space/facility for operation of the learning factory
	There should be sufficient funding, personnel and space/facility for improvement of the learning factory
	The learning factory should constantly evaluate the attainment of learning objectives and goals
	The learning factory should constantly implement concepts based on evaluation to improve effectiveness
Concept selection	The learning factory should follow systematic methods for learning factory design
	The learning factory should foster documentation during systematic design for proper choice justification
	The learning factory should employ systematic approaches for assessing the current state
	The learning factory should employ systematic approaches for assessing the potential for improvement in relation to the target state
	The learning factory should employ systematic approaches for deriving improvement measures

Purpose

Topic	Requirement
General	The main purpose of the learning factory should be learning through education, training, and/or research
	The purpose of the learning factory should be tailored to the requirements of the target group(s) and stakeholders
	The targets of the learning factory should be tailored to the requirements of the target group(s) and stakeholders
	The content of the learning factory should be tailored to the requirements of the target group(s) and stakeholders
Concept selection	The learning factory should have changeable and flexible process, setting and/or product

Process

General	Requirement
General	The learning factory processes should be authentic, multi-stage, technical and organizational
	The learning factory processes should fit and support the requirements of the learning factory product
	The learning factory should address processes tailored to the requirements of the target group(s) and stakeholders
Limitations	The learning factory should have changeable and flexible process.
	The learning factory should address a wide scope of life cycle processes
	The learning factory setting should allow for quick feedback cycles in the used methods
	The learning factory should address challenges on all factory levels across the entire value stream
Concept selection	The learning factory should encompass both physical and virtual aspects at the factory level.
	The learning factory should allow for a changeable process depending on the needs of the target group
	The automation degree should be manual.
	The life cycle processes should include assembly.
	The product life cycle processes should include product design.
	The factory life cycle processes should include processes planning.
	The processes type should be mass production.

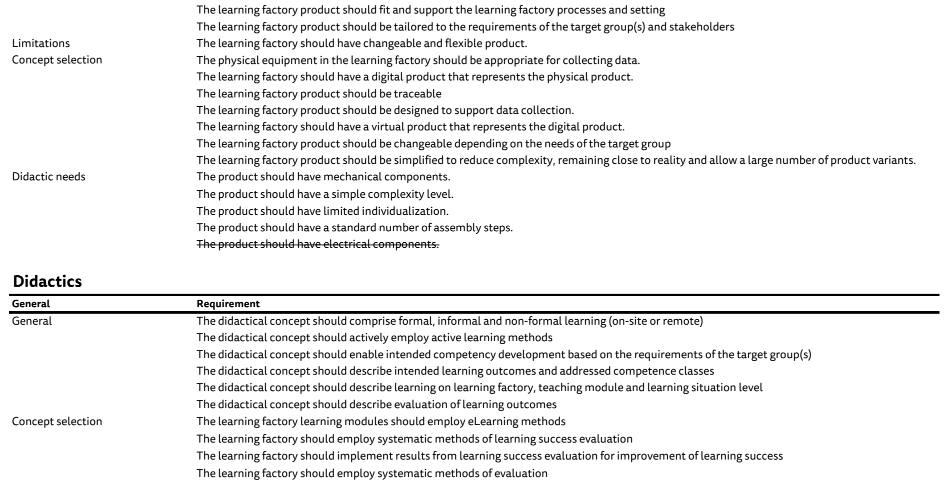
Setting

General	Requirement
General	The learning factory setting should represent a real value chain
	The learning factory setting should include multiple work stations (physical/virtual)
Limitations	The learning factory should have changeable and flexible setting.
	The learning factory setting should allow for maximum accessibility concerning mobility
	The learning factory should allow for scalability of group sizes of participants
	The learning factory should allow for scalability of the setting
Concept selection	The learning factory setting should contain Multimedia tools that allow for monitoring of the learning process
	The learning factory setting should contain ICT tools for visualisation of information
	The digital setting of the learning factory should be built upon the foundation of its physical setting.
	The virtual setting of the learning factory should be created based on the digital setting.
	The learning factory setting should include tools that enable the visualization and interaction of data.
	The learning factory setting should include tools that enable the visualization and interaction of the virtual representation.
	The learning factory setting should include tools that facilitate interaction with the physical equipment.
	The learning factory should provide capabilities for storing and analyzing data.
	The learning factory setting should include tools that enable quality control
	The physical learning factory equipment should allow for mobility within the learning factory
	The physical learning factory equipment should be modular to allow for different configurations
	The learning factory equipment must have components that facilitate effortless movement (such as wheels)
	The learning factory facility should allow for different configurations of equipment

Product

General	Requirement
General	The learning factory product should be as similar as possible to real industrial products
	The production of the learning factory product should be sustainable

Figure 2. Figure G.22. Case study requirement list part 1

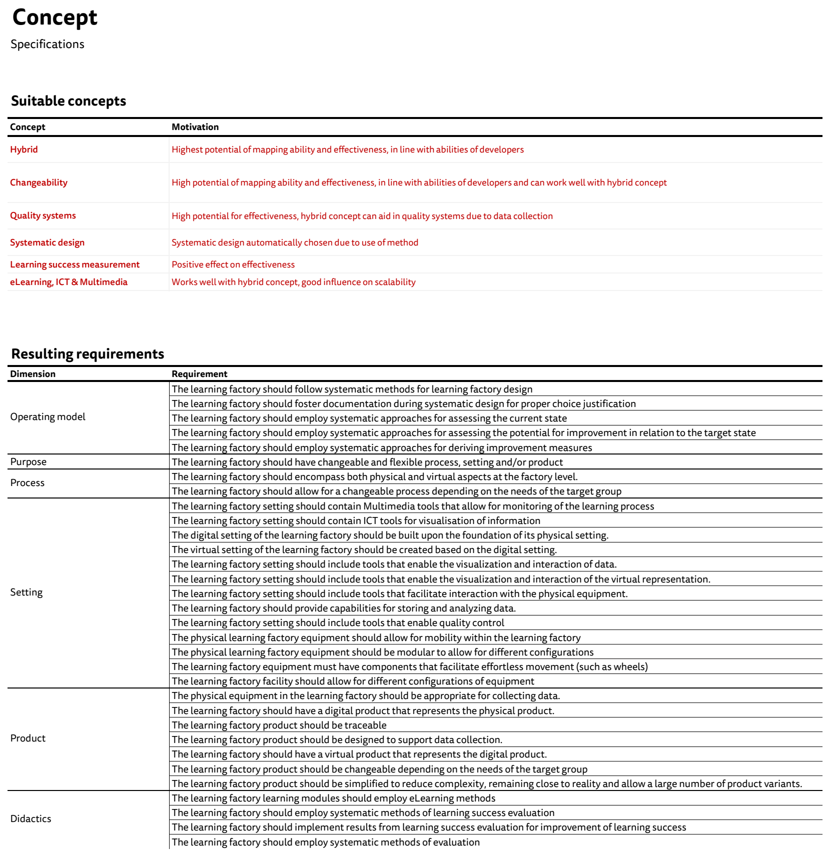


	The learning factory product should fit and support the learning factory processes and setting
	The learning factory product should be tailored to the requirements of the target group(s) and stakeholders
Limitations	The learning factory should have changeable and flexible product.
Concept selection	The physical equipment in the learning factory should be appropriate for collecting data.
	The learning factory should have a digital product that represents the physical product.
	The learning factory product should be traceable
	The learning factory product should be designed to support data collection.
	The learning factory should have a virtual product that represents the digital product.
	The learning factory product should be changeable depending on the needs of the target group
	The learning factory product should be simplified to reduce complexity, remaining close to reality and allow a large number of product variants.
Didactic needs	The product should have mechanical components.
	The product should have a simple complexity level.
	The product should have limited individualization.
	The product should have a standard number of assembly steps.
	~~The product should have electrical components.~~

Didactics

General	Requirement
General	The didactical concept should comprise formal, informal and non-formal learning (on-site or remote)
	The didactical concept should actively employ active learning methods
	The didactical concept should enable intended competency development based on the requirements of the target group(s)
	The didactical concept should describe intended learning outcomes and addressed competence classes
	The didactical concept should describe learning on learning factory, teaching module and learning situation level
	The didactical concept should describe evaluation of learning outcomes
Concept selection	The learning factory learning modules should employ eLearning methods
	The learning factory should employ systematic methods of learning success evaluation
	The learning factory should implement results from learning success evaluation for improvement of learning success
	The learning factory should employ systematic methods of evaluation

Figure G.23. Case study requirement list part 2



Concept

Specifications

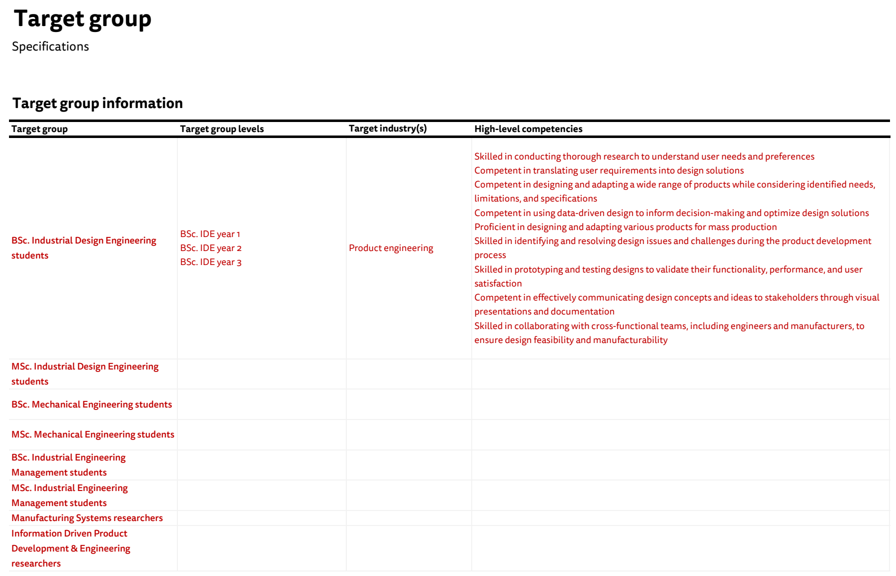
Suitable concepts

Concept	Motivation
Hybrid	Highest potential of mapping ability and effectiveness, in line with abilities of developers
Changeability	High potential of mapping ability and effectiveness, in line with abilities of developers and can work well with hybrid concept
Quality systems	High potential for effectiveness, hybrid concept can aid in quality systems due to data collection
Systematic design	Systematic design automatically chosen due to use of method
Learning success measurement	Positive effect on effectiveness
eLearning, ICT & Multimedia	Works well with hybrid concept, good influence on scalability

Resulting requirements

Dimension	Requirement
Operating model	The learning factory should follow systematic methods for learning factory design
	The learning factory should foster documentation during systematic design for proper choice justification
	The learning factory should employ systematic approaches for assessing the current state
	The learning factory should employ systematic approaches for assessing the potential for improvement in relation to the target state
	The learning factory should employ systematic approaches for deriving improvement measures
Purpose	The learning factory should have changeable and flexible process, setting and/or product
Process	The learning factory should encompass both physical and virtual aspects at the factory level.
	The learning factory should allow for a changeable process depending on the needs of the target group
Setting	The learning factory setting should contain Multimedia tools that allow for monitoring of the learning process
	The learning factory setting should contain ICT tools for visualisation of information
	The digital setting of the learning factory should be built upon the foundation of its physical setting.
	The virtual setting of the learning factory should be created based on the digital setting.
	The learning factory setting should include tools that enable the visualization and interaction of data.
	The learning factory setting should include tools that enable the visualization and interaction of the virtual representation.
	The learning factory setting should include tools that facilitate interaction with the physical equipment.
	The learning factory should provide capabilities for storing and analyzing data.
	The learning factory setting should include tools that enable quality control
	The physical learning factory equipment should allow for mobility within the learning factory
	The physical learning factory equipment should be modular to allow for different configurations
	The learning factory equipment must have components that facilitate effortless movement (such as wheels)
	The learning factory facility should allow for different configurations of equipment
Product	The physical equipment in the learning factory should be appropriate for collecting data.
	The learning factory should have a digital product that represents the physical product.
	The learning factory product should be traceable
	The learning factory product should be designed to support data collection.
	The learning factory should have a virtual product that represents the digital product.
	The learning factory product should be changeable depending on the needs of the target group
	The learning factory product should be simplified to reduce complexity, remaining close to reality and allow a large number of product variants.
Didactics	The learning factory learning modules should employ eLearning methods
	The learning factory should employ systematic methods of learning success evaluation
	The learning factory should implement results from learning success evaluation for improvement of learning success
	The learning factory should employ systematic methods of evaluation

Figure G.24. Case study concept specifications



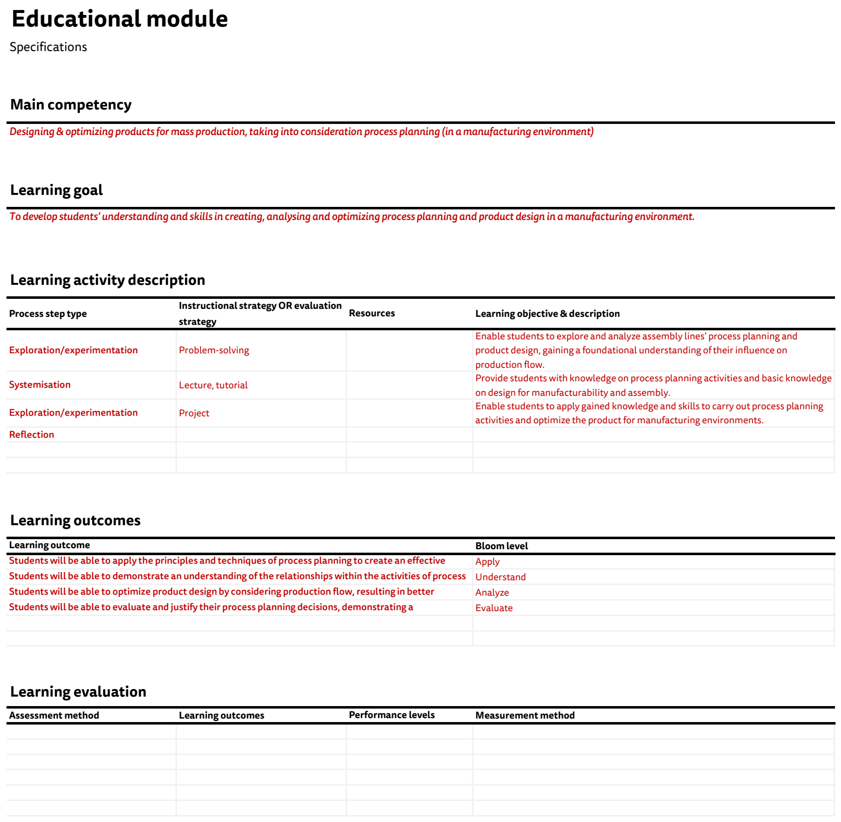
Target group

Specifications

Target group information

Target group	Target group levels	Target industry(s)	High-level competencies
BSc. Industrial Design Engineering students	BSc. IDE year 1 BSc. IDE year 2 BSc. IDE year 3	Product engineering	Skilled in conducting thorough research to understand user needs and preferences Competent in translating user requirements into design solutions Competent in designing and adapting a wide range of products while considering identified needs, limitations, and specifications Competent in using data-driven design to inform decision-making and optimize design solutions Proficient in designing and adapting various products for mass production Skilled in identifying and resolving design issues and challenges during the product development process Skilled in prototyping and testing designs to validate their functionality, performance, and user satisfaction Competent in effectively communicating design concepts and ideas to stakeholders through visual presentations and documentation Skilled in collaborating with cross-functional teams, including engineers and manufacturers, to ensure design feasibility and manufacturability
MSc. Industrial Design Engineering students			
BSc. Mechanical Engineering students			
MSc. Mechanical Engineering students			
BSc. Industrial Engineering Management students			
MSc. Industrial Engineering Management students			
Manufacturing Systems researchers			
Information Driven Product Development & Engineering researchers			

Figure G.25. Case study target group specifications



Educational module

Specifications

Main competency

Designing & optimizing products for mass production, taking into consideration process planning (in a manufacturing environment)

Learning goal

To develop students' understanding and skills in creating, analysing and optimizing process planning and product design in a manufacturing environment.

Learning activity description

Process step type	Instructional strategy OR evaluation strategy	Resources	Learning objective & description
Exploration/experimentation	Problem-solving		Enable students to explore and analyze assembly lines' process planning and product design, gaining a foundational understanding of their influence on production flow.
Systemisation	Lecture, tutorial		Provide students with knowledge on process planning activities and basic knowledge on design for manufacturability and assembly.
Exploration/experimentation	Project		Enable students to apply gained knowledge and skills to carry out process planning activities and optimize the product for manufacturing environments.
Reflection			

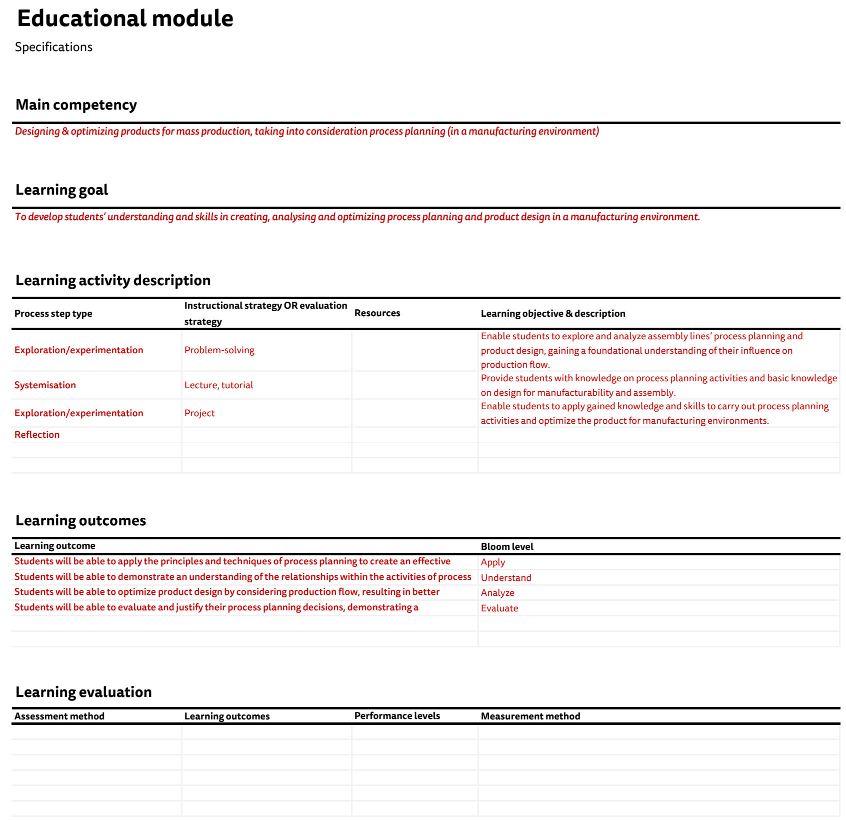
Learning outcomes

Learning outcome	Bloom level
Students will be able to apply the principles and techniques of process planning to create an effective	Apply
Students will be able to demonstrate an understanding of the relationships within the activities of process	Understand
Students will be able to optimize product design by considering production flow, resulting in better	Analyze
Students will be able to evaluate and justify their process planning decisions, demonstrating a	Evaluate

Learning evaluation

Assessment method	Learning outcomes	Performance levels	Measurement method

Figure G.26. Case study educational module MOD4 specifications



Educational module

Specifications

Main competency

Designing & optimizing products for mass production, taking into consideration process planning (in a manufacturing environment)

Learning goal

To develop students' understanding and skills in creating, analysing and optimizing process planning and product design in a manufacturing environment.

Learning activity description

Process step type	Instructional strategy OR evaluation strategy	Resources	Learning objective & description
Exploration/experimentation	Problem-solving		Enable students to explore and analyze assembly lines' process planning and product design, gaining a foundational understanding of their influence on production flow.
Systemisation	Lecture, tutorial		Provide students with knowledge on process planning activities and basic knowledge on design for manufacturability and assembly.
Exploration/experimentation	Project		Enable students to apply gained knowledge and skills to carry out process planning activities and optimize the product for manufacturing environments.
Reflection			

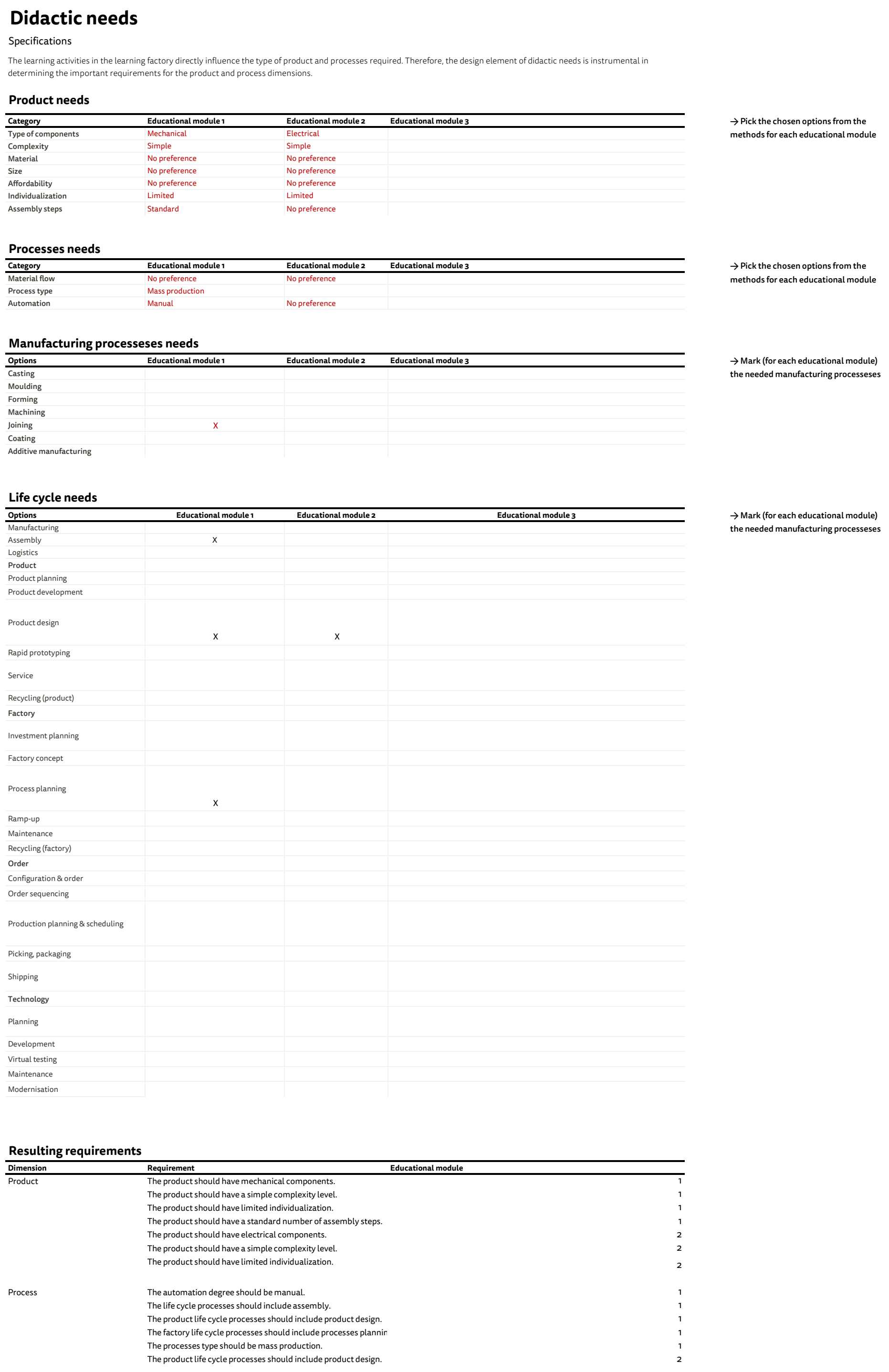
Learning outcomes

Learning outcome	Bloom level
Students will be able to apply the principles and techniques of process planning to create an effective	Apply
Students will be able to demonstrate an understanding of the relationships within the activities of process	Understand
Students will be able to optimize product design by considering production flow, resulting in better	Analyze
Students will be able to evaluate and justify their process planning decisions, demonstrating a	Evaluate

Learning evaluation

Assessment method	Learning outcomes	Performance levels	Measurement method

Figure G.27. Case study educational module MOD5 specifications



Didactic needs

Specifications

The learning activities in the learning factory directly influence the type of product and processes required. Therefore, the design element of didactic needs is instrumental in determining the important requirements for the product and process dimensions.

Product needs

Category	Educational module 1	Educational module 2	Educational module 3
Type of components	Mechanical	Electrical	
Complexity	Simple	Simple	
Material	No preference	No preference	
Size	No preference	No preference	
Affordability	No preference	No preference	
Individualization	Limited	Limited	
Assembly steps	Standard	No preference	

→ Pick the chosen options from the methods for each educational module

Processes needs

Category	Educational module 1	Educational module 2	Educational module 3
Material flow	No preference	No preference	
Process type	Mass production		
Automation	Manual	No preference	

→ Pick the chosen options from the methods for each educational module

Manufacturing processeses needs

Options	Educational module 1	Educational module 2	Educational module 3
Casting			
Moulding			
Forming			
Machining			
Joining	X		
Coating			
Additive manufacturing			

→ Mark (for each educational module) the needed manufacturing processeses

Life cycle needs

Options	Educational module 1	Educational module 2	Educational module 3
Manufacturing			
Assembly	X		
Logistics			
Product			
Product planning			
Product development			
Product design	X	X	
Rapid prototyping			
Service			
Recycling (product)			
Factory			
Investment planning			
Factory concept			
Process planning	X		
Ramp-up			
Maintenance			
Recycling (factory)			
Order			
Configuration & order			
Order sequencing			
Production planning & scheduling			
Picking, packaging			
Shipping			
Technology			
Planning			
Development			
Virtual testing			
Maintenance			
Modernisation			

→ Mark (for each educational module) the needed manufacturing processeses

Resulting requirements

Dimension	Requirement	Educational module
Product	The product should have mechanical components.	1
	The product should have a simple complexity level.	1
	The product should have limited individualization.	1
	The product should have a standard number of assembly steps.	1
	The product should have electrical components.	2
	The product should have a simple complexity level.	2
	The product should have limited individualization.	2
Process	The automation degree should be manual.	1
	The life cycle processes should include assembly.	1
	The product life cycle processes should include product design.	1
	The factory life cycle processes should include processes plannin	1
	The processes type should be mass production.	1
	The product life cycle processes should include product design.	2

Figure G.28. Case study didactic needs specifications

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