A factory planning and design framework for integrating the Digital Twin in Industry 4.0

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A factory planning and design framework for integrating the Digital Twin in Industry 4.0

Abstract: Factory planning and design is a key building block for coining the strategic competitiveness of a manufacturing company. Novel trends in Industry 4.0 such as mass customization for increasingly dynamic markets, the emergence of the Industrial Digital Twin, or growing connectivity and cloud manufacturing are leading to changing requirements for planning and designing factories. Especially small and medium-sized enterprises (SMEs) struggle with these complexity challenges. A novel process model for factory planning and design in Industry 4.0 is presented. To enhance the current state-of-the-art for factory planning and design frameworks, the model enables the integration of the Industrial Digital Twin i.e., the Asset Administration Shell, into the overall factory planning and design process. Eventually, the process model is exemplarily applied to designing a container factory. Based on this case, its efficacy as well as its suitability for SMEs is verified. Thus, the process model can support SMEs in realizing a higher return on investments by creating novel digital and data-driven business models based on connected manufacturing assets.

Keywords: Systems Engineering and Design, Manufacturing Systems, Asset Administration Shell
1. Introduction

1.1 Rationale and Objective

During the last 30 years, the occurrence of three different paradigms in manufacturing can be distinguished: Computer Integrated Manufacturing (CIM), Lean Manufacturing, and Industry 4.0, which all led to different requirements for the planning and design of factories [1]. Current evolvements in Industry 4.0 require high flexibility and connectivity while introducing new concepts such as Industrial Digital Twins, Artificial Intelligence, or cloud and edge computing [2, 3]. Planning and designing factories in this constantly changing manufacturing environment poses great challenges to manufacturing companies and especially SMEs. SMEs usually have difficulties in driving knowledge and technology-based innovations [4] as well as in adopting digital technologies across all areas [5]. This challenge becomes particularly relevant since SMEs represent 99% of all enterprises in the EU [6]. Concepts for planning and designing factories in Industry 4.0, which are also particularly suitable for SMEs, have hardly been addressed in the current academic debate. This research intends to contribute to closing this gap by perusing the following research question:

How can a factory be efficaciously planned and designed with the limited capabilities and capacities of SMEs while considering the trends and technologies of Industry 4.0?

Thus, this qualitative research aims to conceptualize and validate a generic model which can be used for planning and designing factories within the Industry 4.0 paradigm. The model should be easily applicable to SMEs. It should not require high investments or specialized knowledge. Consequently, the framework should include a step-by-step guide to factory planning and design, starting with the requirements provided by the product to be manufactured and concluding with a detailed layout and equipment selection for the factory that fulfills the requirements of Industry 4.0. An emphasis shall be put on the integration of the Industrial Digital Twin since it is considered the key technology in Industry 4.0 facilitating the digitalization as well as the automation of manufacturing systems.

1.2 Approach and Structure

The research encompasses a qualitative research approach. The conceptual model for planning and designing a factory in Industry 4.0 has been elaborated in expert workshops incorporating four engineers from the University of Southern Denmark. Throughout structured workshops, the concept had been drafted by combining state-of-the-art methods and tools for factory planning and design with Industry 4.0 technologies. Subsequently, the Delphi method [7] was used to iteratively create a consensus among the experts on the relevant building blocks of the model. Simultaneously, a case was created to test and validate the model, especially its principal suitability for SMEs. The model has been continuously updated based on the learnings from the case.

The paper is structured as follows: Chapter 2 describes the state-of-the-art for Industry 4.0 and factory planning based on a narrative literature review. Within Chapter 3, the model for planning and designing a factory in Industry 4.0 is conceptualized. Chapter 4 focuses on a case for testing and validating the specific development phases of the model while designing and planning a container factory. Throughout Chapter 5, a discussion of the research results and limitations of the proposed model and case are laid out. Chapter 6 concludes the research and addresses potential future research activities.

2. State-of-the-art

2.1 Industry 4.0

Competition in Industry 4.0 requires manufacturing companies to meet the customers increasing demand for customization. This requires high flexibility and adaptability of value creation. Flexible production equipment in an Industry 4.0 setup must produce customized products, components, and parts in increasingly smaller batches, and even in batch size "one" specifically for customers' orders [8, 9]. Flexibility and adaptability also facilitate
resiliency throughout value networks. This means that both concepts allow the efficacious adaption of the manufacturing system to unforeseen internal and external shocks and demonstrated competitive advantages during the Covid-19 pandemic [10]. Adaptability and Flexibility throughout manufacturing systems in Industry 4.0 are essentially driven by digitalization as well as by automation and artificial intelligence (AI) [11].

Digitalization and the digital connectivity of assets along the value network, enabled by the utilization of ICT is an important success factor for adaptable and flexible manufacturing systems in Industry 4.0 [12]. ICT enables the system infrastructure to share data and information between manufacturing assets as well as between stakeholders and allows a company to respond quickly to dynamic markets. The implementation of ICT in a manufacturing set-up is based on sensors, embedded in manufacturing equipment, which are connected to PLCs and share data from the equipment to the edge or cloud storage [13]. Next to the ICT infrastructure, digitalization and digital connectivity also require a structure for the digital representation of physical assets and processes, i.e., the Digital Twin. The framework of the Asset Administration Shell (AAS) has been defined as the Industrial Digital Twin in Industry 4.0 by relevant stakeholders [14, 15]. The AAS offers new standardized solutions for connecting manufacturing assets with different IT service layers. It aims at storing and collecting relevant data and data streams, such as technical data, operational data, identification data, etc., over the whole life cycle of an asset and is clustered according to specific sub-models which are defined by standardized semantic properties [16, 17, 18]. Consequently, the AAS substantially facilitates interoperability by enabling a data exchange of manufacturing assets across the different hierarchy levels of a factory as well as along value chains and the asset’s life cycle. In doing so, it serves as the enabling technology for implementing the Reference Architecture Model Industry 4.0 (RAMI4.0) [19] by connecting the different RAMI4.0 dimensions data-wise. It helps to predict future scenarios and states of manufacturing systems and thus can provide decision-makers with recommendations on how to prepare for and handle incidents and problems before they occur in the physical system.

Automated industrial systems are important building blocks for adaptable and flexible manufacturing systems in Industry 4.0 [3]. These systems can be characterized according to their autonomy level for human-machine interaction and can range from no autonomy to autonomous operations of the system in all areas. Higher levels of autonomy require monitoring of the system environment by AI technologies. AI technologies reduce the necessity for human intervention in manufacturing systems and increase the system's degree of independence within defined boundaries [20]. AI technologies are usually based on machine learning techniques such as transfer learning, reinforcement learning, and deep learning neural networks including feed-forward neural networks, recurrent neural networks, convolutional neural networks, and generative adversarial networks [21]. AI also expands the functionality of industrial robots which create value through automatically controlled manipulators [22]. AI allows industrial robots to respond to their environment in real time and eventually creates collaborative industries with a connected workforce of robots and humans [23, 24]. To summarize, automation is usually driven by combining AI with industrial robots and is facilitated by digitalization and digital connectivity. Consequently, the AAS also serves as a key technology for enabling automation.

2.2 Factory Planning and Design

Factory planning and design, sometimes also referred to as facility planning, is the process of developing a factory from the first idea to the start of production [25]. It aims at designing necessary digital and physical assets as well as at arranging them in a layout for efficaciously complying with specified manufacturing objectives. Factory planning is key to improving the competitiveness and productivity of a manufacturing facility [26]. The factory layout has a substantial impact on material handling costs, as higher transportation distances between assets will increase costs [27]. Factory planning and design are considered important operations management tasks. Its set of useful methodologies, methods, and tools must be constantly updated due to new technological and market trends, regulations, or as a reaction to internal and external shocks. In an Industry 4.0 context, factory planning and design must be able to cope with the new adaptability and flexibility requirements, e.g., due to the mass customization of a product, while utilizing digital and automated technologies such as the AAS.
Factory planning and design can be classified into the development of completely new factories without any existing layout and/or manufacturing assets in the sense of a greenfield planning and into a brownfield planning where a factory and/or its sub-systems are designed by taking an existing layout and/or existing manufacturing assets into account [28].

According to VDI 5200, which is a commonly applied industrial standard for planning and designing factories, the factory planning, and design process can be divided into seven relevant phases [29]. The process phases address a specific sequence of actions for developing a factory from setting specific objectives to supporting the production ramp-up. Relevant assets for the factory planning and design process can be structured in Industry 4.0 according to the different levels of value creation: products, field devices, stations, and work centers [19].

A crucial aspect of the planning process is the development of an efficacious layout for the factory and its manufacturing assets. For planning the layout, often two different methods are applied. The first method, which is known as static facility layout planning (SFLP), is applied in cases where the demand for the product is rather constant over a specific period. In SFLP, the layout remains the same throughout the planning period and is optimized for one specific production volume [30]. The second method, dynamic facility layout planning (DFLP), deals with cases where the product demand is expected to be variable. This means that the layout needs to adapt following the demand, both in volume and type or variants of products [31].

A relevant task of layout planning is the design of the manufacturing process chain and includes the selection of manufacturing equipment for the execution of specific manufacturing processes to produce the intended product according to its specifications. This can be done by specifying the manufacturing operations [32, 33].

Selected, relevant research clusters in the scientific field of factory planning and design in an Industry 4.0 context are listed as follows:

- design frameworks for Industry 4.0 factories, e.g., as discussed by [34, 35].
- designing a digital factory or the digital twin of a factory, e.g., as discussed by [36, 37].
- model-, simulation- and algorithm-based design of a factory, e.g., as discussed by [38, 39].

2.3 Research Gap

This paper intends to contribute to the scientific field of factory planning and design in an Industry 4.0 context by presenting a design process that:

- focuses on adaptability and flexibility of the manufacturing system by enabling mass customization for a batch size "one";
- is especially suitable for SMEs and start-ups by offering a straightforward design process based on commonly available engineering competencies and standard simulation tools;
- takes the design of the key technology for digitalization and automation, the AAS, into consideration.

Especially, the design of the system of AASs based on recently standardized semantic sub-models [40] seems to be relevant from an industrial perspective. The relevant industry associations are currently trying to close the interoperability gap between assets in Industry 4.0. SMEs can utilize the AAS to connect their manufacturing assets to the digital world and thus gain the opportunity to offer new digital services to their customers.
3. Model

3.1 Model Description

The model for planning and designing a factory for Industry 4.0 requirements is depicted in Figure 1. The model consists of four main phases, which aim at developing specific artifacts of an Industry 4.0 factory: manufacturing technology, material flow, ICT, and the AAS. The phases consist of three tasks (or activities) each, 1.1 to 4.3, for creating relevant sub-artifacts, e.g., manufacturing equipment as a sub-artifact for manufacturing technology. The artifacts are typically developed iteratively throughout the phases, and tasks are also interlinked which means that the output from one task serves as a relevant input for another task. The description of tasks 1.1 to 4.3 is outlined in sections 3.B to 3.E.

The overall development process for creating the artifacts is derived from the typical phases of Integrated Design Engineering (IDE) [41]. It consists of phases A to E and reflects an iterative development process. The maturity level of solutions or results might fluctuate between lower and higher states on its pathway towards a fully realized factory.

![Figure 1. Model for Planning and Designing a Factory in Industry 4.0.](image)

Researching and Analysis (A.) covers the investigation of frame conditions, needs, literature, industrial standards, and guidelines. Conceptualization (B.) includes the clarification of tasks, finding, specifying, and selecting solution ideas, the determination of target characteristics, or the creation of attribute structures. Designing and Modelling (C.) focuses on finding geometry, drafting solutions and designs, creating function models, or 3D modeling and visualization. Evaluating, Comparing, and Selecting (D.) addresses the definition of evaluation criteria, running virtual or physical tests, evaluating the required performance and scope of work, or selecting suitable designs, variants, and solutions. Realization (E.) requires the implementation, installation, and commissioning of selected designs and solutions and the creation of the required documentation [41].
3.2 Phase 1: Manufacturing Technology

The first phase aims at designing the manufacturing technology by selecting the manufacturing and supporting equipment (Table 1). Recommended tools supporting this phase are for example CAD/CAM software.

Table 1. Description of tasks/activities 1.1, 1.2, 1.3

<table>
<thead>
<tr>
<th>Task/Activity</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1.1</strong></td>
<td>This task aims at analyzing the characteristics of the product(s) and its components and parts. This usually entails a definition of the manufacturing requirements based on the product's bill of material. Relevant requirements, for example, might be material, quality, manufacturing requirements (i.e.: fabrication, assembly including handling requirements), or safety requirements. The sequence of generic fabrication, assembly, and material handling operations which is required for producing the product(s) and its assemblies, components, and parts is determined, e.g., cutting, picking parts, etc. Additionally, relevant production objectives are determined and continuously updated.</td>
</tr>
<tr>
<td><strong>Results:</strong></td>
<td>Defined technological boundaries; list of requirements for the manufacturing system of the factory; determined sequence of manufacturing operations (fabrication, assembly, and material handling operations); defined production objectives.</td>
</tr>
<tr>
<td><strong>1.2</strong></td>
<td>This task aims at selecting manufacturing processes for the sequence of fabrication, assembly, and material handling operations. This includes, for example, the selection of a sawing process based on the DIN8580 [42] for realizing a cutting operation. Subsequently, specific manufacturing equipment is selected for the sequence of manufacturing processes also iteratively considering the results from Phase 2. For example, a specific sawing machine for the sawing process or a 3-axis robot for a carrying process needs to be selected. The selection of manufacturing equipment is usually influenced, among others, by the required capacity, machine hour rate, energy consumption, agility, and flexibility requirements, or the set of different materials that can be processed. The selection of manufacturing equipment often goes together with a decision towards a hybrid or fully automated manufacturing system. For the design of an automated manufacturing cell, a decision on tool changers, feeders, grippers, and workpiece carriers is relevant. The selection of manufacturing equipment also incorporates a decision on the internal logistics equipment. For example, the selected material handling equipment such as robots, AGVs, and warehouses yield the internal logistics strategy.</td>
</tr>
<tr>
<td><strong>Results:</strong></td>
<td>Fixed sequence of manufacturing processes; defined set of manufacturing equipment; strategy for the internal logistics.</td>
</tr>
<tr>
<td><strong>1.3</strong></td>
<td>The determined set of manufacturing equipment provides the foundation for designing the necessary auxiliary and technical building system as well as the safety system which is necessary to operate the factory. This includes for the auxiliary system a selection of cooling, compressed air, and lubrication equipment. For the technical building system (TBS), the factory building shell, heating, ventilation, air conditioning (HVAC), lighting, and distribution grid is selected. Safety measures usually include health-related equipment such as virtual and physical fences and emergency shut-off solutions or health support equipment.</td>
</tr>
<tr>
<td><strong>Results:</strong></td>
<td>Determined set of supporting equipment: TBS, factory building shell, HVAC, lighting, distribution grid; determined set of safety and health supporting measures and equipment.</td>
</tr>
</tbody>
</table>
3.3 Phase 2: Material Flow

The second phase aims at designing and planning the material flow by selecting a sourcing and supply chain strategy, as well as key performance indicators and the factory layout (Table 2). Recommended tools supporting this phase are for example Discrete Event Simulation, Value Stream Mapping, and Layout Planning software.

Table 2. Description of tasks/activities 2.1, 2.2, 2.3

2.1 Task/Activity: The expected demand for the product(s), i.e., the expected product quantity over time, is calculated for the determined planning period. This includes the demand for the product(s), and product variants, as well as from all assemblies, components, and parts. The analysis further requires considering possible fluctuations in demand. Additionally, the sourcing strategy for the product is determined, including make-or-buy decisions, and the selection of suitable suppliers for assemblies, components, and parts.

Results: Forecasted demand for products, assemblies, components, and parts for the planning period; determined sourcing strategy.

2.2 Task/Activity: The quantity of manufacturing equipment is determined in such a way that the forecasted demand can be fulfilled. This also requires a determination of the number of workers who are needed to carry out manual manufacturing tasks. The manufacturing equipment is arranged within a concept for the material flow. Different types of material flow organizations might apply for hybrid or fully automated manufacturing systems. The capacity and other relevant production (key) performance indicators, e.g., cycle time, throughput time, delivery time, and energy consumption, are estimated based on the selected manufacturing equipment and the demand forecast for parts, components, assemblies, and products. Potential bottlenecks of the manufacturing system are identified.

Results: Qualifiable and quantifiable key performance indicators (KPIs) of the manufacturing system; identified bottlenecks.

2.3 Task/Activity: This task aims at determining the layout of the factory. This includes a definition of spaces for the equipment of the manufacturing system, i.e., the different types of manufacturing entities and machines, the safety equipment, storage, material provision, and warehouses, as well as an analysis of how these spaces should be connected with the material handling equipment. The factory is further structured into single workplaces, stations, cells, lines, or work centers. For each of these hierarchy levels, a detailed layout is defined, e.g., the placement of joining spot, tool changers, material provision, feeder, gripper, workpiece carriers, and the safe integration of the human.

Results: Determined layout(s) and hierarchical structure of the manufacturing system including defined layouts for all workplaces, stations, cells, lines, and work centers.

3.4 Phase 3: Information and Communication Technology

The third phase aims at designing the Information and Communication Technology (ICT) by creating a data measuring, management, and evaluation strategy as well as by selecting the required ICT hardware and software (Table 3). Recommended tools supporting this phase are for example Systems Modeling Language (SysML) or the Object Process Methodology (OPM).
Table 3. Description of tasks / activities 3.1, 3.2, 3.3

3.1 Task/ Activity: The creation of the measuring strategy includes the development of a (1) measuring method, including a selection of measuring devices, interfaces, temporal resolution, of a (2) measuring procedure, i.e., a decision on what parameters will be measured, when and how long / often, and where will it be measured, and of (3) the actual data acquisition phase [32]. The measuring strategy should consider the manufacturing processes, the TBS, factory building shell, HVAC, lighting, distribution grid, as well as the safety system.

Results: Defined data measuring strategy.

3.2 Task/ Activity: The data evaluation and management strategy describes the approach for transferring the measured data into useful applications, e.g., by deriving machine states from the measured data of a milling machine. This usually requires some degree of manufacturing domain knowledge a. Data evaluation and management also includes the specification of a suitable database system, i.e., the decision on edge or cloud solutions.

Results: Defined data evaluation and management strategy.

3.3 Task/ Activity: This task aims at selecting the actual ICT hardware and software. This includes a selection of sensors and control devices such as PLCs, and other required computer hardware and services for setting up an edge and/or cloud infrastructure for storing and analyzing the data based on the data measuring, management, and evaluation strategy. Additionally, software solutions for the different planning and scheduling functionalities of the factory are selected such as the Advanced Process Control (APC), Supervisory Control and Data Acquisition (SCADA), Manufacturing Execution Systems (MES), Fleet Planning and Management, Enterprise Resource Planning (ERP). Eventually, a strategy for cybersecurity needs to be designed for ICT and software solutions.

Results: Determined set of ICT hardware and software for operating the manufacturing system; defined cybersecurity strategy.

3.5 Phase 4: Industrial Digital Twin

The fourth phase aims at designing the set of AASs for representing the Industrial Digital Twin of the factory. This includes designing the specific AAS sub-models, integrating the AASs into the overall manufacturing system, as well as defining relevant digital services (Table 4). Recommended tools supporting this phase are for example the AASX Package Explorer software (AASX-PE).

Table 4. Description of tasks/activities 4.1, 4.2, 4.3

4.1 Task/ Activity: For the selected manufacturing assets, i.e., the software solutions, ICT equipment, manufacturing equipment, safety, auxiliary, and technical building equipment, specific AASs including asset IDs and sub-models are defined. Relevant sub-models are "Nameplate", "Identification", "TechnicalData", "ConfigurationalData", "OperationalData", or "Documentation" among others [40]. The definition of the sub-models takes into consideration the defined measuring strategy (Phase 3.1) and the strategy for data evaluation and management (Phase 3.2). For example, the identified operational state of a machine tool as a result of the data evaluation and management can be connected to the “OperationalData” sub-model of the machine tool’s AAS.

Results: Fixed sub-models of the AASs for the manufacturing assets.
Table 4. Cont.

4.2 **Task/ Activity:** The layout, as well as the set of manufacturing equipment (Phase 2.), provide the building blocks for creating a structure of the AASs for the different hierarchy levels of the manufacturing system/factory [11]. This task addresses the integration of the single AASs into an overall manufacturing system as well as the integration of the AASs into the selected ICT hardware and software solutions.

**Results:** Structure and hierarchy of AASs for the manufacturing system; Integration of AAs into the overall manufacturing system.

4.3 **Task/ Activity:** This task aims at developing the service and information exchange between the different integrated AASs. An AAS-based service exchange is executed as a service request by one asset which then receives a response from another asset, for example, the request of a 3D printer to pick up a printed part, which requires a response from an AGV to pick up the part. This requires a definition of the logic for each service exchange between assets.

**Results:** In the AASs implemented logic for exchanging services between the manufacturing assets of the factory.

4. Case

4.1 Case Description

The fictive case takes place at a university. Every student receives a customized graduation medal with their name engraved on it. The university intends to manufacture the medals in a factory which shall offer flexibility and adaptably enabled through a high level of digitalization and automation. Another requirement from the university is, that the factory must fit in a 20-foot ISO container. This allows easy up-scaling of the manufactured production capacity as well as production at different university locations. The container factory will be developed as part of a greenfield approach.

4.2 Manufacturing Technology

A prototype and drawing of the product, i.e., a graduation medal, can be seen in Figure 2. The medal material is ABS. The ring diameter (orange) is 60 mm. The inner circle (black) is 20mm. The ring is engraved with the students’ name and their education. Afterward, the two parts are pressed together and placed in a box, which gets labeled with the information of the student.

![Figure 2. Prototype and drawing of the product for the factory planning and design case.](image-url)
For each operation that is required to manufacture the product, suitable manufacturing processes are evaluated and selected, according to their process requirements, i.e., set of materials that can be equipped, degree of automation, or processing time. Eventually, the following manufacturing processes are chosen: 1) 3D Printing (FFF), 2) Laser Engraving, 3) Automated Pressing, 4) Automated packaging, 5) Automated labeling, and 6) Pick and Place.

For the selected manufacturing processes, suitable equipment is selected. Therefore, the specific equipment capabilities and characteristics are typically retrieved from the vendor’s equipment specifications. The selected equipment is highlighted in grey in Table 5. The evaluation criteria used for selecting and designing the manufacturing equipment are capacity, cost, and equipment space. However, other relevant evaluation criteria might be adaptability and flexibility, time, quality, or some sustainability-oriented criteria such as power or material consumption.

Table 5. Matching manufacturing processes with manufacturing equipment

<table>
<thead>
<tr>
<th>Manufacturing Process</th>
<th>Suitable Manufacturing Equipment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) 3D Printing (FFF)</td>
<td>FLSUN q5</td>
</tr>
<tr>
<td></td>
<td>Flashforge adventure 3</td>
</tr>
<tr>
<td></td>
<td>Creality 3D - Sermoone D1</td>
</tr>
<tr>
<td>2) Laser Engraving</td>
<td>Atomstack A5 20W</td>
</tr>
<tr>
<td></td>
<td>SpeedMarker 700</td>
</tr>
<tr>
<td>3) Automated Pressing</td>
<td>Sealey PPB15 Hydraulic Press</td>
</tr>
<tr>
<td></td>
<td>Premier 15tonne</td>
</tr>
<tr>
<td></td>
<td>SIP 03650 10 Ton Bench Press</td>
</tr>
<tr>
<td>4) Automated packaging</td>
<td>UR 5</td>
</tr>
<tr>
<td></td>
<td>LBR iiwa</td>
</tr>
<tr>
<td></td>
<td>TM5-700</td>
</tr>
<tr>
<td>5) Automated labeling</td>
<td>6900 PLC Based Printer-Applicators</td>
</tr>
<tr>
<td></td>
<td>2010 Series M-Class Mark II</td>
</tr>
<tr>
<td></td>
<td>Based Printer-Applicators</td>
</tr>
<tr>
<td>6) Pick and Place</td>
<td>UR 5</td>
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<tr>
<td></td>
<td>LBR iiwa</td>
</tr>
<tr>
<td></td>
<td>TM5-700</td>
</tr>
</tbody>
</table>

4.3 Material Flow

The university graduates between 8.000 and 10.000 students every half a year from which everyone receives a graduation medal. Manufacturing times are split into set-up times and cycle times for each process step. The selected FLSUN q5 can for example print one graduation medal in around 1 hour and 30 minutes. Thus, 71 medals can be produced in one batch without changing the filament spool in the printer. A tool set-up with new material is approximated to take 3 minutes. The filament material for the printing is sourced from different 3D printing suppliers.

The block layout of the factory is created based on the logical interconnection between the manufacturing equipment/workplaces based on the processing sequence [43]. The results of the layout for the graduation medal container factory are shown in Figure 3.
Subsequently, the machining parameters and the block layout are implemented in a simulation model, to test the production capacity and material flow. The capacity is tested to see if the selected manufacturing equipment can meet the product demand. Eventually, the quantity of five 3D printers as well as four UR robots for material handling and one unit each for the other manufacturing equipment is chosen. This provides a capacity for 11,382 graduation medals within 150 days. For material handling purposes, chutes are foreseen. The UR robot will drop the graduation medal on the chute, and it will slide to the designated process.

The material flow is tested to find potential bottlenecks. It shows that 3D printers are the bottleneck for material flow. The other equipment is idling 85% to 90% of its time. Thus, the capacity of the whole factory can be simply increased by adding more 3D printers. Relevant evaluation criteria for designing the material flow are the capacity and throughput time of the manufacturing processes as well as the reachability of all processes by the UR and the overall space utilization of the equipment in the limited dimensions of the container.

The detailed factory layout is visualized in a 3D view Figure 4, which fosters a discussion with relevant stakeholders such as operators and production planners.
4.4 Information and Communication Technology

A connectivity matrix is created for analyzing the required data flow between the manufacturing equipment. The printer must communicate with the UR robot which picks and places the products after being printed while the printer is initiating the next printing job. Additionally, the engraver and the labeling machine must communicate with the UR robot to start the machining and material handling tasks. Further, the manufacturing machines must be connected to an ERP or MES to retrieve the production schedule as well as the required student information for personalizing the product.

The selected 3D printer is by default not easily connectable to ICT equipment. A possible solution for enabling connectivity is thus to install an external laser sensor that will be activated whenever the printer head moves to the desired end position. Additionally, a camera can monitor in real-time the printing progress of the product. The sensors are linked to an Arduino PLC. The UR robot and the other machining equipment are by default connectable through an internet connection and by digital signal in- and outputs. Laser sensors are also used to identify whether a product is going through the chutes to start the pick and place process. A cloud system is selected for storing and processing the data. All equipment will be connected via WLAN to the cloud solution. For the MES/ERP system also a cloud-based solution is chosen. Evaluation criteria for designing the ICT are the number of sensors and communication standards applied as well as the ease of use of the equipment for the human operator.

4.5 Industrial Digital Twin

For each of the external sensors as well as for the single manufacturing equipment, an AAS is created which is in turn integrated into an AAS representing the container factory as a manufacturing system. The AASX Package Explorer software (AASX-PE) is used to create the relevant sub-models of the specific assets [44]. The connection between the AASs is made by linking the unique semantic IDs from the AASs of the manufacturing equipment to the AAS of the manufacturing system. Eventually, a logic for exchanging services, e.g., a material handling task between the UR robot and the 3D printer, is established as an additional “services” sub-model in the AAS of the manufacturing system. Figure 5 shows a first draft of the logic for exchanging services between the FLSUN printer and the UR robot. The evaluation criterion for the design of the AAS system is the functionality of the exchange and storage of relevant data and services between the manufacturing equipment.

Figure 5. Logic for exchanging services between the FLSUN printer and the UR robot.
5. Discussion and Limitations

The model for planning and designing a factory in Industry 4.0 (Figure 1) enables the planning of a graduation medal factory placed within the limits of a 20-foot container. The case exemplarily demonstrates how the necessary artifacts of an Industry 4.0 factory can be shaped: manufacturing technology, material flow, ICT, and the Industrial Digital Twin. Even though the case is addressing a factory planning challenge in the context of a university, the case intention is to mimic a typical Industry 4.0 factory planning and design challenge, a typical SME could face as well. The design process seems to be relatively straightforward, and the individual phases of the model can be conducted by applying standard tools. Besides an Office software suite, Siemens plant simulation is used for realizing the material flow simulation. The visualization of the factory is created in 3DView while the AAS modeling is using the AASX Package Explorer software. These tools are all considered common software tools also available to SMEs. However, the authors experienced some difficulties in utilizing the AASX explorer for referencing assets across different manufacturing hierarchy levels and eventually realizing the service exchange between the assets. This challenge could still pose a hurdle for SMEs to use the tools.

Also, no special engineering competencies are required to carry out the individual design phases, but basic knowledge in manufacturing, ICT, as well as production planning, and control seems to be a prerequisite.

However, the following limitations of the research have been identified:

- The research is merely utilizing a fictive case for validation purposes. It is not based on a design challenge, conducted with the involvement of actual SMEs. Thus, the efficacy of the proposed model for Industry 4.0 requirements as well as its suitability for SMEs has not been validated and evaluated in a real-life manufacturing context.
- Most solutions described throughout the case are still rather on a more conceptual level. The implementation and detailed design as well as the production ramp-up have not been addressed in every aspect as part of the case.
- Despite these limitations, the authors believe that the proposed model for planning and designing a factory in the context of Industry 4.0 could demonstrate its basic efficacy for planning automated and digitally enabled factories with a high level of adaptability and flexibility as well as its potential suitability for SMEs.

6. Conclusion and Outlook

The proposed process model enhances the current factory planning and design frameworks by offering a rather straightforward approach while also emphasizing the AAS system as a relevant sub-system for the design process of factories. The proposed process model is thus laying the foundation for efficaciously designing digital and automated factories with high-level data and digital service interoperability. Especially, the integration of the AAS in the factory operation is a priority of SMEs and its relevance is expected to even increase in the future. Interoperability and the exchange of manufacturing services are key priorities in Industry 4.0 [45]. The presented process model for planning and designing factories can help SMEs to realize a higher return on investments by creating novel digital and data-driven business models based on connected manufacturing assets.

Future research will further investigate the design of the sub-model of the Industrial Digital Twin so that a service exchange between assets can be enabled as well as the interlinkage and relations between designing Industrial Digital Twin and the other relevant artifacts. Additionally, the brownfield planning as well as the scaling-up of already established manufacturing systems in Industry 4.0 seems to be relevant for future research activities.
References


