APEM journal
Advances in Production Engineering & Management
Volume 18 | Number 1 | March 2023 | pp 92–103
https://doi.org/10.14743/apem2023.1.459
ISSN 1854-6250
Journal home: apem-journal.org
Original scientific paper

Design and operations framework for the Twin Transition of manufacturing systems

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ABSTRACT

Manufacturing companies are facing what recently has been called the Twin Transition. They must conduct a digital transition as well as a transition from mere linear toward more circular value creation. The research presents an integrated Design and Operations Framework for digital and circular manufacturing systems. Defined process phases of the framework are described which address: the maturity assessment, Objectives and Key Results, the design (Des) and operations (Ops) of the manufacturing system, and a training concept. The authors follow a qualitative research approach for developing the integrated DesOps Framework for Circular and Digital Manufacturing Systems. The framework is conceptualized by combining state-of-the-art procedures and methods in the field of maturity and readiness assessment, Objectives and Key Results, Systems Engineering, and DesOps. Eventually, a case study is utilized for verifying the principal efficacy of the conceptualized framework. The research intends to scientifically contribute to the field of manufacturing systems design by proposing a novel design framework. From industrial application perspective, the research intends to contribute to improving decision-making in manufacturing companies by providing them with a practical-oriented guideline for transforming their manufacturing systems in the sense of the Twin Transition.

ARTICLE INFO

Keywords:
Manufacturing systems design;
Circular economy;
Sustainability;
Digital twin;
Twin transition;
Digital transition;
Design and operations (DesOps)

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Article history:
Received 29 December 2022
Revised 20 April 2023
Accepted 25 April 2023

1. Introduction

European Manufacturing companies are constantly facing the challenge to adapt their value creation to novel regulations as well as to relevant technology trends. The EU Commission is pushing forward the implementation of the European Green Deal throughout the EU member states via regulatory activities such as the new circular economy action plan (CEAP), Registration, Evaluation, Authorization, and Restriction of Chemicals (REACH) including the introduction of the SCIP database, The Supply Chain act, and the Sustainable Finance taxonomy. Additionally, technology trends, for example in the context of Industry 4.0 sensors, robotics, cloud and edge computing, cyber security, artificial intelligence, and the Industrial Digital Twin are increasingly influencing the design and operation of manufacturing systems. Political stakeholders, industry associations, and manufacturing companies are facing what recently has been called the Twin Transition: a sustainable and digital transition of the industry, which will be of increasing importance as an industrial strategy in the future [1]. For manufacturing companies, the Twin Transition can be translated into two concrete pathways of innovation: (1) transitioning from a mere linear towards a more circular economy, and (2) realizing a digital transition of their value creation, i.e., business models and manufacturing systems.

According to the WEF, “in 2019, over 92 billion tonnes of materials were extracted and processed, contributing to about half of global CO_2 emissions” while the resulting waste substantially promotes environmental degradation and human health deterioration [2]. Transitioning from a linear toward a circular economy will serve as a cornerstone for tackling these global challenges [3], can realize up to $4.5 trillion in economic benefits by 2030 [2], and is already determined as the main pillar of Europe’s sustainable growth [4]. A key principle of the circular economy is to keep products and materials circulating in closed-loop life cycles [5]. With it, industrial symbiosis, reuse, remanufacture, and recycling moves to the center of interest in industrial value creation [6]. Remanufacturing, for example, enables the circular economy by maintaining the high value of used products, assemblies, components, and parts, so-called cores, throughout multiple life cycles. However, remanufacturing is still a comparably new approach for most companies, since only 8.6 % of the global value networks are circular [2]. It thus poses novel complexity challenges in terms of managing the reverse logistics, reprocessing the used products, assemblies, components, and parts, or in terms of designing products for remanufacturing.

The transition towards circular value networks will be essentially enabled by a digital transition of the manufacturing systems. A digital transition is coined by novel digital and automation technologies fostered by digital ecosystems such as GAIA-X and becomes a more and more important success factor for adaptable and flexible manufacturing systems in an Industry 4.0 context. Manufacturing companies face the challenge of constantly monitoring digitalization trends and evaluating relevant digital technologies to integrate them into their value creation based on their digital maturity level. Given the complexity of these tasks, many manufacturing companies still struggle to create a suitable strategy for their digital transformation.

The presented research aims at supporting the digital and circular transformation of manufacturing companies by addressing the following research question:

How can manufacturing systems be efficaciously designed and operated to support the Twin Transition of the manufacturing sector?

The paper intends to scientifically contribute to the field of manufacturing systems design by proposing a novel design framework. From industrial application perspective, the research intends to contribute to improving decision-making in manufacturing companies by providing them with a practical-oriented guideline for transforming their manufacturing systems in the sense of the Twin Transition. The research methodology follows a qualitative approach (Fig. 1). A narrative literature review provides the foundation for positioning the research within the state-of-the-art and for deriving the research gap and contribution. Throughout phases of analyses and syntheses, the novel DesOps Framework was conceptualized based on the expert knowledge and experience of the authors. For this purpose, the idea of the Delphi method was followed until a consensus on the framework concept was reached. A case study in the field of manufacturing engineering served to verify, validate, and evaluate the fundamental efficacy of the DesOps Framework. Feedback from the case study was constantly used for improving the framework.

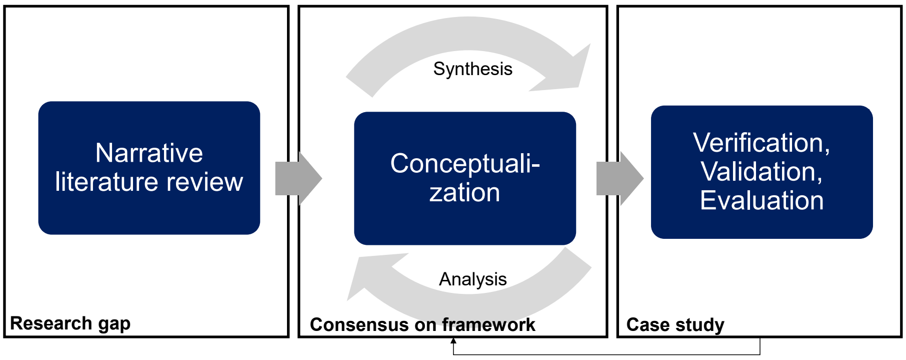

Fig. 1 Research methodology

The paper is structured as follows. The second section describes the state-of-the-art for design of manufacturing systems in general as well as for circularity and digitalization. The section also includes a description of the scientific contribution. The third section introduces the DesOps framework including a description of the framework's relevant process phases. Section 4 addresses the verification, validation, and evaluation of the proposed framework based on a relevant case study in manufacturing, while Section 5 covers a discussion of results and limitations and gives an outlook on future research activities.

2. State-of-the-art

2.1 Design of manufacturing systems

Designing manufacturing systems requires the design of relevant manufacturing artifacts while following a certain design process for developing the manufacturing system with its sub-systems. The artifact and design process point of view is broken down into the following.

Manufacturing artifacts can be interpreted from a technology as well as from a management system perspective [7]. From a technology system perspective, the selection of the manufacturing process chain, i.e., concrete fabrication and assembly technologies, processes, and parameters based on product (or product portfolio) characteristics, is at the core of the design task. The management perspective incorporates a broader scope of manufacturing systems addressing the integrated design of the value network (i.e., of technology and equipment, material flow including the logistics and supply chain, ICT infrastructure, digital components), value proposition (i.e., product-related mechanics, electronics/ electrics, software, and services), and value delivery (i.e., customers, communication channels, cost, and revenue structure) [8]. Thus, the design of the management systems can be rather interpreted in the sense of designing a business model for a hardware product which might also include a software or service component [9]. Different levels of system aggregation can be relevant for designing the manufacturing system from a management perspective. For example, Wiendahl *et al*. distinguish between process, station, cell, system, segment, site, and network levels [10].

The actual design process of manufacturing systems is subject to different design procedures: (1) Design procedures with an emphasis on product development, such as Integrated Design Engineering [11], also address elements of designing manufacturing systems from an integrated design perspective. (2) Other design procedures are more linked to the field of Systems Engineering, e.g., [12], and cover the design of the overall manufacturing system with its different domains in a rather generic manner. (3) Further, design procedures are more specifically tailored to the different levels of aggregation or concrete design tasks of manufacturing systems. For example, Factory Planning and Design [13] as a more high-level approach or designing factory layouts [14], process chains [15], adaptive and flexible automation systems [16], and human-robot collaborative workstations [17] are aimed at delimited design tasks of manufacturing systems. (4) In addition, business-model-oriented design procedures for manufacturing systems have attracted some attention lately. For example, the integrated design of the business model including the design of the manufacturing system linked to the design of the hardware product is presented by [9]. (5) Lastly, design procedures emphasizing on the application of determining design principles are available for manufacturing systems. Designing lean manufacturing systems [18], applying axiomatic design principles [19], or designing resilient manufacturing systems [20] are e.g., based on concrete design principles.

2.2 Design of circular and digital manufacturing systems

The relevance of sustainability and/or digitalization in the context of manufacturing systems is the subject of ongoing academic discussions in production engineering and management, e.g., as presented by [21, 22]. Design procedures for circular manufacturing systems cover comprehensive development frameworks such as e.g., described in [23]. Other procedures focus more on specific end-of-life phases of products. In this context, procedures are proposed for designing manufacturing systems enabling reuse [24], remanufacturing, and recycling [25] capabilities.

Additionally, design procedures for designing industrial symbiosis ecosystems, business models, and (reverse) supply chains are gaining attention, e.g., described by [26]. Design procedures for digital manufacturing systems cover design frameworks for smart factories in Industry 4.0, e.g., as discussed by [27] as well as for digital manufacturing systems [28] or the digital twin of factories [29]. Other approaches focus on the model-, simulation- and algorithm-based design of manufacturing systems, e.g., as discussed by [14, 30]. From an industry perspective, the integrated design of the Industrial Digital Twin / Asset Administration Shell and the physical system of manufacturing assets is a key building block for realizing manufacturing systems in Industry 4.0 and is the subject of relevant manufacturing industry associations [31]. The target-oriented and integrated design of the standardized Industrial Digital Twin, the so-called Asset Administration Shell, and the physical manufacturing system seems to be insufficiently addressed by current academic research activities. Furthermore, structured design procedures for manufacturing systems supporting the Twin Transition by enabling circular through digital value creation seem to be inadequately discussed so far, even though some researchers started investigating how digital technologies, e.g., the digital twin, can enable specific product end-of-life phases such as recycling and remanufacturing [32].

2.3 Scientific contribution

The paper intends to contribute to the scientific field of manufacturing systems design by proposing a framework for the design and operations of digital and circular manufacturing systems which:

- Provides a structured and agile procedure for designing the relevant artifacts of manufacturing systems in the domains: value proposition, value network, and value distribution;
- Incorporate objectives and key results for creating digital and circular manufacturing systems;
- Incorporates the key technology for digitalization, the Asset Administration Shell/Industrial Digital Twin, for enabling circular value creation.

3. DesOps framework

3.1 Framework elements

The integrated DesOps Framework for Circular and Digital Manufacturing Systems is a further development of [8] and combines state-of-the-art procedures and methods in the field of maturity and readiness assessment of organizations concerning digitalization and circularity [33-35], of Objectives and Key Results (OKRs) [36], and DesOps [37].

The DesOps Framework intends to provide manufacturing companies with a practical-oriented guideline for transforming manufacturing systems towards circular value creation enabled by digitalization. The framework consists of nine process phases (Fig. 2). Phase 0 covers the maturity and readiness assessment for determining the initial status of the company's manufacturing system in terms of digital and circular value creation. Phase 1 aims at defining the Objectives and Key Results (OKRs) for the manufacturing system development. OKRs determine the target state for a pre-defined development period which then is continuously updated in alignment with the progress of the development progress. OKRs, therefore, serve as management and control measures for the design process. Phases 2 to 7 are the core of the development methodology by describing the relevant process phases for the design (Des) and operations (Ops) of the manufacturing system. Phase 8 comprises the creation of a training concept for developing the competencies for working in a circular and digital manufacturing environment.

Since the proportion of digital components in manufacturing systems is steadily increasing and will become even more important in the future, design frameworks must reflect the challenges coming along with this trend. Thus, agile practices, which originate in software development find their way also in the development methodologies of hardware systems. The proposed DesOps framework follows the philosophy of agile development by combining the concept of OKRs, for controlling the design process progress, with the DesOps approach which allows the integration of agile principles into the actual design and realization process of the manufacturing system.

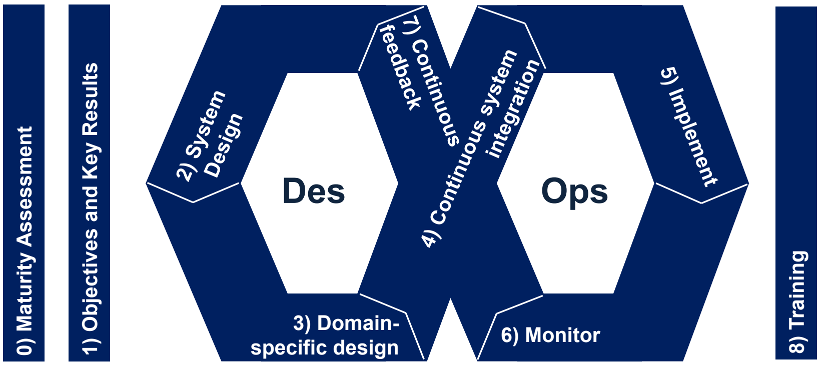

Fig. 2 DesOps Framework (following the idea from [8])

3.2 Phase 0: Maturity assessment

The first framework step aims at assessing the capabilities and maturity of the prevailing company's manufacturing system concerning digitalization and circularity. For that purpose, a range of industry or scientifically-based maturity models can be applied which outline a sequence of either digital and/or circularity capabilities representing a desired evolutionary path for the manufacturing system toward higher levels of maturity and performance. Models typically describe 5 or 6 capability levels and related technology, management, cultural and business practices as well as how they enable higher levels of business and sustainability performance. They are preferably applied to benchmark the current state and develop a future strategic direction for the manufacturing system, including the definition of OKRs and identification of relevant system and domain-specific design components. Table 1 provides examples of recently developed relevant maturity models for this purpose, where two models have an assessment of automation and digitalization maturity in scope, and the third model focuses on the assessment of circularity.

Table 1 Examples of maturity models for digitalization, automation, and circularity

Topic	Digitalization	Automation	Circularity
Level & Authors	[33]	[34]	[35]
Level 0	Computerization	No Autonomy	-
Level 1	Connectivity	Functional Assistance	Linearity
Level 2	Visibility	Partial Autonomy	Industrial CE Piloting
Level 3	Transparency	Delimited Autonomy	Systemic Materials Management
Level 4	Predictive capacity	Flexible Autonomy	CE Thinking
Level 5	Adaptability	System Autonomy	Full Circularity

3.3 Phase 1: Objectives and Key Results (OKRs)

The OKRs serve as steering, management, and control method for the DesOps phases. The initial ORK work cycle (Fig. 3) for the DesOps process is started based on the results of the maturity assessment (Phase 0).

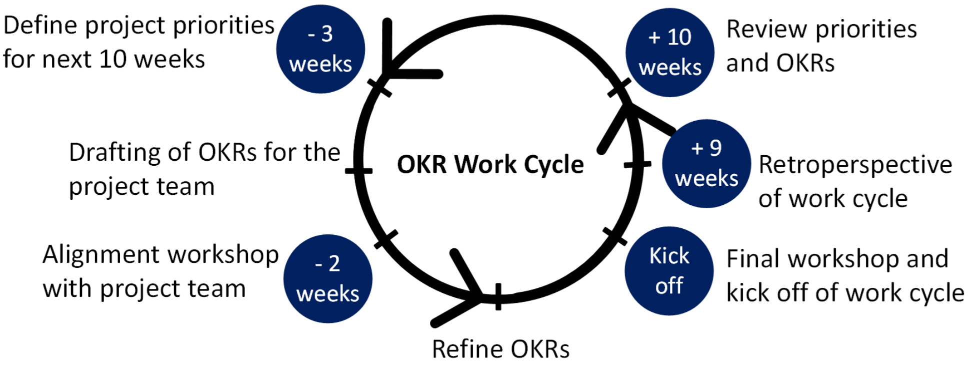

Fig. 3 ORK Cycle (adapted from [36])

Table 2 highlights some important characteristics of the OKR concept. In other words, the first Objectives and Key Results are defined based on the initial digital and circular maturity levels of the organization. Digital maturity is used here in a broader sense and incorporates automation maturity. If the assessed level of maturity is in the range of 0 and 1, then the OKRs should focus on establishing a maturity level of the manufacturing system in the range of 1 to 2. An example of how the achievement of OKRs linked to digital value creation can enable the definition of OKRs linked to circular value creation for the subsequent OKR cycle is presented in Table 3. The OKRs set concrete and time-dependent objectives and results for the pursuit of engineering tasks for all DesOps phases. For example, an OKR work cycle during the "Implement" phase (Phase 6) of the DesOps process would define objectives and results for implementing the domains of the manufacturing system such as production lines and cells, machine tools and assembly stations, ICT-equipment, software tools, or new product variants.

Table 2 Characteristics of the OKR concept [36]

Objectives	**Key results**	**Rules**	**Roles**
… describe an aspirational future state or condition.	… define specific results on how to realize the Objective.	Set an OKR cycle of 4 to 10 weeks and align OKRs accordingly after each cycle.	OKRs are distributed among the available teams, i.e., the OKR owners.
… are qualitative.	… are quantitative and measurable.	Set a maximum of three objectives per organizational unit	Objective owners should also be the owner of at least one Key Result linked to the objective.
… are developed bottom-up and top town.	… are ambitious but realizable.	Limit the number of Key Results to 2 to 5 per Objective.	OKR coaches facilitate the weekly communication and check in on OKR progress.
… should be realizable in one cycle.	… are time-phased and accepted by stakeholders.	Define OKRs for the organizational and team level.	Program leads are responsible for the rollout and development of the OKR process.

Table 3 Example of "digital" OKRs enabling "circular" OKRs

	Digital Value Creation		**Circular Value Creation**	
Maturity	**Objectives**	**Key Results**		**Objectives**
Low (Level 0-1)	Automate simple repetitive manual manufacturing tasks	Robot cell for a certain workplace	Enables	Automate the repairing process for all product lines
Medium (Level 2-3)	Use real-time data for identifying anomalies and states of manufacturing equipment	Real-time mapping of energy profiles for two machine tools	Enables	Integrate renewable energy sources into the manufacturing system
High (Level 4-5)	Implement a self-optimized manufacturing strategy	Industrial Digital Twin for all instances of a certain product variant	Enables	Use the Industrial Digital Twin for the identification of used products and components, so called cores, inside the EU

3.4 Phases 2 to 7: Design and operations

Table 4 lists the relevant engineering task and exemplary engineering methods for the system levels for the design (phases 2 to 4) and operations phases (phases 5 to 7).

Phases 2 to 4 aim at designing the overall manufacturing system with its relevant domains: value proposition, value network, and value delivery [8]. The value proposition domain incorporates the actual hardware product including its potential services to be processed within the manufacturing system, i.e., the subject of value creation. The design of the value proposition also addresses the design of the whole life cycle of the product with its beginning, middle, and end-of-life phases. From a circular economy perspective, embedding the product in closed-loop lifecycles with distinct consideration of opportunities for reuse, remanufacturing, and recycling. The value network is the object of value creation and covers the connected manufacturing assets, e.g., machine tools and other manufacturing equipment, as well as their digital representations, i.e., the Industrial Digital Twins / Asset Administration Shells, which are required to produce the value proposition. The detailed design of the reuse, remanufacturing, and recycling processes as well as of industrial symbioses networks is coined within the value network domain. The value delivery domain comprises the stakeholders including potential customers, the profit structure, as well as the communication channels with the customers. The value delivery has rather supporting functions for circular value creation. However, the domain depicts if the design solutions for value creation are contributing to the competitiveness of the company by demonstrating their contribution to the company's profit and providing value to the customers and identified customer segments while efficaciously considering other stakeholders such as suppliers. Developed solutions within each domain need to be constantly integrated across the domains to ensure the functional fit between the domains, for example between the product geometry and the required manufacturing process. Integration usually requires the creation of experiments based on digital and/or physical prototypes to test the interfaces and intended interplay between the single-domain solutions. Integration of domains helps to identify potential faults as well as to verify the domain and system functions.

Table 4 System level, engineering tasks and engineering methods of the DesOps phases [38]

System-level	**Engineering tasks**	**Engineering Methods (Examples for solving the tasks)**
System Design (Phase 2)		
System concept	Defining system and domain requirements Determining system and domain functions Selecting basic system and domain solutions	Ideation, conceptual design, creativity methods
Domain-specific Design (Phase 3)		
Domain 1: Value proposition	Designing the mechanics, software, electrics/electronics, services	Integrated design engineering, systems engineering, service design
Domain 2: Value network	Designing the manufacturing technology, material flow, information flow and ICT, Industrial digital twin / Asset administration shell	Factory planning and design, supply chain design, design for cybersecurity
Domain 3: Value delivery	Designing the stakeholders including the customers, channels, cost and sales structure	Innovation accounting, lean analytics
Continuous System Integration (Phase 4)		
Domain Solutions	Integrating different design solutions across the domains in a pilot manufacturing environment	Experimentation, verification
Implement (Phase 5)		
Domain solutions and overall manufacturing system solutions	Rolling-out and ramping-up of domain and system solutions for the value proposition, value network and value delivery within the real manufacturing environment	Lean manufacturing
Monitor (Phase 6)		
Domain solutions and overall manufacturing system solutions	Monitoring the operations of the implemented domain and system solutions for the value proposition, value network and value delivery	Assessment and evaluation, Key performance indicators, manufacturing metrics, auditing
Continuous feedback (Phase 7)		
Domain solutions and overall manufacturing system solutions	Deriving improvement measures for the next iteration of domain and system solutions based on the outcomes of all phases, but especially the monitoring phase Feeding back the derived measured into the system design (Phase 2) of the next iteration	Quality management, Lean manufacturing, KAIZEN

Phases 5 to 7 essentially aim at bringing the designed manufacturing system with its different domains into an operational state. For this purpose, iterations of the manufacturing system are implemented and ramped up; and the overall system architecture including the developed domains is tested under real manufacturing conditions. Monitoring serves to qualify but even more important quantify relevant system performance indicators and other parameters which might also be directly linked to the OKRs. Thus, monitoring allows tracking the degree of circular and digital value creation of the designed manufacturing system. The indicators and parameters monitored under real production conditions serve to derive improvement measures for subsequent iterations of the overall system as well as for its domains. The process shall be conducted with the consideration of relevant stakeholders' opinions. For example, suppliers or customers might provide useful inputs for improving the system and its domains based on auditing the operational state of the system or on evaluating the monitored indicators and parameters. Specific improvement measures are constantly fed back to the system design phase to generate new iterations of the system and/or domains. However, continuous feedback is also created based.

3.5 Phase 8: Training

Phase 8 aims at skill building for relevant stakeholders and especially for the employees who must operate and maintain the manufacturing system in the future. This phase requires the development of training curricula for the specific target groups. Curricula usually incorporate the teaching objectives and outcomes as well as specific teaching activities to realize the intended outcomes. Teaching objectives are linked to the development of a set of certain skills and competencies. In a manufacturing context, the approach of a learning factory or a Learnstrument can be suitable for conveying the curriculum, especially for teaching aspects of digital and circular value creation.

4. Verification, validation, and evaluation

The verification and validation of the DesOps framework are performed based on a case study. In other words, the purpose of the case study is to test the efficacy of the DesOps framework in the context of a real manufacturing challenge. The case study itself is based on a funded project which aims at developing an automated and digitalized Additive Manufacturing (AM) system embedded in an Industry 4.0 manufacturing environment. This includes:

1. The automation of the value creation in the context of an AM system from setting up and equipping the machine tool (3D printer) with materials, up to quality control, and all material handling steps, i.e., removing the printed parts and products from the machine tool.
2. The digitalization of the physical AM system by creating an Industrial Digital Twin for linking the physical system to the virtual system, which enables the exchange of services e.g., transportation, maintenance, and manufacturing tasks, with the internal logistics system as well as the exchange of data with other relevant systems e.g., product design.

The development of the automated and digitalized AM system followed the DesOps framework, was carried out by a group of 7 master's students from the University of Southern Denmark and resulted in a project report [39]. The project kicked off in January 2022.

The group specifically focused on phases 1 “OKRs”, 2 “System Design”, and 3 “Domain-specific Design” of the DesOps framework over the course of four months.

OKRs were established throughout two cycles, which were updated after the first and second months of the project. Table 5 provides an example of the OKRs for the first months.

During the System Design phase, a conceptual solution for automating and digitalizing the AM system was drafted (Fig. 4). The overall system consists of five relevant sub-systems: 1) Storage, 2) transportation, 3) 3D-Printing, 4) quality control, and 5) communication and infrastructure.

Table 5 OKRs for the first month of the project, i.e., the first OKR cycle [39]

Key Objective for month 1 (first OKR cycle)	Key Results
We have developed a conceptual model for the overall system architecture.	Key result 1: We have held 2 workshops investigating possible solutions based on requirements and functions. Key result 2: We have developed a conceptual model showing physical and virtual environments. Key result 3: We have developed a conceptual solution for the. The communication system between all assets and systems.

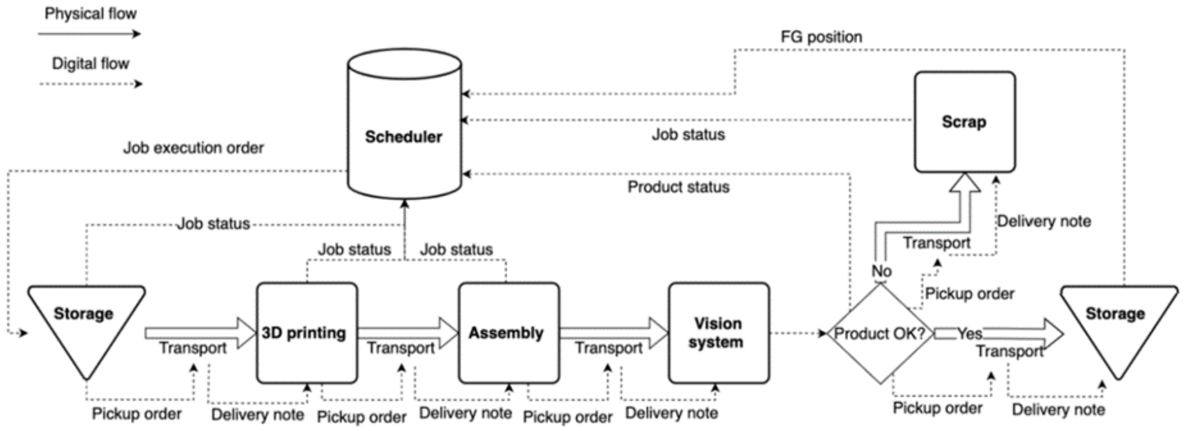

Fig. 4 Conceptual solution for automating and digitalizing the AM system [39]

The storage sends a "pickup order" to the transport system which will then transport raw materials to the 3D printer. As soon as the 3D printer finished the printing process, it sends a "pickup order" to the transport system to pick up and transport the printed part to the assembly process. When the assembly is completed, another "pickup order" is initiated to transport the assembled product to a vision control process, from where the product is then either transported to the storage or scrap, depending on the result of the quality check. "Delivery notes" ensure the exchange of information between the transport system and the destination, e.g., the 3D printer or the vision system. The job statuses of all processes and the finished good (FG) are reported back to the scheduling system (scheduler) via wireless communication and infrastructure. For each of the sub-systems requirements and functions for both, the physical and virtual systems, are defined.

The functions and requirements create the basis for detailing the five sub-systems. Morphological analysis was used to match functions with concrete equipment. For example, an Autonomous Mobile Robot with an attached articulated robot and gripper, a so-called Enabled Robot, was selected for realizing the transport sub-system, which for example must fulfill the main functions of "pick and place objects" and "drive from requested initial location A to an end location B". The selection was made based on a utility analysis of alternative suitable equipment for fulfilling the functions.

Eventually, an assessment of the concept with the selected equipment was carried out. This assessment included the calculation of the total costs, the calculation of the potential customer lifetime value, and the creation of a Failure Modes and Effects Analysis. The total cost including planning, material, set-up, and installation is in sum of 2.301.000 DKK, while the customer lifetime value is calculated as 777.500 DKK.

5. Conclusion

5.1 Discussion and limitations

The authors believe that the case study can serve as initial verification and validation of the DesOps framework. The framework complies with its intended purpose of designing manufacturing systems while demonstrating a basic efficacy for designing relevant design artifacts. Especially, the OKRs as the project management layer for facilitating teamwork during the actual DesOps phases seem to be a promising approach for continuously integrating and updating relevant objectives and results according to the project progress and new learnings. OKRs provide a simple yet powerful method to realize efficacious management of the manufacturing systems design through an agile work cycle (Fig. 3) and defined rules and roles. Especially since the project management layer is an often-neglected aspect of design approaches. In the context of the OKRs, the case study is essentially addressing the aspect of integrating digitalization objectives.

However, since circularity was not a key objective for the case study, only limited conclusions can be drawn about the efficacy of designing circular manufacturing systems. The authors believe that circularity objectives can be integrated with similar effectiveness by using the OKR method. Further evaluation is needed for determining how the proposed DesOps framework compares to other manufacturing system design methodologies. Another aspect of the framework that might need a more careful evaluation is the "Ops" cycle since it was not part of the case study. DesOps originates in software development, but the integration (Phase 4) as well as the implementation and testing (Phase 5) of hardware systems is more time-consuming and costly and includes human resources. Thus, hardware and social systems usually cannot be developed in these highly frequent cycles of pivots and iteration compared to software systems. Finding the right moment for starting the implementation process seems to be a crucial aspect of development. Besides, stakeholder management and training, and skill building seem comparably important for the development of hardware systems.

The focus on circular value creation and the end-of-life phase of products as well as on the digitalization of value networks is today often not supported by prevailing business models of manufacturing companies. Thus, the design and operation of digital and circular manufacturing systems might be rather coined by new regulations than by voluntary commitments of companies or pressure from customers. Thus, policy makers will play a crucial role in facilitating this Twin Transition of the economy. Finding competitive business model innovations based on circularity and digitalization within the framework of the new regulations could be the future key to strengthening industrial competitiveness in Europe and companies who struggle in creating these business model innovations might fail on the long run. Business model innovations implemented through digital and circular manufacturing systems will also lead to increasing importance of cybersecurity and reverse supply chains and logistics for managing risks.

5.2 Summary and outlook

The research presented a conceptual DesOps framework for supporting the Twin Transition of manufacturing companies, i.e., for improving the level of digital and circular value creation. The procedures and methods underlying the framework were selected based on their proven contribution to operational excellence in companies. The DesOps framework covers nine phases, starting with the assessment of the initial level of digital and circular maturity. Subsequent phases focus on defining Objectives and Key Results (OKRs), on the relevant design (Des) and operation (Ops) phases, as well as on training the required competencies of stakeholders. The verification of the empirical efficacy of the presented framework is ongoing and carried out at SDU's Industry 4.0 laboratory.

Future research will first focus on verifying, validating, and evaluating the efficacy of the framework to support the development of circular and digital manufacturing systems. Secondly, suitable methods for integrating, implementing, and testing iterations of manufacturing systems will be the subject of future investigations.

Acknowledgment

The research was supported by funding from the Fabrikant Mads Clausens Fond for the project "Design of an automated and digital additive manufacturing system embedded in an Industry 4.0 manufacturing environment".

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