Digitalization of Manufacturing Processes with Startup Collaboration: Arçelik Developing a Digital Twin with Simularge

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Abstract

(a) **Situation faced**: Arçelik is a major manufacturer of durable consumer goods. As one of the primary products of Arçelik, refrigerators constitute 35% of its annual production. Thermoforming is a critical process of manufacturing a refrigerator's inner body, which consumes more than 20,000 tons of plastics every year. The company has decided to develop its production quality further, reduce plastic consumption, and improve its environmental footprint by integrating a digital twin into its production planning and management.

(b) **Actions taken**: Arçelik has partnered with Simularge from Istanbul, a startup specializing in digital twins. The project team has developed a digital model of the thermoforming process by combining high-end engineering formulations, simulation modeling, and real-time sensor data. They have integrated and fine-tuned the digital twin in one plant. Currently, the company plans worldwide deployment.

(c) **Results achieved:** Arçelik's partnership with Simularge has successfully generated a digital twin of the thermoforming process. Implementing the digital twin with real-time operational data has improved the product quality, has decreased scrap ratios, and has reduced plastic consumption. It has resulted in an initial cost-saving of more than $2 million annually. Gaining know-how about the manufacturing processes' digitalization has promoted a shared vision. It has also

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provided a strong example to encourage the digitalization of other manufacturing processes.

(d) **Lessons learned**: The digital twin has enabled resource efficiency and improved manufacturing execution. Additionally, integrating the Internet of Things data into the digital twin has enabled better feature engineering results and improved algorithms with extracted features from data mining. Furthermore, the Internet of Things and programmable logic controller infrastructures and engineering capabilities at Arçelik has been crucial for the digital twin's success. Arçelik's Atölye 4.0 Lab and its relationship with Istanbul Technical University's ITU Çekirdek Incubator also have a significant role in cultivating a collaborative project. Lastly, effectiveness in project management appears as a significant driver of success for a digital twin project.

1 Introduction

Digital transformation has become a hot topic of the manufacturing industry with the advent of Industry 4.0. In this context, digitalization, as the adaptation of new business models, invites technological progress and calls for innovations to the manufacturing environment, enabling manufacturing firms to adapt changes rapidly (Kotarba 2018). Digital technologies shape processes and their management (Lockl et al. 2018). These technologies transform business models by allowing new product and service offerings while requiring new business partnerships (Schallmo et al. 2017). However, organizations usually face a process improvement black box due to the variety and high uncertainty of novel digital technologies (Denner et al. 2018). This situation challenges traditional approaches to efficiency improvement, forcing manufacturing companies to build external collaborations with technology vendors and startups to adopt new technologies. Production processes' efficiency and level of raw material consumption have become primary concerns of manufacturing companies due to their need to improve their sustainability. Therefore, digital technologies' adoption has become critical since they optimize raw material consumption, improve efficiency, and deliver benefits for sustainability (Demartini et al. 2019).

Digital twins are virtual representations of physical processes or systems, showing identical behaviors with their physical counterparts. These representations utilize different simulation techniques. Digital twins consist of a physical product, a virtual functionality model, and bi-directional data connections. However, digital twins are beyond traditional simulation models. They behave like their physical counterparts in numerous dimensions and enable digital experimentation by leveraging computational techniques (Jones et al. 2020). Thus, a digital twin enables optimizing operation parameters like temperatures and pressures, therefore helping manufacturing professionals to operate systems in their best theoretically possible condition. It helps its users to decide on the desired physical state of the corresponding physical system, as in process control (Lohtander et al. 2018), machine parameters

(Kritzinger et al. 2018), and production management (Zhuang et al. 2018). Digital twins are at the forefront of manufacturing digitalization, enabling a sustainable and intelligent future (He and Bai 2021). They also align with product life cycles (Grieves and Vickers 2017). Gartner estimates that by 2021, half of all large-scale industrial enterprises will use digital twins to improve their effectiveness (Gartner 2017).

This case study describes how Arçelik and Simularge collaboratively and successfully developed a digital twin to improve the thermoforming process at Arçelik's refrigerator production. Arçelik is a large-scale durable goods manufacturer with a global presence. Simularge is a technology startup with offices in Istanbul and San Francisco. The digital twin project has resulted in significant improvements in quality and plastic consumption. Arçelik has initially saved 1600 tons of plastic each year, with a value exceeding $2 million while improving its environmental impact.

The case study illustrates several important issues and themes: First, the case study describes a digitalization project that brings significant performance and sustainability improvements. Second, the case study illustrates the importance of feature engineering, extracting raw data features with data mining to improve algorithmic performance. Third, the case study illustrates how the engineering expertise and existing infrastructures, such as programmable logic controllers (PLCs) and Internet of Things (IoT), leverage implementing a digital twin. Fourth, the case study demonstrates a successful enterprise-startup collaboration project and suggests that enterprises need to establish links with an entrepreneurial ecosystem. Startups may offer extensive digital capabilities and assume consultative roles in guiding and mobilizing large firms (Wildhirt et al. 2019). Startups also may have essential edges over big firms' speed and flexibility (Weiblen and Chesbrough 2015). Successful collaborations between startups and enterprises rarely appear in the literature. Last, the case study illustrates the critical role of effective project management for a successful digitalization project.

In the following sections, we present the situation faced by Arçelik at the thermoforming process, followed by the action taken to develop and deploy a digital twin in collaboration with Simularge. Next, we describe what the project team has achieved and what outcome measures Arçelik has observed. We conclude the case study with a discussion on the lessons learned and several implications.

2 Situation Faced

2.1 Background Information

Arçelik had founded in 1955 as a member of Koç Group, the largest industrial and services conglomerate in Turkey. As one of the leading companies in the Turkish durable goods industry, the company offers products and services worldwide with its 30,000 employees, under 12 brands manufactured in 23 different production

Fig. 1 A view from Arçelik Atölye 4.0 Advanced Robotics Lab (Source: Arçelik)

facilities worldwide. As of 2019, with an annual production volume of approximately 20 million units, the company has become the third-largest home appliances company in Europe. With 17 research and development (R&D) units in six countries and significant R&D investments, the company has a strong orientation toward innovation and technology development (Arçelik 2020a). Arçelik had introduced its first future factory in Romania to manufacture washing machines with diverse cyber-physical systems, machine learning (ML) capability, and as a testbed for Industry 4.0. World Economic Forum has selected the future factory in Romania as the Global Lighthouse Factory in 2019. The company aims to gain experience from this factory's intelligent capabilities and deploy results to other plants to engage with digitalization (Arçelik 2020a).

Arçelik prioritizes sustainability across its value chain besides financial performance. The company has been featured in the Dow Jones Sustainability Index since 2017. It has also been named an industry leader in 2019 and 2020 (Arçelik 2019, 2020b). For getting 98% of its waste recycled, the company also received the Zero Waste Award from the Turkish Ministry of Environment and Urbanization in 2019. Maintaining a sustainable performance requires Arçelik to experiment with new technologies.

In 2016, Arçelik had established Atölye 4.0 as a competency center and a startup interface to adopt innovative technologies in production lines. Specialized in industrial automation and robotics applications (see Fig. 1), Atölye 4.0 has hosted R&D projects and collaborative projects of Arçelik with universities. It also provides training to partners and employees on digital transformation and Industry 4.0. The digital twin development started in Atölye 4.0 in 2019 with Simularge.

Two engineers established Simularge in 2017 at ITU Çekirdek, Istanbul Technical University (ITU)'s incubation center. The co-founders had PhD degrees and advanced industrial experience. They decided to focus on digital twins for the manufacturing and energy industries, as they have advanced simulation expertise.

In 2019, the Global Impact Manufacturing List ranked Simularge among the top 5 manufacturing simulation startups worldwide (Start-ups Insights 2019).

2.2 Thermoforming Process

Thermoforming is among Arçelik's 14 major critical production processes. Arçelik has 8 refrigerator plants and 32 thermoform production lines in 9 locations worldwide (Fig. 2). These production lines consume more than 20,000 tons of plastics per year.

The thermoforming process involves heating plastic sheets and forming pre-heated flexible materials against a mold's contours by mechanical and pneumatic tools. After holding a mold's shape with negative air pressure, the material cools down in the intended form. Due to the high plasticity, curing, and heat allowances of the material, the technique applies only to thermoplastic components, such as a refrigerator's interior body. The finished surfaces and dimensional precision of a refrigerator's interior body are critical parameters for the product quality. Problems in the thermoforming lead to visible defects in the final product and directly affect customer satisfaction (See Fig. 3).

Maintaining the process precision and the product quality in thermoforming with reworking components and performing trial runs were problematic. These issues caused high-volume plastic scrapping, excessive plastic usage, and high levels of energy consumption. Maintaining a high level of quality also had high financial and environmental costs. Therefore, the Arçelik production team decided to decrease plastic usage and improve production quality at the thermoforming stations simultaneously.

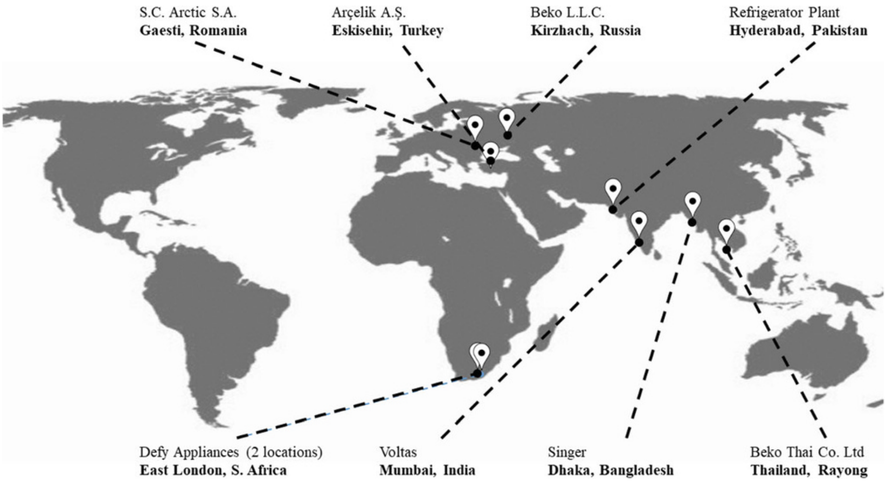

Fig. 2 Arçelik thermoforming locations (Source: Arçelik)

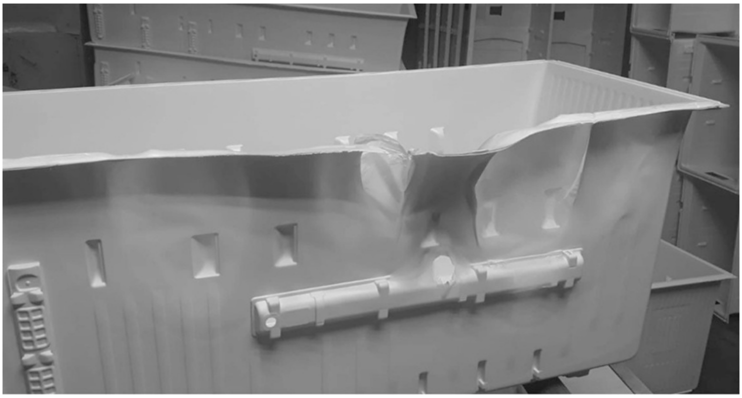

Fig. 3 A sample quality problem in refrigerator bodies (Source: Arçelik)

For this purpose, the team aimed to detect specific conditions causing process variation and quality problems. At that stage, they assumed that the existing process conditions were ideal or near-ideal as the process performance depends on the temperature, pressure, and other process parameters. However, initial tests revealed various problems, pushing them to monitor and control every step of the thermoforming process.

At that time, operators adjusted all the process parameters at the thermoforming process with their judgment and expertise. They accumulated years of experience and a deep level of process understanding. They were also deciding on corrective actions when problems arise. However, this was mostly tacit knowledge. The operator-dependent and the opaque nature of the process also were calling for digitalization.

At this stage, the Arçelik team followed the process parameters in real-time with an advanced process monitoring and control system for process intelligence. However, there were numerous parameters to follow, and they were only able to record variations after their occurrence. Thus, the Arçelik team identified digital twins as a potential solution based on the literature. They were also hoping to foresee potential production problems and automatically adjust process parameters to prevent them, as digital twins were known to enable experimentation. However, the Arçelik team came to this point after some earlier attempts.

2.3 Attempts Before the Digital Twin Project

The Arçelik team had first attempted to utilize ML techniques to predict thermoforming process's parameters and failures. They had trained various ML models with real-time process sensor data; however, they could not achieve the required accuracy and precision.

The Arçelik production team had also attempted using the finite element analysis (FEA) to estimate and analyze the process. As a well-established mechanical engineering method (Argyris et al. 1979), FEA is a numerical solution approach to model problems in heat transfer, solid mechanics, and fluid dynamics (Zienkiewicz et al. 2013). The Arçelik team had already been familiar with the FEA technique. After lengthy discussions, the production team had decided to integrate an FEA module to improve extracted features to better estimate and control process variation. They had also given up their ideal condition assumptions since they had needed to consider variability in process parameters systematically.

To check alternatives and the feasibility of FEA-based solutions, the production team had conducted a detailed literature review and field research about monitoring systems for thermoforming processes. Based on this study, the Arçelik team had realized that they require an advanced level of know-how in digital twins. The digital twin project requires developing a comprehensive simulation model and integrating an FEA-based best-fit solution into the production monitoring and control system.

2.4 Alternative Paths to a Digital Twin

Despite the uncertainties, the Arçelik team had a strict target schedule and significant budget constraints. Therefore, instead of pursuing internal development, working with an expert partner on FEA applications in process monitoring looked attractive. Therefore, the Arçelik team started considering established vendors and emerging startups for the desired system.

Established vendors were providing software solutions in this domain in the form of a black box. A customer could not learn much about what was inside and became entirely dependent on the vendor. The Arçelik team was not expecting an established vendor to provide the full rights of modifying, customizing, or scaling up their product across global locations to an enterprise like Arçelik at a reasonable price. Therefore, while established vendors had promised a potentially complete solution, the Arçelik team eliminated this option.

Arçelik team decided to partner with a startup to generate their digital twins together. They also aimed to expand Arçelik's know-how in advanced manufacturing simulations with this partnership. Therefore, they decided to seek partnering options with startups in this domain. However, it was not an easy task. Arçelik, as a large enterprise, had a lot of strict rules, stringent procedures, and structural inertia for collaborating with a startup.

3 Action Taken

3.1 Locating a Startup to Collaborate

Arçelik had contacted ITU Çekirdek, the startup incubator of ITU, to locate a startup specializing in manufacturing and engineering simulations. ITU Çekirdek had been a prominent option as it had been a well-known incubator beyond Turkey. The global university incubator rankings, for example, the UBI Index, has been listing ITU Çekirdek among the world's top 5 university business incubators (ITU Çekirdek 2019). ITU Çekirdek was a generalist startup incubator and had already generated hundreds of startups in various domains. Existing relationships of Arçelik's Atölye 4.0 with ITU Çekirdek had contributed to communicating the desired startup profile and locating the alternatives quickly.

ITU Çekirdek had introduced Arçelik to several startups from its current cohort, as well as its alumni. After meeting with potential alternatives, Arçelik had decided to seek a partnership with Simularge. They had an advanced specialization in engineering simulations, including digital twins, and had a positive attitude. After a series of meetings and a short proposal stage, Arçelik and Simularge agreed to collaborate.

3.2 Teaming Up

Participants from Arçelik's smart manufacturing group, production group, engineering group, and domain experts from Simularge established the digital twin project team. Due to the nature of digital twin projects, the digital twin's exact specification, the predictive model, and the operating application were not easy to describe at the beginning of the project. Therefore, a waterfall-type classical project management methodology was not applicable because it required a detailed definition of the final product from the beginning.

To overcome the traditional waterfall approach's pitfalls, the project team agreed to adopt an agile project management philosophy. Due to the novelty of the digital twin technology and the uncertainties involved, the project's scope focused on elaborating the problem rather than attempting a complete system analysis that froze requirements. The project team arranged regular, frequent, and short joint meetings to speed up the analysis and solution design iterations. Regular and frequent short meetings helped the entire team to get involved in project problems timely. Otherwise, such issues could disturb the project management. Agile meetings and planning also enabled rapid progress during the project.

The team performed general online sessions twice a week to continuously share their progress and identify new issues to keep the entire team updated. Team leaders also reviewed the tasks every week. The project team took an inter-disciplinary and inter-functional perspective for distributing tasks among the Arçelik participants. A sub-team worked closely with the other engineers of Arçelik at stages of design, implementation, and testing to engage Arçelik user groups. Engineers from different groups also participated in the teamwork and provided their experience:

- The process and materials technologies group investigated the thermoforming process, participated in developing the mathematical model, studied how to use data obtained from the production line sensors, and listed other teams' requirements. They were also responsible for gathering meaningful data, testing the mathematical model, and giving other groups feedback according to the production line results.
- The industrial robotics group collected and visualized the data, performed extensive research on the sensor and measurement systems, and planned further investments.
- The simulation and modeling group supported all other groups during the construction and internal dissemination of the resulting digital twin.
- The information technologies group set up the network infrastructure of the machines to collect the process data.
- The automation group installed the required hardware.
- The production group supported all other groups to understand the complete process and the sensors' functioning.
- Arçelik's Atölye 4.0 acted as the owner of the production line during the system development phase. They trained the production team before the conversion and monitored the new system in production for 6 months.

3.3 Developing a Virtual Representation

The project team needed to create a virtual representation of the thermoforming process's physical behavior. Developing a digital twin of the thermoforming process required an advanced understanding of thermoforming and in-depth expertise in complex simulation models. The project team consulted with experienced operators and production engineers to understand the production process's behavior, determining the product quality and the required material volumes.

Then, the project team observed how operators were controlling the thermoforming process and how they overcame quality problems. In this way, the group maintained the user involvement and the information flow. They also analyzed the process parameters and performance metrics, such as the availability rate, the overall equipment effectiveness, the scrap ratio, and the process costs. Then the team developed a physical representation of the process as a mathematical model based on finite elements.

To develop a FEM-based model simulating the process's physical nature, the project team used an open-source software named Calculix. However, their assumptions in developing the initial model decreased the digital twin's accuracy. This situation urged the team to make further iterations and to revise the model's assumptions.

3.4 Fine-Tuning the Digital Twin

After developing the initial model, the project team started to leave some of their assumptions, iterating with the IoT sensors' real-time data. This approach further improved the realism and increased the validity of the resulting model. At this stage, they used existing and additional sensors to achieve a comprehensive and dynamic data flow. They examined the physical aspects and the mathematical architecture of the thermoforming line from the data flow. Collecting, visualizing the data, and making the data meaningful were essential to understand the production line's mathematical and physical behavior and its material consumption.

Simularge provided insights about the methods of feature extraction for accurate prediction. During the digital twin's improvement and fine-tuning with real-time data, the project team took several steps.

Firstly, the Arçelik production team performed a design of experiment (DOE) study by varying process parameters to determine the critical parameters and acceptable error margins. Then, Simularge performed FEM simulations with the process data. Simularge engineers also met with the Arçelik team twice a week to analyze interim results and discuss current improvements/updates.

To estimate the process's theoretical behavior, the project team members ran the simulation model for all potential cases. Then, the project team used the simulation results to generate a simple function of the process characteristics. The function mimics the thermoforming process's input-output relations using the reduced-order modeling (ROM) method. The team integrated this function into the thermoforming machine, changing the PLC's operating parameters.

Arçelik's Atölye 4.0 owned the responsibility of preparing the automation and data infrastructure in this project. Together with the Simularge team, they calibrated the functional model by conducting the production trials and developed the backend and frontend application software.

3.5 The Digital Twin's Structure

The digital twin's operational process has four stages at Arçelik: Shopfloor-PLC, cloud, operator panel/feedback, and alarm control (see Fig. 4).

At the Shopfloor-PLC stage, the digital twin acquires real-time data from sensors installed on its physical counterpart. This data comes from the PLC of the thermoforming machine on the shop floor in the proposed solution. These measurements include the servo motor motions, temperature, and pressure data from sensors.

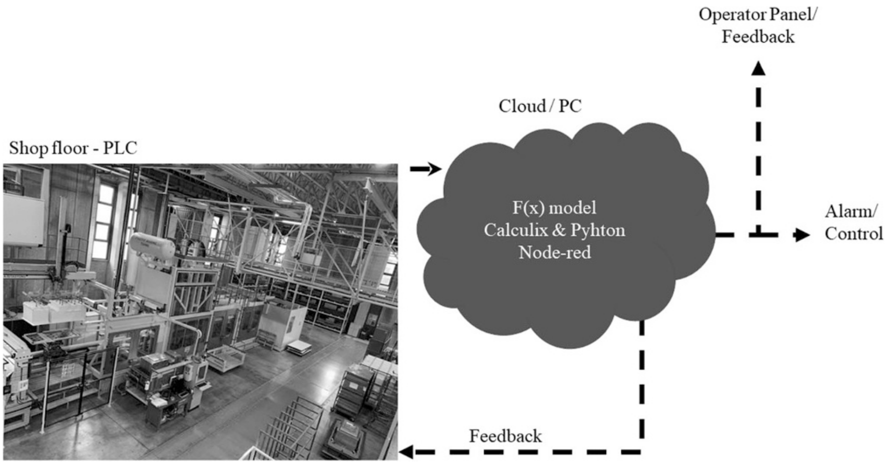

Fig. 4 The context diagram of the digital twin (Source: Arçelik)

An open-source database, created with Python Node-Red, stores the shop floor's sensor measurements on the cloud infrastructure. Engineers use this data to calibrate the characteristic function in simulations and ROM. Therefore, the digital twin is a complete virtual replica of the physical asset on the cloud. The digital twin responds to real-time sensor measurements, calculates the input-output relationship, analyzes the system's condition, and provides feedback in real time.

At the operator panel/feedback stage, the digital twin integrates the thermoforming machine and the FEM model's process parameters on an engineering tool developed based on an encoded version of the operator's know-how. This system consists of two modes to adjust the manufacturing process. The first mode generates warnings in the operator panel, where manual inputs from technicians are required. The second mode directly interferes with the thermoforming machine and automatically adjusts the process parameters to avoid process errors.

At the alarm/control stage, a dashboard monitors critical sensors to identify a systematical failure and prompt a warning. As shown in Fig. 5, the dashboard provides the cause of the loss for technical intervention.

4 Results Achieved

The digital twin project has significant benefits for critical stakeholders and the thermoforming process performance at Arçelik.

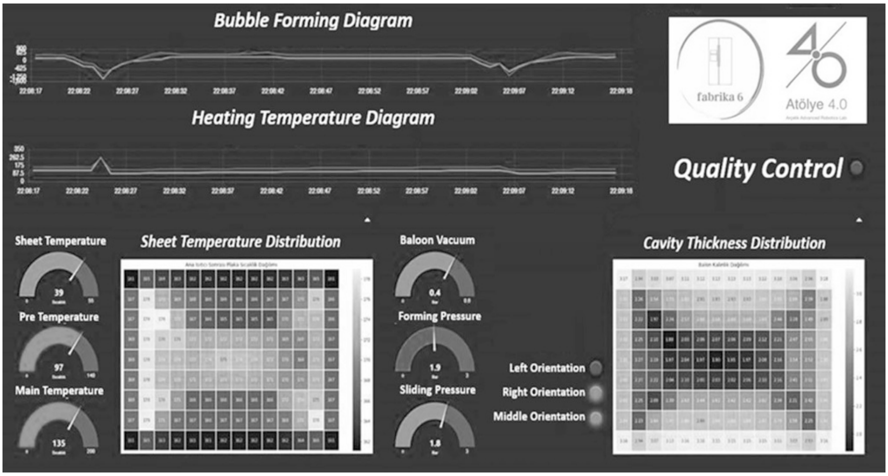

Fig. 5 Operator control dashboard (Source: Arçelik)

4.1 Business Impact

Optimized Material Consumption Conventional production systems cannot perform real-time control on the process parameters and material consumption. Arçelik has increased its sustainability performance with real-time control and has reduced its plastic usage, scrap ratio, and energy consumption. As emphasized before, the company has saved 1600 tons of plastic each year, with a value exceeding $2 million while improving its environmental impact.

Quality The material defects and process errors result in product quality problems. When a defective product is recyclable or reusable, it needs reworking. Such rework is also a waste (Ohno 1988), as it consumes additional energy and time and reduces input efficiency. However, if a defect is irreversible, then the product becomes scrap, causing a significant loss of value. Figure 6 indicates the scrap ratio has dropped from 5–8% to 1–2% with the digital twin's adoption, indicating a substantial improvement in the product quality.

Overall Equipment Efficiency (OEE) OEE accounts for the availability and performance of equipment. It is among the most critical parameters to measure manufacturing productivity (Hansen 2005). With the digital twin involving a dashboard, the machine and equipment features have become observable in real time.

Corrective and preventive interventions to the production have improved the overall efficiency. The digital twin enabled engineers to decide on the optimum production parameters without making any trial runs for planning. As Fig. 7 describes, the production line's efficiency, the OEE performance index, has risen from 68–75% to 82–92% after the digital twin.

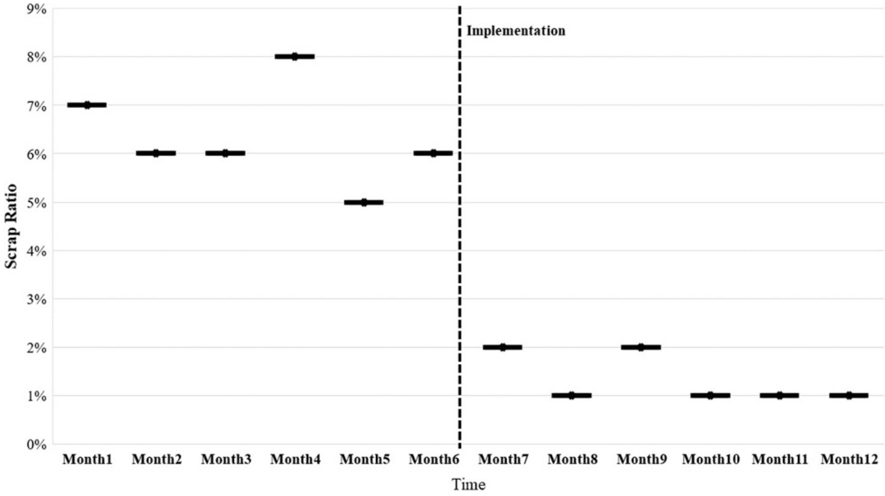

Fig. 6 Quality performance index based on the scrap ratio (Source: Arçelik)

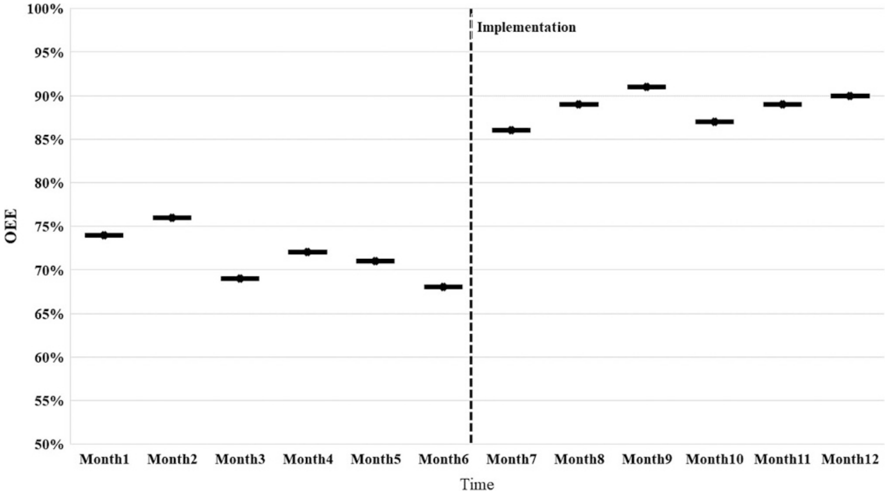

Fig. 7 OEE performance index (Source: Arçelik)

4.2 Digitalization

Encoding Operators' Knowledge The thermoforming operators' knowledge had been crucial for adjusting the thermoforming parameters. This knowledge was operators' tacit knowledge, which was action-oriented and developed with practical experience (Blackler 1995; Ambrosini et al. 2009; Collins 2010; Soler 2011). In this project, the digital twin had encoded parts of the thermoforming operators' tacit knowledge into the digital twin, as the model stores every alteration on the production line. As parts of operators' knowledge have become explicit, they also have opened to analytical scrutiny and experimentation.

Data Collection and Sensor Infrastructure Data collection had been the backbone of the digital twin project. While examining the production process, PLCs had played a significant role in collecting data from manufacturing systems. Most of the devices already have built-in sensors. However, hundreds of embedded sensors on the production line had meant terabytes of data to process. Instead of collecting every sensor data for the digital twin, the engineering team had eliminated unrelated data fields based on their expertise. They had concluded that even a single sensor might be enough to simulate the production line. After defining the measurement limits, the data collection frequency, the required data precision, and the sensor accuracy, sensor requirements had determined more precisely with different production scenarios.

Digital Dashboard as a Process Engineering Tool With the digital twin project, the project team has decided to install a dashboard on thermoforming machines' PLC unit. This device automatically modifies parameters according to the changing production conditions and enables responsive error correction.

The dashboard's user interface serves operators and production engineers for exploring parameter alterations and introducing incremental changes quickly. When a team cannot fix a production problem, production and R&D engineers collaborate to modify the parameters. The dashboard also has a developer interface for production and R&D engineers.

When a new refrigerator starts production, it requires a new FEM model using new process parameters that updates the thermoforming machine via PLC. Arçelik has a database that stores every refrigerator model's thermoforming process parameters. Hence, the system calculates thermoforming machines' production efficiency and helps the production team take timely precautions.

4.3 Project Management

As a large-scale enterprise, Arçelik has some rigid rules and conventional structures in project management. While the digital twin project team had aimed for flexibility and speed, they were still required to get approvals from various departments at different project stages. The time required to get these approval certainly caused inefficiencies and increased non-value-adding tasks in the project.

In such cases, Simularge acted as a partner with agile project management principles. When needed, they expedited the project by taking the initiative to manage change and balance the schedule variance caused by Arçelik's administrative procedures. In some instances, the Arçelik management team hesitated to delegate some tasks to the startup. However, the project team benefitted extensively from adopting agile practices and iterative development. For example, the scope definition had changed many times during the project. The project team had to reiterate the requirements analysis, design, and prototyping stages many times. However, such changes did not cause a budget or schedule overrun due to the immediate actions taken to re-plan and re-organize the tasks without sacrificing the project objectives.

5 Lessons Learned

The case described in this chapter has several lessons for manufacturing companies and potential stakeholders. This section summarizes five critical takeaways and provides two topics for further discussions.

5.1 Digitalization for Better Performance and Sustainability

As emphasized in the United Nations Global Sustainable Development Goals Number 12 – Sustainable Consumption and Production (Sustainable Development Goals 2015), manufacturing companies have to reduce their material footprints (Gasper et al. 2019). Following the vision on sustainability and responsible production, Arçelik has aimed to minimize its excessive raw materials usage, mostly composites, and plastics in its products.

Digital tools deliver resource efficiency to improve sustainability performance by optimizing material and energy consumption (Demartini et al. 2019). Our digitalization case is also in line with this principle. The digital twin project has the purpose of reducing raw material usage, significantly consuming less energy and materials in every Arçelik plant.

Digital twins enable sustainable, intelligent manufacturing (He and Bai 2021). Our case illustrates how developing and implementing a digital twin may allow manufacturers to reduce their materials and energy consumption. Arçelik prevents material and energy waste, offering a better environmental footprint. Digital twins may help in meeting conflicting key performance indicators, such as maintaining high product quality while keeping raw material usage and scrapping at a minimum.

5.2 Feature Engineering and Data Mining

Feature engineering is the process of extracting raw data features with data mining to improve an algorithms' performance. As highlighted in the "Situation Faced" section, the Arçelik team assumed that the process conditions are ideal at the beginning of the project. The group performed FEA only on the product instead of integrating FEA with the entire production line.

Arçelik had used the process data to train an ML model for modeling the thermoforming process. However, this attempt has given limited results and limited feature extraction. During the partnership with Simularge, Arçelik has increased its awareness of the criticality of feature extraction, especially for predicting critical process parameters.

Feature engineering improves the performance of ML models since the features determine model accuracy. Our case follows previous research and practice since our case study reveals that integrating IoT data, a digital twin provides reliable and effective results than limited feature extracting ML models (Min et al. 2019).

5.3 Leveraging Engineering Expertise and Technical Infrastructures

As mentioned before, PLCs played a significant role in data collection in the digital twin project. The engineering knowledge and shop floor experience of Arçelik brought an advanced understanding of the process data. As a result, the project minimized additional investment requirements.

In our case, the project team had left their earlier assumptions about the thermoforming process using the data from the IoT sensors. Availability of data helped the project team develop a better representation of the thermoforming process. Integration of the FEM and IoT data streams enhanced the validity of the digital twin with real-time data.

Recently, a similar system is reported in the literature, where a PLC collects real-time data and an open platform communications server synchronizes a digital twin with a cloud platform (Židek et al. 2020). Our case reports a similar system where a digital twin runs for quality and production control, synchronizing with IoT devices on the shop floor.

Our case also illustrates how digital twins can detect problems before they happen in a manufacturing environment, reducing material usage by enabling proactive and preventive actions.

5.4 Connecting with an Entrepreneurial Ecosystem

Intermediaries may provide substantial benefits for creating linkages between large enterprises and startups in entrepreneurial ecosystems. There are significant barriers to the manufacturing industry's digitalization (Deloitte 2015; Oesterreich and Teuteberg 2016; Semolic and Steyn 2018). Lack of effective collaboration is also a high-impact challenge for digitalization (Camarinha-Matos et al. 2017). Our case study illustrates that companies can overcome barriers to digitalization by establishing collaborative inter-organizational linkages.

In our case, Arçelik's Atölye 4.0 had acted as a hub to accelerate the collaboration between the ITU Çekirdek (incubator), Simularge (technology startup), and the Arçelik production team (enterprise). The existing relationship of Atölye 4.0 with ITU Çekirdek had speeded up the process of locating alternative startups. Based on this observation, we also suggest that large enterprises build collaborative relations and partnerships with existing innovation centers and startup incubators in their environment.

The competency, startup variety, and openness to collaborate of ITU Çekirdek had also played a critical role in overcoming inter-organizational boundaries and potential procedural obstacles. Arçelik's industrial competency in applying a specific technical solution and Simularge's real-time manufacturing experience has played a significant role in developing a successful partnership. Collaboration and partnership between Arçelik Atölye 4.0, ITU Çekirdek, Arçelik teams, and Simularge stand out as remarkable examples of collaboration in digital ecosystems against the complexity of new technologies (Bedford et al. 2018).

The partnership has contributed both to the efficiency and the sustainability performance of Arçelik and the growth of Simularge. The case shows how a collaborative attitude may be a critical success factor for digitalization. Even large manufacturing enterprises with an advanced resource base can expand their digital capabilities taking a collaborative attitude with entrepreneurial talent residing in startups.

We believe this case is an essential resource for manufacturing companies. In its planning phase, Arçelik faced a lack of detailed use-cases describing digital twin implementations in manufacturing. The manufacturing industry needs to open up inter-organizational research practices, embrace knowledge exchange, and share their case studies.

5.5 *Project Management as a Critical Skill*

Startup and enterprise collaborations offer new opportunities. For startups, it enables privileged access to a larger market and more complex needs. For enterprises, it may bring strategic renewal and open innovation. Agile practices provide a repertoire for both parties to collaborate more effectively (Weiblen and Chesbrough 2015).

Resource allocation and scheduling are crucial factors in R&D projects funded by corporate firms. Startups may help enterprises accelerate their R&D projects (World Economic Forum 2018) and refrain from traditional project management approaches' problems. In our case, Simularge intervened the project management by introducing agile practices in design, development, and testing. The Arçelik team had experienced iterative working and has acquired a practical understanding of agile practices through the project.

The advanced forms of the waterfall-type project management could be preferable if the project were predictive, including technologies or methods. As a linear project management process, it is also simple to follow and to understand. However, in projects with high uncertainty, the exact specifications of the product and the scope of the project cannot be determined precisely. Therefore, an agile project management approach would be more appropriate (Project Management Institute 2017). Our case shows that choosing the waterfall model for project management was not the right decision. Because the project team had to iterate the requirements analysis, design, and prototyping stages, revising the project's scope definition repeatedly.

Managing inter-disciplinary teams in a digitalization project is also a critical success factor (Project Management Institute 2017; Lanzolla et al. 2020). In our case, people from different units of Arçelik contributed to the project collaboratively. Rather than establishing a functional project organization, the project team implemented a matrix organizational structure. Members from different functions shared the responsibility of different project milestones with different units. They also divided project responsibilities among participants based on their expertise. Teamwork had speeded up the digitalization project and enabled engineers from diverse backgrounds to team up.

5.6 Further Discussions

Besides the critical takeaways above, our case study also highlighted the importance of open-source software and startup partnership as critical areas that are worth further discussion and research:

Open-source software is vital in delivering digital solutions. Packaged manufacturing software from established vendors offers lower implementation risks. The project team, in our case, had preferred to use open-source software to prepare a dashboard application for several reasons. Besides their high costs, proprietary packaged software is less flexible in terms of configuration and customization. The licensing limits the additional developments that the user can perform. Moreover, open-source programs let software engineers learn about the application architecture and manage their development processes. Using configurable open-source software, the project team developed a tool to read and change the process parameters, apply dynamic analytics, and conduct detailed experiments.

Defining the project scope and partnering with a startup contributed significantly to the digital twin project's success. Enterprises usually find it hard to collaborate or commit to a startup. However, this commitment and task distribution can balance and level the workload of engineers who work in an enterprise. It also helps enterprises reach a more extensive talent basis and participate in open innovation. Collaborating with a startup usually involves performing concurrent and iterative practices and agile project management. Iterative and agile project management requires developing mutual trust between all parties. Undertaking a significant change in an enterprise's project management mindset may be a prerequisite for collaborative development and partnership.

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