Green Digital Twins in the Product Life Cycle

Opportunities and Challenges for Sustainability Engineering

Jochen Deuse, David Wagstyl, Victor Hernandez Moreno,
Mikhail Polikarpov, René Wöstmann, Florian Hoffmann

1. Introduction and Motivation

Reducing emissions from industrial processes is a critical step toward achieving global climate protection goals since this sector is a major contributor to global emissions (ClimateWatch 2023). As a result, several countries worldwide set aspirational targets. For instance, Germany has set a goal of reducing its emissions from industrial production by at least 20% before 2030 (BMWK 2021). In order to achieve these objectives, innovative technologies are required that pave the way for sustainable industrial production systems.

Digital technologies offer new opportunities to analyze energy and resource consumption and derive data-driven improvements that contribute to climate protection. The demand for traceability solutions up to the product carbon footprint and digital product passports has increased since the establishment of EU regulations (Europäische Union 2019, 2020), and digital technologies have emerged as a powerful enabler to meet this demand (Europäische Union 2019). The potential benefits of green Digital Twins offer a technological solution for a sustainable transformation. The term 'green' refers to sustainable and environmentally friendly practices and attributes designed to optimize energy efficiency, minimize carbon emissions and reduce the environmental impact of physical systems. These include particularly its ability to provide traceability and reduce climate-damaging emissions by up to 8% and energy consumption by 20% (accenture 2021). Various industries use digital twins to optimize processes, predict failures and facilitate decision-making (Barthelmey 2021; Barthelmey et al. 2019). Standardization and demonstration activities such as the Asset Administration Shell (Bader et al. 2022), the Digital Factory Framework (IEC 62832 2020), and the Equipment Behaviour Catalogues (ISO 16400 2020) help significantly to establish the digital twin as a tool in the industrial environment. However, existing approaches do not yet consider sustainability and its environmental impact throughout the product life cycle.

DOI: https://doi.org/10.30844/wgab_2023_10

The product design establishes the basis for sustainability throughout the product life cycle. Sustainable material choices based on environmental impact and recycled or biodegradable materials can reduce the product's impact. Optimizing energy efficiency and resource consumption during the design stage is possible by simulating different scenarios. Furthermore, designing products with a circular approach supports reusing or recycling at the end-of-life. Digital twins can also evaluate end-of-life scenarios to optimize sustainability. By considering sustainability during the design stage, products can be innovative and environmentally responsible.

Today's production planning phase focuses on optimizing the trade-offs between cost, quality, and time. Industry 4.0 and its technologies offer opportunities to improve production planning holistically, including sustainability aspects. In order to find not only the most efficient but also the most environmentally friendly solution, aspects such as carbon dioxide equivalents (CO_2e) must be taken into account in production planning with tools such as simulation and forecasting.

Digital twins provide transparency into the production process by establishing data structures focusing on sustainability, real-time energy consumption, resource use, and carbon emissions. This information enables producers to identify areas for improvement and implement strategies to reduce environmental impact. By using the digital product twin to assess the sustainability information of (semi-finished) products in the production process, such as raw materials and packaging materials, producers obtain the ability to make informed decisions.

The end-of-life (EOL) management of products plays a significant role in environmental protection, which involves the implicit target of safe waste disposal. However, existing products on the market pose a particular challenge due to missing component composition and emission transparency. A representative example is refrigerating appliances, which commonly contain halogenated chlorofluorocarbons (CFCs). Approximately 1.5 million used refrigerators are estimated to contain fully or partially halogenated CFCs in Germany, with a total climate potential of roughly 4 million tonnes of CO_2 equivalents (Deutsche Umwelthilfe 2016). Therefore, the development of green Digital Twins for the end-of-life cycle could provide efficient and input-adapted control for the recycling process. Existing approaches have yet to create green Digital Twins of EOL products to predict the presence of climate-damaging components such as refrigerants.

This research paper explores how green Digital Twins lead to sustainable industrial production along the product life cycle. The research findings contribute to achieving climate protection targets by presenting opportunities and challenges to reveal emissions and construct green Digital Twins for different purposes.

2. Integration concepts and techniques

Digital Twins have emerged as a powerful tool for simulating, analyzing, and optimizing physical assets, systems, and processes across various industries. They are considered the highest level of digitization of physical assets (see Figure 1). Digital Models represent the baseline, which provides a reliable and accurate representation of their physical counterparts. However, integrating data from physical entities into digital models is typically done manually. Digital Shadows are characterized by the automated, unidirectional data flow from the physical to the digital object. Digital Shadows are widely used in the manufacturing industry to monitor and analyze the performance of machines and equipment in real-time. Automated information flow from the digital to the physical entity and vice versa defines Digital Twins. These can provide recommendations to the user and intervene in production planning and control to find optimal operating points.

Figure 1: The distinction between digital model, digital shadow and digital twin (Kritzinger et al. 2018; Wöstmann et al. 2022)

The Asset Administration Shell (AAS) is a standardized information model developed by the platform Industry 4.0 describing the characteristics and behavior of an industrial asset, providing a way to represent and exchange information about assets, enabling interoperability and integration across different systems and organizations. In the AAS, submodels are logical components that represent specific aspects of an asset, such as its structure, behavior, or capabilities. One example is the carbon footprint submodel which enables sharing and retrieving of relevant information per product throughout the supply chain while considering the existing standards. This will enable interoperability and transparency regarding carbon footprint information. (Platform Industie 4.0 2022)

The integration of existing industrial plants into the Internet of Things (IoT) and Services offers many opportunities and poses challenges for many users. IoT lends itself to the merging of internal machine data, external sensors, and adjacent system landscapes.

In the IoT area, numerous cloud solutions offer suitable options for performing both data storage and data aggregation, thus creating with DT an essential basis for data analysis.

IoT and AAS submodels have initial applications in the field of sustainability, but the spread of holistic methods and systems is yet to be established.

3. Sustainable integration concepts

Over the past few decades, there has been an emerging awareness of sustainability as a crucial factor in industrial practices. With increasing concerns over the impact of anthrophonic climate change (Weart 2008), industries worldwide are beginning to recognize the importance of adopting sustainable practices, as producing products inherently generates CO_2 emissions through value-adding processes and associated logistics. As a response, many companies and research institutions are seeking solutions for sustainable integration concepts.

In the face of the pressing need to reduce greenhouse gas (GHG) emissions globally, principles for their objective assessment were established in the ISO 14060 series of greenhouse gas standards (Blue Carbon Projects 2023). In this context, the DIN EN ISO 14064-1:2019-06 (DIN EN ISO 14064-1 2019) defines the essential fundamentals for quantitatively determining Carbon Dioxide equivalent (CO_2e) emissions for organizations. The GHG protocols have been established as widely recognized international accounting tools to further aid in measuring, managing, and reporting GHG emissions. These protocols distinguish between three scopes of emissions: direct GHG emissions (Scope 1), indirect GHG emissions from energy consumption (Scope 2), and all other indirect GHG emissions (Scope 3). Moreover, the DIN EN ISO 14064-2:2020-05 (DIN EN ISO 14064-2 2020) expands upon the principles of CO_2e emissions balancing with procedures for quantifying, monitoring, and reporting emission reductions. Furthermore, the DIN EN ISO 14064-3:2020-05 (DIN EN ISO 14064-3 2020) provides guidelines for those who verify and validate greenhouse gas data and information.

The Life Cycle Assessment (LCA) method, as standardized by ISO 14040:2006 (ISO 14040 2006) and ISO 14044:2006 (ISO 14044 2006), is the dominant approach for evaluating the environmental impact of products. This method considers the entire product life cycle, enabling the calculation of the ecological impact of a product through a standardized procedure. LCA can also be used to analyze subprocesses of the life cycle, such as production, through Simplified Life Cycle Assessment (SLCA) studies. However, LCA is a static method based on statistical data, and dynamic aspects of production can greatly influence production processes. Therefore, the Discrete Event Simulation (DES) method has been combined with LCA in DES-LCA to include dynamic aspects of production in LCA analysis. Overall, LCA provides a comprehensive understanding of the environmental impact of a product or service, including its contribution to climate change, air and water pollution, land use, and resource depletion, which can help identify opportunities for improvement in the production process, use, and disposal stages. (Deuse et al. 2022)

Sustainable integration concepts are at the forefront of Industry 4.0, leveraging advanced technologies to create a more sustainable and responsible future for the industrial sector. A key idea in this regard is the green Digital Twin, which combines the emerging trends of digitization of physical systems and sustainability efforts. Green Digital Twins can identify inefficiencies and optimization opportunities by providing real-time information on energy usage, carbon emissions, and other environmental metrics. It aims to reduce energy consumption and emissions, promote environmentally friendly practices and improve the properties of physical systems. Green Digital Twins are a promising technological solution for achieving sustainable transformation in the industrial sector and have the potential to play a crucial role in shaping a more sustainable future.

4. Conception of a green Digital Twin in the product life cycle

The green Digital Twin is based on an information model that focuses on sustainability aspects at each stage of the product life cycle. It enables the optimization of processes, products, and resources in terms of material use, waste, and greenhouse gas emissions throughout the life cycle. Early decisions have a major impact on the later stages of the product life cycle, shaping product and process design and setting the boundaries for subsequent production, usage and end-of-life cycle. Later stages rely on the strategic planning established in earlier stages. The green Digital Twin extracts, transforms, and loads selected information for sustainable applications. Each stage of the product life cycle requires different information regarding sustainability aspects. Relevant emission information is created by generating electric energy, process heat, physical processes, chemical processes, transportation, and fugitive emissions. To create a holistic model, each stage must define climate-damaging processes and the data behind them. In the context of climate protection, linking product development, process development, production, usage, and end-of-life through the green Digital Twin can significantly impact the product’s carbon footprint. The interconnectivity enables a data-based LCA.

DOI: https://doi.org/10.30844/wgab_2023_10

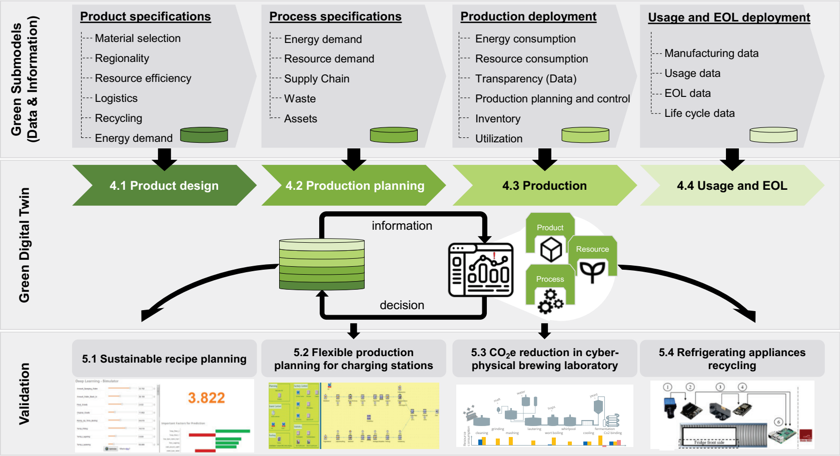


Figure 2: Proposed framework of a green Digital Twin in the product life cycle

4.1. Product design

The product design stage has a crucial role in determining the resource allocated to a product, thus impacting production planning, production, usage, and EOL considerations. Key aspects influencing the carbon footprint include material selection, regional and international impacts, use of renewable energy, resource efficiency, energy consumption, packaging, and transportation. The integration of simultaneous engineering and agile planning methods into product design allows the product lifecycle to be directly considered, enabling flexible adaptation towards green product design. It is therefore essential that recycling aspects such as disassembly, recyclability, disposability, remanufacturability and reusability are taken into account during product design. By incorporating these factors, sustainable practices can be integrated into the product design process, ensuring resource efficiency, environmental responsibility, and circular economy principles.

4.2. Production planning

Modern approaches to production planning focus on parallel work rather than just the sequential process. However, the data of classical and modern planning methods and their decisions must be evaluated for their sustainability. The sustainable information must be considered by existing approaches such as agile product development planning, simultaneous engineering, and classical planning approaches.

Existing approaches, such as ISO 18828 (ISO 18828 2018), describe a framework for production planning. It includes a reference planning process, descriptions of information flows between each discipline (manufacturing, assembly, logistics, and layout), key performance indicators in the planning process, and impulses for data-driven manufacturing change management. Existing standards need to be expanded to include an ecological production planning perspective. Technological approaches in engineering can lead to significant energy savings, such as the use of direct drives, optimization of power transmission, standby measures, dual production, and avoidance of over-engineering. Integrating technologies in the early stage of the production planning process brings immense potential to minimize energy and resource consumption (Braun et al. 2010; Herrmann/Thiede 2009; Hülsemeyer 2016; Thiede 2012). Novel approaches consider the future energy requirements of a process chain during its planning stage (Schrems et al. 2011). This allows for a comparison of various manufacturing processes based on their energy usage and the anticipation of the overall energy demand of the forecasted process chain. Also, the reflection of energy consumption in specific operating states of the production equipment can create insights into the process chains' energy consumption (Weinert et al. 2011). Another approach is to compare the energy demand of each process step and materials to determine energy-intense processes which may be relocated. An energy-efficient production planning can be achieved by considering factors such as process technology, batch size, scheduling, and peak load reduction (Abele et al. 2020; Bank et al. 2021; Biel/Glock 2016; Liang et al. 2019; Mousavi et al. 2016). Scientific approaches for integrating ecological factors in process chain planning include forecasting energy and resource consumption. Process knowledge is generated through data collection and analysis while facilitated by digitization and process models. Both methods are based on historical, real-time, or simulation data, which needs to be aggregated in the corresponding submodel of the green Digital Twin. By integrating green Digital Twins of the production process, it is possible to predict output variables, such as energy demand, based on the input variables and process parameters. At the process design stage, process parameters can be selected to reduce energy consumption. Inputs include raw materials, supplies, and energy, while outputs can be products, semi-finished products and/or waste. Simulations, Cloud Technology, and IoT can also be used to test different production scenarios to create a flexible production planning that meets the customer's demand, and no unnecessary resources are planned (Carvalho et al. 2020). Intralogistic concepts are reducing the energy consumption of cyber-physical fleets due to data-driven fleet management and vehicle routing (Wang/Wang 2019).

Flexible production systems are important in terms of economic efficiency and resource consumption. Oversizing a system can lead to additional environmental impacts even before implementation due to the production of additional machines, systems, and conveyors that are not needed in later production operations. During production, too large production capacities result in additional resource consumption, which has a negative impact on the product's carbon footprint.

DOI: https://doi.org/10.30844/wgab_2023_10

For this reason, the choice of a simultaneous planning approach consisting of product design and production planning is essential when planning future production capacities. Since individual market environments exhibit a certain degree of volatility, system-immanent flexibility must be considered in a simultaneous planning approach. It makes it possible to react to market changes despite basic capacity planning and thus reduces the waste of resources. Production system flexibility can be achieved, for example, by integrating partial automation technologies (e.g. human-robot interaction). Human-robot interaction enables the division of labor between humans and robots, which allows planning configurations to be made depending on the number of units. (Hoffmann et al. 2022)

Such planning approaches are highly complex and require suitable planning tools and methods, such as the discrete-event material flow simulation (VDI 3633 2014). It enables the simulation of different line, organization, and number-of-units configurations for mapping within a digital image of the later system. Thus, the implementation within a green Digital Twin is also possible, making the simulation results available for other life stages.

4.3. Production

Throughout the production stage, the previously developed sustainability-conscious measures are implemented. This takes effect in the framework of sustainable manufacturing through the consortium of intelligent manufacturing equipment, systems, and services (He/Bai 2021). Approaches to drive sustainability during manufacturing incorporate aspects ranging from sustainable manufacturing technology, workstations and manufacturing system, standard measures, value stream audits for evaluating sustainability performance, and lean manufacturing practices to real-time monitoring and control of the whole supply chain (Hariyani/Mishra 2022). A key enabler in the context of sustainability is Industry 4.0 and its technologies (Blunck/Werthmann 2017; Enyoghasi/Badurdeen 2021), providing important environmental, economic, and social prosperity (Sartal et al. 2020).

The submodel of a green Digital Twin for production entails key factors and indicators of sustainability, including transportation, energy consumption, and processed materials considering the three emission scopes of the GHG protocols (ISO 14040). It is crucial to guarantee a certain level of transparency during production to provide monitoring capabilities of the actual process. This allows the identification of discrepancies between planned and occurring emissions as well as the detection of potential bottlenecks in production processes. Such transparency is achieved through Big Data uncovering actual resource and energy consumption as well as resulting environmental impact. Furthermore, appropriate optimization and simulation achieve increased reliability of demand planning and overproduction, optimal manufacturing component utilization, increased resource consumption efficiency, and improved inventory management (Enyoghasi/Badurdeen

2021). During operation, Industrial Internet of Things (IIoT) provides insights into the production and helps in enhanced decision-making toward sustainability-aware directions. Finally, a green Digital Twin-driven production system assists through industry 4.0 technologies in the efficient setup of machines that require calibration beforehand by reducing the amount of produced defective goods and associated material costs.

In case sustainability awareness arises during or after the production stage within the product life cycle, it is difficult to draw conclusions on the sustainability impacts of planning decisions. A retrospective analysis of existing product design and production planning decisions is essential to generate future transparency and improvement regarding the sustainability of developed products.

4.4. Usage and EOL

According to the "Proposal for the new Ecodesign for Sustainable Products Regulation" (ESPR) of the European Commission (European Commission 2022), Digital Product Passports (DPP) contain information about a product's composition, the origin of the components and should also provide data necessary to assess the environmental and societal impacts during production, usage and transformation stages of the product life cycle. Jansen et al. (Jansen et al. 2023) distinguish between the DPP itself and the supporting DPP system, which is the underlying software system that facilitates interactions between various stakeholders along a product's life cycle to consolidate required information. General DPP system and software quality requirements incorporate aspects in regard to legal obligations, functional suitability, security, confidentiality, IP protection, interoperability, modularity and modifiability, accessibility, availability and time behavior (Jansen et al. 2023).

Requirements for a DPP were alternatively subdivided by (Plociennik et al. 2022) into information, collaboration, identification, and legal requirements. Especially interesting in the context of the current paper is the classification of required data into:

- Manufacturing data (product composition, materials, component weights, details about the manufacturing process, physical and chemical properties of materials, hazard class)
- Usage data (documentation of changes in a complex product, e.g. documentation of part replacement or repair)
- EOL data (documentation on collection, sorting and treatment, applied recycling method, recording of achieved collection fraction)
- Life cycle data (sales volume, guidelines for storage and usage, purchasing decision aid based on environmental and societal criteria)

5. Use cases of green Digital Twins in the product life cycle

The following four use cases describe representative green Digital Twins for the product life cycle stages. These include sustainable recipe planning, flexible production planning for charging stations, CO_2 reduction in a cyber-physical brewing lab and refrigerating appliances recycling. Utilizing real-time data, machine learning models and simulation, these green Digital Twins showcase informed decision-making, optimized resource consumption, and reduced environmental impact throughout the product life cycle.

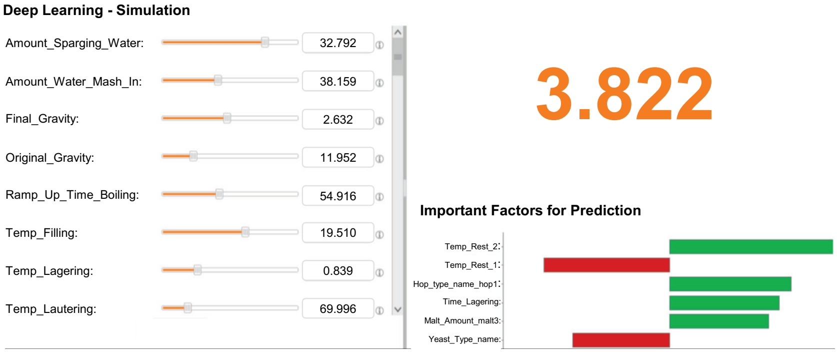
5.1. Sustainable recipe planning

A first approach of proactively predicting CO_2 emissions and optimizing products and processes can be demonstrated within a cyber-physical brewing laboratory at the RIF Research Institute for Research and Transfer e.V. (RIF) in Dortmund and at the Centre for Advanced Manufacturing University of Technology Sydney (CAM UTS) in Sydney with the goal of ML-based recipe planning. By enhancing the physical brewing assets towards green Digital Twins regarding CO_2 emissions as well as material and energy consumption, machine learning models are developed to predict and optimize CO_2 emissions. Key sources of CO_2 emissions include fermentation (Scope 1), energy consumption for heating and cooling (Scope 2) as well as raw material sourcing (Scope 3).

To predict CO_2 emissions, data on recipe parameters and their influences have to be collected and provided in a unified and integrated form. Therefore, AAS structures as well as a specified green Digital Twin information model and database, are used (Wöstmann et al. 2022). In the next step, multivariate supervised machine learning models are trained on this data to estimate CO_2 emissions accurately.

The models consider factors such as process times and temperatures within the mashing, lautering, boiling, cooling, fermenting, and maturing, as well as the amount and PCF of hop, yeast, and malt. By adjusting recipe parameters within the models, brewers can generate optimized recommendations that minimize CO_2 emissions while maintaining product quality.

This data-driven approach enables continuous optimization of CO_2 emissions during early recipe planning (see Figure 3). By leveraging machine learning, brewers can make informed decisions to reduce the environmental impact of a brewed beer by, for example, adjusting recipe parameters or changing their raw material sourcing.



Deep Learning - Simulation

Amount_Sparging_Water: 32.792

Amount_Water_Mash_In: 38.159

Final_Gravity: 2.632

Original_Gravity: 11.952

Ramp_Up_Time_Boiling: 54.916

Temp_Filling: 19.510

Temp_Lagering: 0.839

Temp_Lautering: 69.996

3.822

Important Factors for Prediction

Figure 3: Recipe Simulator in RapidMiner

5.2. Flexible production planning for charging stations

The second approach reacts to flexible market conditions to create sustainable production planning. Planning production systems under flexible market conditions require a high level of interlinking between production planning and product development. This aspect is being analyzed for charging station assembly in the research project SimUltane Product and Process Development of a Charging Station Outlet Module Suitable for Automation (SUPPLy). For this purpose, the simulation model of a flexible-man-power line shown in Figure 4 was set up and analyzed using various configuration scenarios.

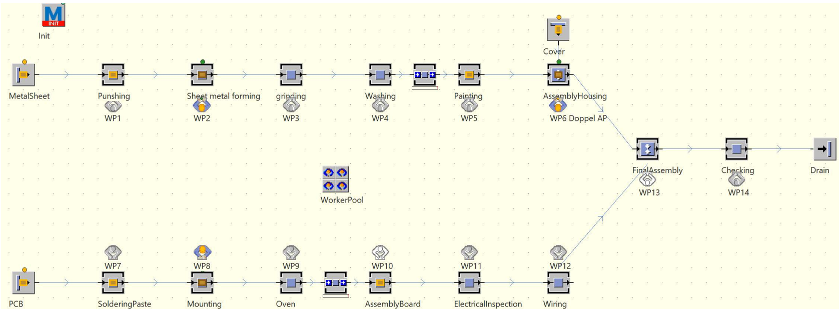


Figure 4: A simulation model of a flexible production line in Tecnomatix Plant Simulation

As can be seen in Figure 4, the line is equipped with workstations capable of human-robot interaction. Different line and organizational configurations can be analyzed in terms of output quantity based on other quantity requirements. The model also enables the output of energy consumption data based on current planning aspects.

DOI: https://doi.org/10.30844/wgab_2023_10

This data serves as feedback for product development with regard to product design. This allows optimization potentials to be quantified and evaluated in terms of their influence on production.

5.3. CO_2e reduction in cyber-physical brewing laboratory

In this approach, the green Digital Twin provides the foundation for visibility and transparency of energy consumption and emissions, which is the starting point for reducing CO_2e in production. The RIF and CAM UTS operate each cyber-physical brewing laboratory for data engineering and analysis. The challenge is to demonstrate and reduce CO_2e emissions while brewing beer based on energy-oriented Digital Twins for both locations.

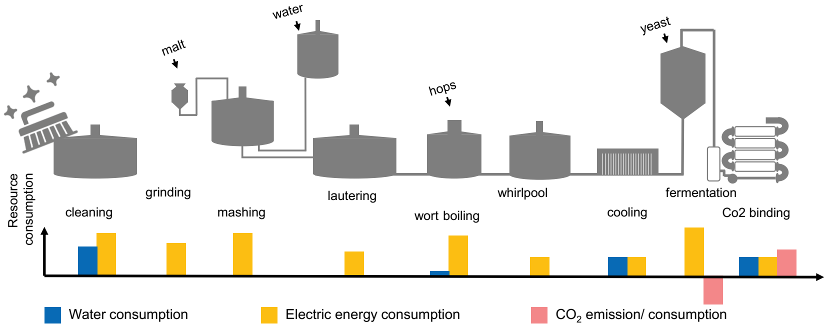


Figure 5: Concept for transparency in resource consumption

To achieve this goal, the green Digital Twin will collect data on energy consumption and emissions from various sources throughout the production process, such as electricity use, process heat, physical and biological processes and transportation. The challenge is integrating all data sources in the complete production system and developing semantic links between energy sources and sinks. This information model will enrich the green Digital Twin.

The next step will include energy and emission-oriented production planning and control of the cyber-physical brewing laboratories based on historical data. Using real-time data and forecast models, the intelligent control system in the green Digital Twin enables improvements in production program planning about emissions. The control system uses prediction models to communicate real-time optimization potentials based on CO_2e allocation to the brewers. The green Digital Twin is continuously monitored and updated by comparing simulation results with actual data. This enables identifying discrepancies and adjusting in real-time, ensuring the production process runs as efficiently and sustainably as possible.

In addition to monitoring emissions from the production process, the green Digital Twin will track excess CO_2 from the fermentation process. This excess can be sequestered into CO_2-binding biomass using a microalgae photobioreactor and reported into the software architecture of the green Digital Twin. A concept for a real-time connection between location-independent CO_2 emitting and compensating production systems was presented by the Estanium Association (Estanium Association 2023) with a photobioreactor operated by CAM UTS. This will enable stakeholders to track and optimize emission offsets (Deuse et al. 2022).

5.4. Refrigerating appliances recycling

An important aspect of the green Digital Twin is to ensure that no stages of the product life cycle are omitted (Wang/Wang 2019). Possible implementation methods and benefits of green Digital Twins at product's EOL are researched and demonstrated in the RIF e.V. project DiKueRec, which focuses on the refrigerating appliances recycling industry. This approach targets products already on the market that have not yet been subject to ecodesign and the integration of generic submodels.

Recycling old refrigerators plays a major role in protecting the Earth's atmosphere from ozone depletion and the emission of greenhouse gases. For instance, half of the handled appliances still contain volatile fluorinated and/or chlorinated hydrocarbons (VFC) (Deutsche Umwelthilfe 2016) with a global warming potential (GWP) up to 8100 times higher than the GWP of carbon dioxide (Abas et al. 2018).

The waste stream of old refrigerators is currently monitored and evaluated through manual records and lists. This is error-prone and prohibits input-dependent process efficiency control. Therefore, a significant potential exists in digitizing the incoming waste stream data to ease the workload of monitoring for the personnel and to introduce a modern energy efficiency control through green Digital Twins. (Polikarpov et al. 2022)

In the first step, an automated data collection system for recycling plants was proposed. Due to the long-life period of fridges, there is a lack of standardized information accompanying the products as their unified DPP is not implemented yet. The labels in the fridges are not easily accessible in recycling plant circumstances where short cycle times must be ensured. The labels are often not standardized and, in some cases, missing due to very long periods of use. The research project validated a retrofit solution using various sensors, including laser scanners and cameras in an IoT setting, to fill in the observed information gap (see Figure 6). The automated measurements of incoming fridges are utilized to create green Digital Twins containing attributes required for efficient control of recycling machinery (e.g., adjusting shredder power consumption to the fridge size, adjusting gas

DOI: https://doi.org/10.30844/wgab_2023_10

filter exchange periods based on the real number of processed fridges, etc.). Using artificial intelligence, green Digital Twins of recycled refrigerators support the calculation of expected material masses, especially foaming and cooling agents.

The comparison of the predicted collection values with the actual output of recycling plants leads to accelerated decision-making and a higher readiness of recyclers for environmental certifications of their plants.

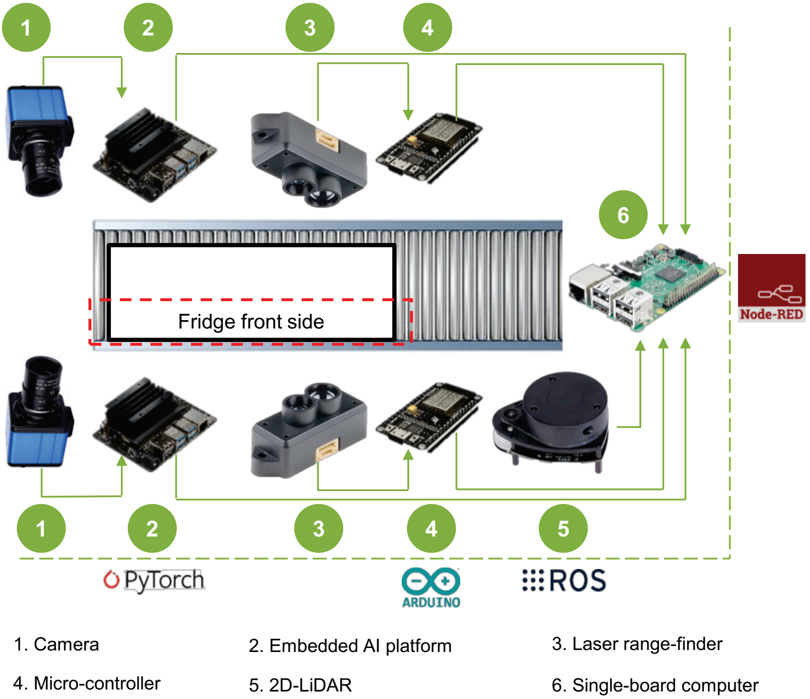


Figure 6: Prototype concept of the refrigerator scanning

Ideally, the information flow between the manufacturers, users, and fridge recyclers should fulfil the respective actors' information demands. Interest conflicts may appear, e.g., EOL actors may require information on product composition, but not all manufacturers will be ready to share this information (Plociennik et al. 2022). In the next step, the observations and the data structure behind the fridge green Digital Twin shall be used to ensure that fridge DPP contains sufficient data for recyclers that the manufacturers are also ready to provide.

The findings and the developments of the DiKueRec project emphasize the need for tight cooperation between manufacturers and recyclers to create a value-added green Digital Twin. For dealing with the existing product information gaps at the recycling stage, Industry 4.0 technologies and concepts can be applied to instantiate a green Digital Twin at the EOL for efficiency control and audit purposes.

6. Discussion and Conclusion

Green Digital Twins demonstrate immense potential in developing sustainable product life cycle management. The focus is to reduce industrial emissions and resource consumption with the help of Industry 4.0 technologies such as real-time data monitoring, machine learning models and simulation to optimize resource consumption and reduce CO_2e. In summary, the described approaches offer chances for improving Scope 1 and Scope 2 emissions, providing a holistic product design and production planning based on transparency in production, usage and EOL. The applications demonstrate green Digital Twins of various domains for each stage of the product life cycle with the potential to reduce climate-damaging actions. Sustainable recipe planning with green Digital Twins enables proactive prediction and optimization of CO_2 emissions during brewing. Integration of green Digital Twins in production planning enhances resource allocation and output optimization. CO_2e reduction in a cyber-physical brewing laboratory is achieved through real-time data collection and the optimization of production planning and control. Green Digital Twins facilitate efficient monitoring and control of the recycling process, improving energy efficiency and material mass calculation.

In conclusion, the contribution of this research highlights the significance of green Digital Twins in driving sustainable practices and reducing global industrial emissions. However, further investigations are vital to exploit its full potential. Specifically, the development of a generalized green Digital Twin is necessary to map semantic, statistical and external information effectively.

Further research and implementation of green Digital Twins are crucial for reducing global industrial emissions. A generalized green Digital Twin with semantic links needs to be developed to map semantic and statistical information. This semantic information model is the basis for performing what-if scenarios and enriches existing information.

To advance this field, future work will involve defining the requirements for building use case-specific and modularized semantic information models. These models will serve as the foundation for conducting what-if scenarios and enriching existing information. By integrating semantic knowledge as well as statistical and external data, industries can gain deeper insights to enhance sustainability efforts.

Acknowledgements

This paper presents the research projects DaPro, SUPPLy, BeverGreen and DiKueRec.

The research and development project "Data-driven process optimization using machine learning in the beverage industry" (DaPro) is funded by the German Federal Ministry of Economics and Climate Protection (BMWK) within the program "Smart Data Economy" (grant no. 01MT19004D) and managed by the DLR.

The project "SimUltane Product and Process Development of a Charging Station Outlet Module Suitable for Automation" (SUPPLy) is supported by the German Federal Ministry for Economic Affairs and Climate Protection (BMWK) on the basis of a decision by the German Bundestag (grant no. 01MV19001B).

The research and development project "Green Digital Twin as the Foundation for the Sustainable Transformation of the Beverage and Brewing Industry" (BeverGreen) is funded by the German Federal Ministry of Economics and Climate Protection (BMWK) in the program "GreenTech Innovation Competition" (grant no. 01MN23008C) and managed by the German Aerospace Center (DLR) project sponsor.

The research and development project "Utilization of digital twins for efficient control of recycling processes in the use-case of refrigerating appliances recycling" (DiKueRec) is funded by the German Federal Ministry of Education and Research (BMBF) within the Action Plan ”Natürlich.Digital.Nachhaltig” (grant no. 02WDG016D) and managed by the Project Management Karlsruhe (PTKA).

References

Abas, N., Kalair, A. R., Khan, N., Haider, A., Saleem, Z., & Saleem, M. S. (2018). Natural and synthetic refrigerants, global warming: A review. Renewable and Sustainable Energy Reviews, 90, 557–569.

Abele, M., Unterberger, E., Friedl, T., Carda, S., Roth, S., Hohmann, A., & Reinhart, G. (2020). Simulation-based evaluation of an energy oriented production planning system. Procedia CIRP, 88, 246–251. https://doi.org/10.1016/j.procir.2020.05.044

accenture. (2021). Klimaeffekte der Digitalisierung: Studie zur Abschätzung des Beitrags digitaler Technologien zum Klimaschutz. https://www.bitkom.org/sites/default/files/2021-10/20211010_bitkom_studie_klimaeffekte_der_digitalisierung.pdf

Bader, S., Barnstedt, E., Bedenbender, H., Berres, B., Billmann, M., & Ristin, M. (2022). Details of the Asset Administration Shell-part 1: the exchange of information between partners in the value chain of Industrie 4.0 (Version 3.0 RC02).

Bank, L., Wenninger, S., Köberlein, J., Lindner, M., Kaymakci, C., Weigold, M., Sauer, A., & Schilp, J. (2021). Integrating Energy Flexibility in Production Planning and Control-An Energy Flexibility Data Model-Based Approach. ESSN: 2701–6277.

Barthelmey, A. (2021). Digitaler Zwilling für durchgängige Datenbereitstellung und -nutzung im Lebenszyklus wandlungsfähiger Produktionssysteme: Dissertation. Shaker Verlag GmbH.

Barthelmey, A., Lee, E., Hana, R., & Deuse, J. (2019). Dynamic digital twin for predictive maintenance in flexible production systems. IECON 2019-45th Annual Conference of the IEEE Industrial Electronics Society, 1, 4209–4214.

Biel, K., & Glock, C. H. (2016). Systematic literature review of decision support models for energy-efficient production planning. Computers & Industrial Engineering, 101, 243–259.

Blue Carbon Projects. (2023). ISO 14060 Family. https://bluecarbonprojects.org/faq-items/iso-14060-family/

Blunck, E., & Werthmann, H. (2017). Industry 4.0--an opportunity to realize sustainable manufacturing and its potential for a circular economy. DIEM: Dubrovnik International Economic Meeting, 3(1), 644–666.

BMWK. (2021). Treibhausgasemissionen in Deutschland nach Sektoren. https://www.bmwk.de/Redaktion/DE/Infografiken/Industrie/treibhausgasemissionen-deutschland-nach-sektoren.html

Braun, S., Maier, W., & Zirkelbach, S. (2010). Intelligent produzieren. Springer.

DOI: https://doi.org/10.30844/wgab_2023_10

Carvalho, A. C. P., Carvalho, A. P. P., & Carvalho, N. G. P. (2020). Industry 4.0 technologies: what is your potential for environmental management? In Industry 4.0-Current Status and Future Trends. IntechOpen.

ClimateWatch. (2023). Historical GHG Emissions. https://www.climatewatchdata.org/ghg-emissions?breakBy=sector&gases=178&source=43

Deuse, J., Hoffmann, F., Sick, N., Bennett, N., Lammers, T., & Hernandez Moreno, V. (2022). Digitization of the work environment for sustainable production – How could algae based sink technologies enable a neutral Product Carbon Footprint? In Digitization of the work environment for sustainable production (pp. 193–205). GITO Verlag. https://doi.org/10.30844/WGAB_2022_10

Deutsche Umwelthilfe. (2016). Wie alte Kühlschränke das Klima anheizen: Hintergrundpapier der Deutschen Umwelthilfe. https://www.zerosottozero.it/files/2016/06/160602_Hintergrundpapier_Kühlgeräte.pdf

DIN EN ISO 14064-1. (2019). DIN EN ISO 14064-1:2019-06 Greenhouse gases - Part 1: Specification with guidance at the organization level for quantification and reporting of greenhouse gas emissions and removals.

DIN EN ISO 14064-2. (2020). DIN EN ISO 14064-2:2020-05 Greenhouse gases - Part 2: Specification with guidance at the project level for quantification, monitoring and reporting of greenhouse gas emission reductions or removal enhancements.

DIN EN ISO 14064-3. (2020). DIN EN ISO 14064-3:2020-05 Greenhouse gases - Part 3: Specification with guidance for the verification and validation of greenhouse gas statements.

Enyoghasi, C., & Badurdeen, F. (2021). Industry 4.0 for sustainable manufacturing: Opportunities at the product, process, and system levels. Resources, Conservation and Recycling, 166, 105362.

Estanium Association. (2023). Estanium Association. https://www.estainium.eco/en/

Europäische Union. (2019). Verordnung (EU) 2019/2089 des Europäischen Parlaments und des Rates vom 27. November 2019 zur Änderung der Verordnung (EU) 2016/1011 hinsichtlich EU-Referenzwerten für den klimabedingten Wandel, hinsichtlich auf das Übereinkommen von Paris abgestimmter EU. https://eur-lex.europa.eu/legal-content/DE/TXT/PDF/?uri=CELEX:32019R2089&from=EN

Europäische Union. (2020). Verordnung (EU) 2020/852 des Europäischen Parlaments und des Rates vom 18. Juni 2020 über die Einrichtung eines Rahmens zur Erleichterung nachhaltiger Investitionen und zur Änderung der Verordnung (EU) 2019/2088.

European Commission. (2022). REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL - establishing a framework for setting ecodesign requirements for sustainable products and repealing Directive 2009/125/EC. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52022PC0142

Hariyani, D., & Mishra, S. (2022). Organizational enablers for sustainable manufacturing and industrial ecology. Cleaner Engineering and Technology, 6, 100375.

He, B., & Bai, K.-J. (2021). Digital twin-based sustainable intelligent manufacturing: A review. Advances in Manufacturing, 9, 1–21.

Herrmann, C., & Thiede, S. (2009). Process chain simulation to foster energy efficiency in manufacturing. CIRP Journal of Manufacturing Science and Technology, 1(4), 221–229.

Hoffmann, F., Wesskamp, V., Bleck, R., & Deuse, J. (2022). Scalability of Assembly Line Automation Based on the Integrated Product Development Approach. Annals of Scientific Society for Assembly, Handling and Industrial Robotics 2021, 275.

Hülsemeyer, L. (2016). Energieeffizienz spanender Werkzeugmaschinen und bedarfsgerechter Betrieb am Beispiel der inneren Kühlschmierstoffzufuhr. PZH Verlag.

IEC 62832. (2020). IEC 62832-1:2020 Industrial-process measurement, control and automation - Digital factory framework - Part 1: General principles.

ISO 14040. (2006). ISO 14040:2006 Environmental management – Life cycle assessment – Principles and framework.

ISO 14044. (2006). ISO 14044:2006 Environmental management – Life cycle assessment – Requirements and guidelines.

ISO 16400. (2020). ISO 16400-1:2020-09, Automation systems and integration - Equipment behaviour catalogues for virtual production system - Part 1: Overview.

ISO 18828. (2018). ISO 18828:2018 Industrial automation systems and integration – Standardized procedures for production systems engineering.

Jansen, M., Meisen, T., Plociennik, C., Berg, H., Pomp, A., & Windholz, W. (2023). Stop guessing in the dark: Identified requirements for digital product passport systems. Systems, 11(3), 123.

Kritzinger, W., Karner, M., Traar, G., Henjes, J., & Sihn, W. (2018). Digital Twin in manufacturing: A categorical literature review and classification. IFAC-PapersOnLine, 51(11), 1016–1022. https://doi.org/10.1016/j.ifacol.2018.08.474

Liang, J., Wang, Y., Zhang, Z.-H., & Sun, Y. (2019). Energy efficient production planning and scheduling problem with processing technology selection. Computers & Industrial Engineering, 132, 260–270.

Mousavi, S., Thiede, S., Li, W., Kara, S., & Herrmann, C. (2016). An integrated approach for improving energy efficiency of manufacturing process chains. International Journal of Sustainable Engineering, 9(1), 11–24.

Platform Industie 4.0. (2022). Asset Administration Shell Reading Guide. https://www.plattform-i40.de/IP/Redaktion/DE/Downloads/Publikation/AAS-ReadingGuide_202201.pdf?__blob=publicationFile&v=1

Plociennik, C., Pourjafarian, M., Saleh, S., Hagedorn, T., Carmo Precci Lopes, A. do, Vogelgesang, M., Baehr, J., Kellerer, B., Jansen, M., Berg, H., & others. (2022). Requirements for a Digital Product Passport to Boost the Circular Economy. INFORMATIK 2022.

Polikarpov, M., Emelianov, G., Hübner, F., Farooq, A., Prasad, R., Deuse, J., & Schiemann, J. (2022). Automated Multi-sensory Data Collection System for Continuous Monitoring of Refrigerating Appliances Recycling Plants. 2022 IEEE 27th International Conference on Emerging Technologies and Factory Automation (ETFA), 1–4.

Sartal, A., Bellas, R., Mejias, A. M., & Garcia-Collado, A. (2020). The sustainable manufacturing concept, evolution and opportunities within Industry 4.0: A literature review. Advances in Mechanical Engineering, 12(5), 1687814020925232.

Schrems, S., Eisele, C., & Abele, E. (2011). Methodology for an energy and resource efficient process chain design. Glocalized Solutions for Sustainability in Manufacturing, 17(3), 299–304.

Thiede, S. (2012). Energy efficiency in manufacturing systems. Springer Science & Business Media.

VDI 3633. (2014). VDI 3633 Paper 1 Simulation of systems in materials handling, logistics and production - Fundamentals. https://www.vdi.de/richtlinien/details/vdi-3633-blatt-1-simulation-von-logistik-materialfluss-und-produktionssystemen-grundlagen

Wang, X. V., & Wang, L. (2019). Digital twin-based WEEE recycling, recovery and remanufacturing in the background of Industry 4.0. International Journal of Production Research, 57(12), 3892–3902.

Weart, S. R. (2008). The Discovery of Global Warming. Harvard University Press. https://books.google.com.au/books?id=5zrjngEACAAJ

Weinert, N., Chiotellis, S., & Seliger, G. (2011). Methodology for planning and operating energy-efficient production systems. CIRP Annals, 60(1), 41–44.

Wöstmann, R., Borggräfe, T., Janßen, S., Kimberger, J., Ould, S., Bennett, N., Moreno, V. H., & Deuse, J. (2022). Data-driven recipe optimisation based on unified digital twins and shared prediction models. The 34th European Modeling & Simulation Symposium.