Advancing Sustainable Manufacturing through Digital Twin-based Simulation: Assessing and Optimising Processes for Social, Environmental and Economic Impacts.

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Abstract. Achieving sustainability in manufacturing is not without its challenges. Various studies have identified the need to balance environmental, economic and social considerations as a key obstacle. Meanwhile, there are increasing methods that promote only environmentally friendly products. This study explores the potential of digital twin-based simulation in advancing sustainable manufacturing by assessing and optimising processes for social, environmental, and economic impacts. The study proposes a framework for integrating concepts and theories related to sustainable manufacturing and digital twin-based simulation to support sustainability decision-making. The framework is validated through a case study in a manufacturing facility. The findings of this study demonstrate that digital twin-based simulation can effectively assess and optimise manufacturing processes for their social, environmental, and economic impact. This study contributes to the existing body of knowledge by highlighting the potential of digital twin-based simulation in advancing sustainable manufacturing. The study also emphasises the importance of considering the three sustainability dimensions in manufacturing decision-making processes. Overall, this research offers valuable insights for researchers, practitioners, and policymakers aiming to promote sustainable manufacturing practices.

1 Introduction

During previous industrial revolutions, the primary focus was on economic enrichment and the empowerment of manufacturing systems. However, the environmental consequences we currently face were not anticipated at that time. Today, there is a growing emphasis on innovative techniques, such as Cleaner Production, Green Manufacturing and Circular Economy for sustainable manufacturing practices [1], [2]. However, these approaches focus primarily on environmental impacts and do not deliberately strive to enhance economic and social sustainability. Research has also suggested that it is ineffective to assess each sustainability dimension independently [3]. To address these challenges, the Life Cycle

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Sustainability Analysis (LCSA) framework [3] advocates for a shift from segmented assessment approaches to a holistic and analytical evaluation of sustainability dimensions. However, due to the qualitative nature of social dimensions, there is a growing need for effective tools that can determine interdependencies and trade-offs within the three sustainability dimensions without compromising the well-being of future generations [3]

The emergence of Artificial Intelligence (AI) and other computing devices is revolutionising the way we direct, design, deliver and develop manufacturing operations to achieve improved and sustainable products and processes [4], [5]. Research also suggests that holistic real-time analytical tools will support real-time sustainability decision-making in a dynamic and agile manufacturing environment [6], [7]. As a result, there is an increasing demand for a cyber-physical system that integrates the physical and digital worlds to mitigate unpredictable circumstances [8]. The concept of Digital Twin (DT) technology refers to a virtual replica or simulation of a physical object, process, or system [8], [9]. It is an emerging technology that holds promise for addressing the challenges of sustainable manufacturing by enhancing digital transformation and business intelligence [9], [10]. DT combines real-time data from various sources, such as sensors, Internet of Things (IoT) devices, and historical records, to create a digital representation that mirrors the real-world counterpart. Digital twins enable real-time monitoring, analysis, and optimisation of physical assets, allowing for predictive maintenance, performance optimisation, and decision-making support [8], [9].

2 Modelling Framework and Methodology

The operations management model (Fig.1) is an established model in operations management. It provides the framework for how manufacturing operations manage and set strategic objectives such as sustainability and competitive goals for the creation and delivery of products [5]. Slack et al [5], describe the operations management functions that deal with setting strategic goals, assessing performance objectives and making strategic decisions as "Directing the operation". The "Designing the operation" function designs the product and process to deliver the product. The "Delivering the operation" function is responsible for planning and controlling the operation and capacity management, while the "Developing the operation" function focuses on continuous improvement of the operations, risk management, quality management and management of the creation of new products [5]. However, besides the increasing changes in the market for competitive products, sustainability challenges are increasing the volume of data practitioners have to decipher to make an effective decision that provides a balance between sustainability and competitive goals.

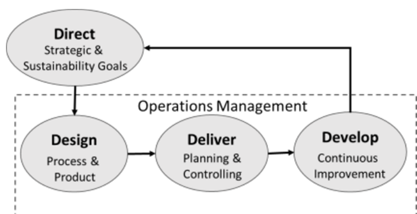

Fig. 1. Sustainable manufacturing operations management model - [5].

In a previous development, the authors have proposed and validated a framework for modelling simulation-based sustainability impact analysis Fig. 2 [7], [11]. The framework integrates the concepts and principles of the ISO 14040 Life Cycle Assessment (LCA) framework [12] with the simulation project cycle and conceptual modelling framework [13], [14]. While this framework (Fig. 2) has been proven valuable in supporting holistic decision-making for the creation and delivery of sustainable products [7], the data acquisition and selection model is based on historical and static data, hence, integrating Fig. 1 and Fig. 2 will provide the foundation for integrating digital twin simulation-based projects.

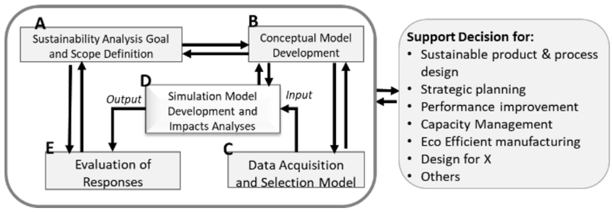

Fig. 2. The Framework for modelling simulation-based sustainability impact analysis [7].

2.1 Digital Twin-based Simulation Framework for Operations Management

The integration of the operations management model with the framework for modelling simulation-based sustainability analysis supports sustainability decision-making at the "Design", "Deliver" and "Develop" phases (Fig. 3). The design of the sustainable products or processes will depend on the sustainability analysis goal and the project scope that was defined at the directing operation phase. Setting realistic and achievable sustainability objectives within a defined boundary such as process, product or system stage is essential in conducting a simulation project [15]. The simulation-based sustainability approach enables the optimisation of production processes and supports decision-making at the operational level for sustainable product and process design, strategic planning, capacity management and operations performance improvement.

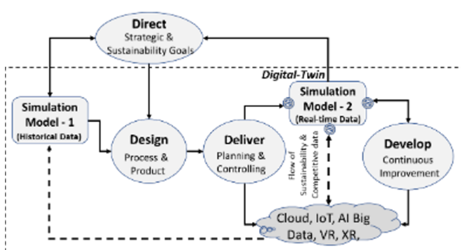

Fig. 3. Digital twin-based Operations Management framework.

2.1.1 Simulation Model-1 – Historical Data

During the design phase, historical data on aspects of the environmental dimension such as energy consumption and carbon emission are modelled for environmental considerations. Factors such as cycle time and production cost are important economic aspects of sustainable manufacturing. Aspects of social dimensions include health and safety, job security, motivation and satisfaction at the workplace. The simulation model deploys the method of Productivity Factor (PF) and weighted Social Impact Coefficient (SIC) as the social inputs to the simulation parameters [16]. The SIC determines the level of satisfaction and motivation of employees within the boundary of the simulation model, Generally, a SIC of "1" represents the highest level of satisfaction and motivation of the employees. In this case, with the aid of the simulation model, "Directing the operation" selects and commissions an optimised sustainable designed product and process for implementation at the "deliver" and "develop" stages.

2.1.2 Digital-Twin Simulation Model-2 – Real-time Data

A Digital Twin is a virtual replica of a physical system or process, created by combining real-time data with advanced analytics and simulation capabilities. In Fig. 3, "Simulation Model–2" has features that enable it to plug into real-time data from the physical production assets and data from the cyber environment. DT is a data-driven knowledgeable system that optimises resource usage by providing real-time data on energy consumption, material utilisation, workers motivation, and waste generation. This technology enables sustainability practitioners to monitor, analyse, and optimise operations in a real-time, leading to improved efficiency, reduced costs, and enhanced sustainability. By analysing this data, manufacturers can identify inefficiencies, implement proactive measures, and reduce their environmental footprints.

2.2 Application of Digital Twin- Simulation-based Framework – A Case Study

This case study was carried out to investigate the sustainability of a UK-based manufacturing SME that specialises in flywheel cast iron. The company's goal is to maintain its competitive position when the operation is at full capacity. The project aims to support the management decision in designing and managing the sustainability of the production process, especially, at infinite demands for finished products and an unlimited supply of materials. Table 1 demonstrates the project scope and long-term, mid-term and short-term objectives within the defined manufacturing process level and boundary.

Table 1. Classification of the long-term and short-term simulation modelling objectives

Sustainability Dimensions	Process level Impact Categories	Objectives		
		Long-term	Mid-term	Short-term
Environmental	Energy Consumption	√		√
	Water Consumption	√	√	
	GHG emission	√	√	
	Materials Usage	√		
	Waste elimination	√		√
Economic	Labour costs	√	√	
	Energy Costs	√	√	
	Throughput	√		√
	Productivity	√		√
Social	Workplace Hygiene	√		√
	Employees' motivation	√		√

The case study deploys SIMIO Discrete Event Simulation (DES) software to model and demonstrate the applicability of the developed simulation-based sustainability impact analysis framework in a real manufacturing environment. Simio DES software provides a flexible and user-friendly environment for modelling in 2D or 3D graphics view. The processing line consists of the Parts' Source, two CNC machines (M1 & M2), connected by a conveyor. The schematic diagram of the processing line of Cell150 is depicted in Fig.4.

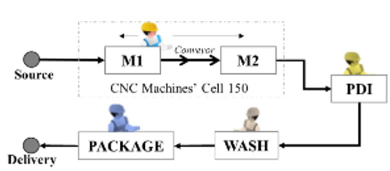

Fig. 4. Schematic diagram showing the layout of flywheel cast iron processing line

Each of the CNC machines is configured to carry out over five operations at a time; then, the workpiece is moved from Cell150 to the Pre-Delivery Inspection (PDI), Wash, Package and final Delivery.

The execution of the simulation project was planned for short-term objectives, hence, it was coded to capture environmental aspects such as “energy consumption” of the machines and “resource utilisation”, the economic aspects include “throughput” and “productivity”, while the social dimension focuses on the aspects of “workplace hygiene” and “employee’s motivation”. The calculated social impact coefficient (SIC) of the organisation was 0.7 which was coded into the simulation model. Fig. 5 depicts the dashboard displaying real-time information at each workstation during a simulation run.

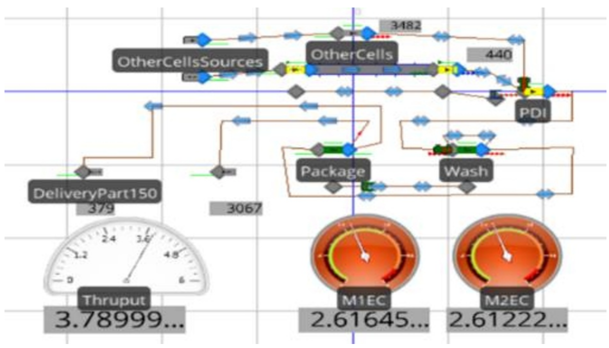

Fig. 5. Simulation model showing real-time information at each station during a run

From the dashboard, there are accumulation of parts at each workstation implying delay or poor resource utilisation. The throughput is an average of 3.8 parts per minute and the energy consumed by the machines per unit process (M1 and M2) were 2.62J (KWhr) each. When the SIC was revised to “1”, the energy consumption and accumulated parts at the workstations decreased and the throughput increased, demonstrating the interdependence of the 3 sustainability dimensions. Plugging this simulation model into the supplies of real-time data (digital-twin) on energy consumption, material utilisation, and waste generation will help to analyse and optimise resource usage, identify inefficiencies, implement proactive measures, and reduce environmental impacts while optimising social and economic impacts.

3 Conclusion

In conclusion, the integration of the operations management model with the framework for modelling simulation-based sustainability analysis, along with the application of Digital Twin technology, offers significant potential for addressing the challenges of sustainable manufacturing. This approach enables real-time monitoring, analysis, and optimisation of manufacturing processes, leading to improved sustainability performance. By considering the interdependencies and trade-offs within the three sustainability dimensions, manufacturers can make informed decisions that balance economic, environmental, and social sustainability objectives. The development and implementation of effective tools and frameworks for real-time simulation-based sustainability assessment will be crucial in achieving the goal of sustainable manufacturing and ensuring the well-being of future generations. Also, by integrating real-time data from the physical production assets and the cyber environment, the simulation model enabled the analysis and optimisation of operations in real-time, leading to improved efficiency, reduced costs, and enhanced sustainability.

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