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Utilising Web-based Digital Twin to Promote Assembly Line Sustainability

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***Abstract*—The shift towards utilising web-based technologies is trending as a reflection of the new business model of modern manufacturing. Web-based digital twin (WDT) has great potential for promoting sustainability in industrial cyber-physical systems. The current work demonstrates the mechanism by which a WDT architecture is established and utilised for improving sustainability. This is achieved by: a) accessing the control parameters that influence energy consumption, b) logging the energy consumption data and c) producing predictions by means of a computational algorithm. The objective is to support the system developer in delivering verified machine functionality along with trusted productivity and sustainability. The implementation is exemplified by an industrial case study adopted from a battery assembly production line.**

***Index Terms*—Sustainable manufacturing, sustainability, web-based digital twin, online technologies**

I. INTRODUCTION

Online technologies invaded all the fields of human activity, and with the progressive advancements in the information science and technology, more is yet to come. The significance of online technologies could be noticed under Covid-19 restrictions and mobility limitations. From business perspective, this will impact both the products and the services. The prosperity of online goods trading (e.g. Amazon) and the service provision platforms (e.g. education) could be easily detected. Manufacturing is strongly affected by the available technologies, and it responds to the technological changes by introducing new business models of creating value. However, the investment in new technologies demands sufficient resources in terms of development time and infrastructure establishment because of the complexity and the heterogeneity of manufacturing/production systems. Sustainable manufacturing, in particular, has to take the chance to preserve resources by making use of every possible technological solution. Consequently, economical and environmental sustainability go in-line with the new business model, and social sustainability in terms of safety and customer satisfaction gains greater opportunities.

Under the recent Industry 4.0 revolution, the abundance of generated data (actually “big data”) leads to the necessity of considering data as an additional manufacturing resource which impacts the manufacturing system at each stage of its life cycle. In a typical sustainable digital manufacturing environment, virtual models can be reused in order to reduce the development time and effort [1]. Further, the sustainability performance across the system lifecycle stages can be monitored. Once the virtual model of a system component, functional unit or the system itself exchanges data with the corresponding physical asset, the outcome is the digital twin (DT) [2]. To enable DT of successfully contributing to sustainable manufacturing, the following should be considered [3]:

- Creating new data management, access, and storage protocols to ensure the free flow of data and information.
- Embedding sustainability as a key metric for success in digital twin applications.
- Aligning digital twin functionalities with sustainability goals.

In the light of this, and in accordance with the trending movement towards resources’ digitalisation and transparency to the different levels of decision making, web-based digital twin (WDT) becomes justified. Establishing WDT constitutes the first step on the road to changing the business model of digital manufacturing, and increasing the sustainability of the added-value. Furthermore, the accessibility to manufacturing resources is granted not by means of a special software but rather the web browser. On the other hand, the consistency of web browsers with the cloud storage platforms already exists, thus, configuring the parameters that control the added-value and analysing their impact are achievable by creating the corresponding applications on the cloud.

Against this background, the current work puts forward a novel approach of using web-based digital twin for monitoring sustainability performance in cyber-physical production systems. For the proof of concept demonstration, the energy consumption of a manufacturing unit will be monitored, predicted by means of the established WDT in addition to accessing its control parameters. The remainder of this paper is organised as follows: Section II reviews the literature related to digital twin and web applications contribution to sustainable manufacturing. Section III explains the methodology of utilising the developed WDT. In Section IV, a case study that exemplifies the application of the proposed approach is introduced. Finally, Section V concludes the paper by summarising the findings and some future insights.

II. LITERATURE REVIEW

A. Web-based technologies for improved sustainability

Achieving sustainable manufacturing requires a large amount of collected data and dealing with uncertainty models. Therefore, a decision guidance management system for sustainable manufacturing is introduced in [4]. The system is accessible through a user interface developed using web-services. A sustainability indicator repository web portal that offers grouped sustainability indicator sets is introduced in [5].

A web-based system that gives manufacturing process engineers access to the performance models stored in a repository is introduced in [6], where a web application acts as an interface that previews multiple flows including service networks and analysis results. In their proposed architecture, Lu et al [7] use two technologies: web-based product data model and energy-aware digital twin model. Thus, by providing the product required features, energy consumption can be calculated. Seeking to enable smart factory and to support resources' virtualisation in its environment, Lu and Xu [8] propose a framework that facilitates creating the digital twin of the manufacturing resources. In this framework, semantic web rule languages are used for abstracting the manufacturing resources and engineering knowledge. To cope with the changes in the production process, smart web-based applications (namely SmartFactory and SmartPlanner) are developed in [9]. Utilising these applications resulted in time and cost reduction in addition to an optimised resources investment.

B. Digital twin contribution to sustainability

Tao et al [2] believe that using digital twin-driven product design helps to close the gap between the product's physical and virtual spaces, which decreases the efficiency and sustainability of the design, manufacturing and service. Barni et al [10] suggest integrating the digital twin with the Life Cycle Assessment (LCA) so that DT-driven sustainability assessment and performance optimisation are resultant. Based on an in-depth literature review, He and Bi [11] propose a framework of digital twin-based sustainable intelligent manufacturing. This framework maps the development of the product life cycle with the development of the manufacturing digital twin.

In the field of machining, the digital twin of the grinding wheel is created in [12], and a web service channel enabled by the Internet of Things (IoT) is established. This could help to reduce the energy and manufacturing resources' consumption by 14.4%. A framework of an energy-aware asset DT is introduced in [13]. In this framework, each DT can have multi-physical models, and its function is to monitor and report the behaviour of the physical counterpart. A service-oriented platform is proposed by [14] to improve the energy efficiency of the dyeing and finishing industry. Then, after obtaining data by means of this platform, the data repository feeds the developed digital twin application with the necessary data required for optimising the sequence and generating the final report. In their work aiming at utilising embedded aggregate digital twin in the hybrid supervised control, Borangiu et al [15] propose an architecture where a high-level decision making twin advises on a solution out of the optimisation space based on energy and raw material cost.

Using open-source tools i.e. SimPy Python library for discrete event simulation, the digital twin of an assembly line that contains legacy machines is built in [16]. Then, the optimisation is conducted using the simulated digital twin aiming at comparing the cycle times and energy consumption based on the buffer capacity. Max-plus Algebra is used by Wang et al [17] to make decisions of machine states (active/idle) after building it as a service in the digital space. In this approach, DT has an event-driven energy-saving decision model which outputs the suitable decision relying on the data received from the physical system.

C. Research gap analysis

In summary, based on the previous literature review, the following can be noticed:

- With their evolvement, web technologies are becoming an essential aspect of the production/manufacturing systems' structure, and they are used at different levels of the system hierarchy.
- The combination of the available open-source/affordable software tools and web browsers can be utilised to improve manufacturing systems' sustainability.
- The movement of virtualisation/digitalisation can aid sustainable manufacturing requirements in relation to the product, the manufacturing system and the associated services.
- Extending DT capabilities in terms of accessing control inputs and outputs can further enhance the value-adding processes' contribution to both productivity and sustainability.

This work builds on the progressive research of investing in DT-driven and data-driven sustainability. It also extends it by enabling the DT of configuring the control parameters that impact energy consumption starting from the development phase. Thus, it enables futuristic emulation and system optimisation with advanced visualisation capabilities. Some of the research works could enable digital twin visualisation and remote control through web browsers and by using web programming languages (e.g. HTML5). However, taking advantage of this technology is not fully accomplished. To address this research gap, a research methodology is constructed and presented in the next section.

III. METHODOLOGY

A. Basic concepts and work objective

Digital twin is "an integrated multi-physics, multi-scale, and probabilistic simulation of a complex product and uses the best available physical models, sensor updates, etc., to mirror the life of its corresponding twin" [18]. Two types of DT can be exhibited [13]: DT of products and DT of the enterprise (including manufacturing systems). For the latter, depending on its model sophistication, connectivity to the data from the physical twin and availability of Artificial Intelligence (AI)

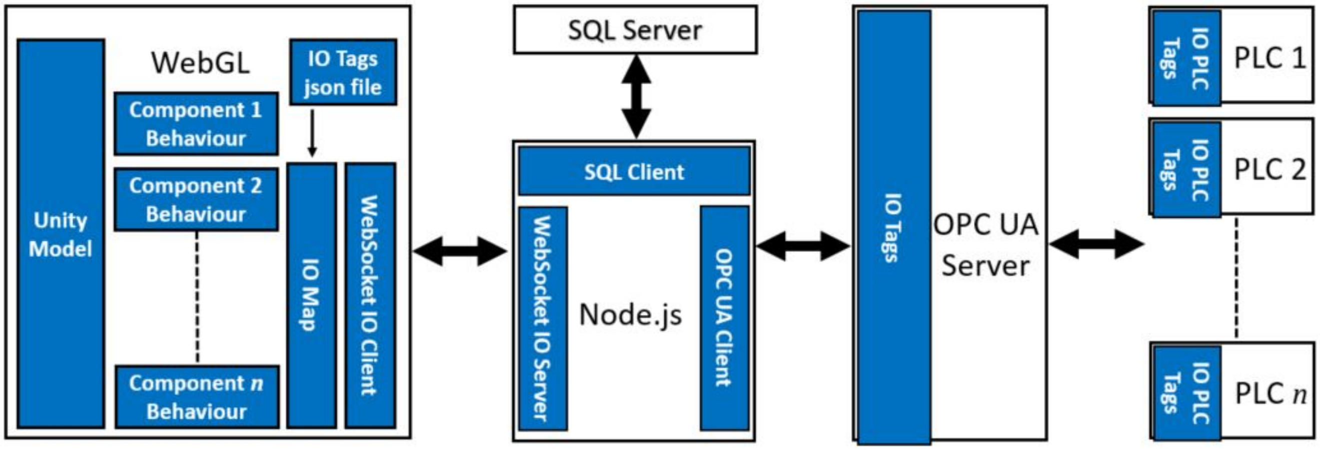


Fig. 1: The architecture of the developed Web-based Digital Twin (WDT)

element, DT can be [19]: Pre-Digital Twin (no physical twin, no AI); Digital Twin (existed connectivity, no AI); Adaptive Digital Twin (existed connectivity, with AI); Intelligent Digital Twin (existed connectivity, with AI).

The current work exhibits a digital twin with existing connectivity to the physical counterpart but without an advanced artificial intelligence capability for the time being but a statistical regression model (machine learning). In general, process performance is evaluated based on its productivity (e.g. optimal cycle time) and sustainability (i.e. low energy consumption) [20]. The aim here is to provide remote access through web browser to control parameters that influence energy consumption and its data of a certain unit of the manufacturing system by using WDT. Besides, it is aimed to test the possibility of adding intelligent algorithms that interact with the received data. Thus, it becomes possible to produce performance reports and develop other system components' virtual models whose function is influenced by this unit. These new features added to the system enable the system developer of verifying machines' functionality with the aid of visualisation in addition to assessing both productivity and sustainability.

B. WDT architecture

To achieve the aforementioned objectives, a Web-based Digital Twin (WDT) has to be developed. The focal point is to guarantee effective data interoperability between the virtual and physical models, and then to reflect the changes that take place in either one of them on the other counterpart. To achieve this, the authors constructed the architecture depicted in Fig. 1. Web Graphics Library (WebGL) is a JavaScript Application Programming Interface (API) for rendering interactive 2D and 3D graphics within any compatible web browser without the use of plug-ins [21]. On the other hand, Unity is a cross-platform game engine that gives the opportunity of creating models with certain behaviours, and building/ deploying them onto WebGL platform. The components were developed in Unity, and their behaviours were defined using C# programming language scripts. Each component behaviour was mapped to the corresponding PLC (Programmable Logical Controller) Inputs and Outputs (IO) using the tags provided in .json file. To establish successful communication between the virtual and physical models, the WebSocket library is utilised. WebSocket is a two-way TCP-based communication protocol that allows fast real-time data exchange. Moreover, this protocol is suitable when directing data to a manufacturing cloud-based application. It should be noted that WebGL and Node.js are open-source platforms, and the Unity engine can be used for free for non-commericial purposes.

Among many programming languages, Node.js also has the capability to use WebSocket API. Node.js reduces the language discrepancies between client and server and is suitable for web applications' development. In the current system architecture, Node.js is needed to translate the industrial process parameters to/from their corresponding values in the Open Platform Communications Unified Architecture (OPU UA) server, and once again, WebSocket is the in-between link. Needless to say, OPC UA server can accommodate different brands of Programmable Logical Controllers (PLCs) such as Siemens, Rockwell, etc.; multiple communication protocols e.g. Modbus, Profinet, etc.; various types of field devices e.g. drives, power meters, etc.; and can handle a high number of tags. Further, data logging to databases servers such as SQL (Structured Query Language) is easily achievable.

C. Sustainability indicators

Once data are made available and transferred appropriately using the architecture presented above, sustainability and productivity data can be accessed through the virtual model on a web browser without the need of a separate software. The performance indicator to be considered in this paper is the energy consumption of the production station measured for each produced part. Assuming that the investigated station is S_n (Fig. 2.) which can be a welding station, inspection station, etc., Autonomous Guided Vehicles (AGVs) move the parts between buffers (B) and stations (S). Meanwhile, the studied

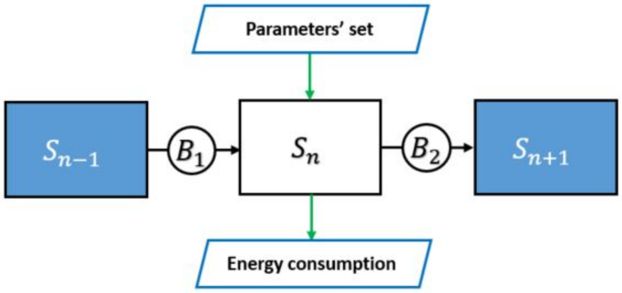


Fig. 2: Decomposition of the production line into functional units

station behaves according to the preconfigured set of rules, instructions and parameters.

Thus, with the implemented architecture, the station sustainability performance in terms of energy consumption and productivity (i.e. cycle time) is evaluated. Once this is achieved for all the stations involved in the production flow, the sustainability of the whole production line can be evaluated along with its productivity.

IV. CASE STUDY

A. Layout description

For proof of concept demonstration, a welding station that performs spot welding on battery modules will be utilised. The Integrated Manufacturing & Logistics (IML) established in Warwick Manufacturing Group (WMG), the University of Warwick demonstrates Industry 4.0 applications and the recent advancements in the field of smart manufacturing. IML contains the following [1]:

- Launch station
- Legacy loop.
- Robotic spot welding station.
- Robotic inspection station.
- Manual disassembly stations.
- Autonomous Guided Vehicles (AGV).
- Manufacturing Execution System (MES)

Welding is of high energy consumption. The complexity of the process increases when moving to mass production which does not guarantee the process sustainability. Therefore, the welding station was chosen to exemplify the proposed methodology of sustainability enhancement using WDT. The expected outcome is to assure the possibility of investigating a variety of cycle times, configuring the parameters remotely through the web browser, and collecting the corresponding data.

B. Results and discussion

The geometry files were added to Unity. Then, the necessary codes that describe the objects' behaviour were prepared and mapped to the model. As shown in Fig. 3, the signals and their representative parameters are updated at the same time on the digital twin, Node js server and OPC UA tags. Each set of station operation parameters include weld current, weld time, electrode force and electrode diameter, clamp time and release time. Referring to the research gaps addressed earlier in II-C, the findings of this work follow the trajectory of placing the digital twin on a web platform with enabling the accessibility to the physical equipment in terms of control code parameters and measured physical quantities. The energy consumption and cycle time could be logged successfully in order to use them for conducting further analysis. Following the successful implementation, a machine learning algorithm (multiple linear regression) is used to correlate the welding current and the cycle time to the station's energy consumption. The general model of multiple linear regression with k regressor variables after number n of observations $(x_{i1}, x_{i2}, ..., x_{ik}, y_i)$ is [22]:

$$y_i = \beta_0 + \beta_1 x_{i1} + \beta_1 x_{i2} + ... + \beta_k x_{ik} + \epsilon \qquad i = 1, 2, ..., n$$

ϵ refers to the random errors and β is the least squares estimator. The model can be written in the matrix form as:

$$y = \begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_n \end{bmatrix}, X = \begin{bmatrix} 1 & x_{11} & x_{12} & \dots & x_{1k} \\ 1 & x_{21} & x_{22} & \dots & x_{2k} \\ \vdots & \vdots & \vdots & & \vdots \\ 1 & x_{n1} & x_{n2} & x_{n3} & x_{nk} \end{bmatrix}$$

$$\beta = \begin{bmatrix} \beta_0 \\ \beta_1 \\ \vdots \\ \beta_k \end{bmatrix}, \epsilon = \begin{bmatrix} \epsilon_1 \\ \epsilon_2 \\ \vdots \\ \epsilon_n \end{bmatrix}$$

To minimise the error ϵ using the least squares as stated in [22], the loss function L is:

$$L = \sum_{i=1}^{n} \epsilon_i^2 = (y - X\beta)^T (y - X\beta)$$

To find the least squares estimator $\hat{\beta}$:

$$\frac{\partial L}{\partial \beta} = 0$$

This yields:

$$\hat{\beta} = (X^T X)^{-1} X^T y$$

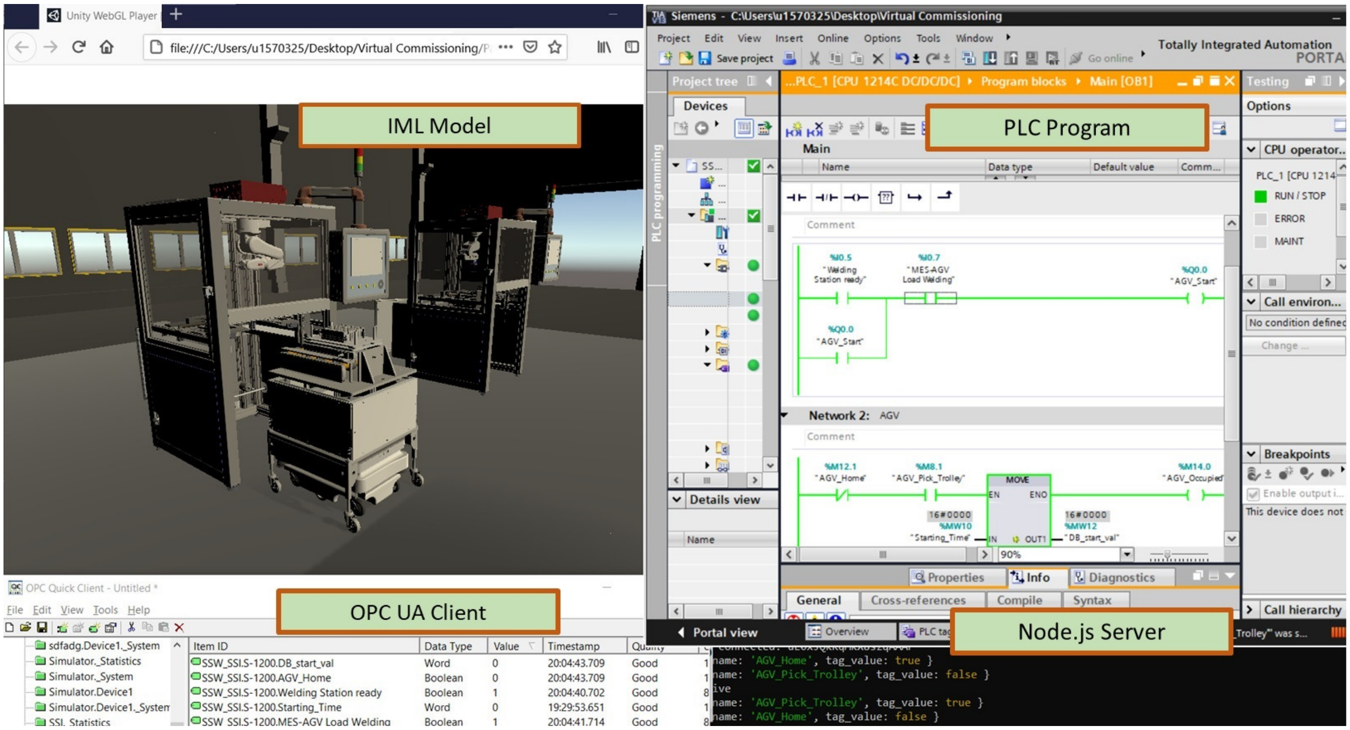
Next, the predicted output $\hat{y_i}$ is calculated using the equation:

$$\hat{y_i} = \hat{\beta_0} + \sum_{j=1}^{k} \hat{\beta_j} x_{ij} \ , \quad i = 1, 2, ..., n$$

or in its equivalent matrix form:

$$\hat{y} = X\hat{\beta}$$

The parameters (X) are considered to be influencing energy consumption for this case study are the welding current (WC) and the cycle time (CT). Cycle time includes the clamping time, welding time and release time. The advantage of WDT implemented here is the possibility of updating the input parameters (writing them to the PLC code) and the actual energy consumption (EC_a) after each run of the station (read from data logs), then the predicted energy consumption (EC_p) can be evaluated. The proposed concept is tested on a patch of battery modules. Table I provides a sample of the output



Item ID	Data Type	Value	Timestamp	Quality
SSW_SSI.S-1200.DB_start_val	Word	0	20:04:43.709	Good
SSW_SSI.S-1200.AGV_Home	Boolean	0	20:04:43.709	Good
SSW_SSI.S-1200.Welding Station ready	Boolean	1	20:04:40.702	Good
SSW_SSI.S-1200.Starting_Time	Word	0	19:29:53.651	Good
SSW_SSI.S-1200.MES-AGV Load Welding	Boolean	1	20:04:41.714	Good

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name: 'AGV_Home', tag_value: true }
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ive
name: 'AGV_Pick_Trolley', tag_value: true }
name: 'AGV_Home', tag_value: false }
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Fig. 3: WDT of the welding station in operation

TABLE I: A sample of the results:training data (upper group), predictions (lower group)

WC (Amp)	CT (min)	EC_a (kJ)	EC_p (kJ)	$\Delta EC(\%)$
120.0	11.19	40.71	-	-
129.9	11.24	41.29	-	-
118.4	11.3	37.65	-	-
119.3	11.28	41.68	-	-
128.7	11.11	38.10	-	-
120.8	11.2	37.48	-	-
135.3	11.25	43.97	-	-
126.1	11.23	43.93	-	-
122.5	11.16	37.75	-	-
123.6	11.12	37.74	-	-
133.9	11.19	44.62	42.07	5.71
124.6	11.2	39.89	41.35	3.66
128.6	11.25	39.21	40.98	4.52
127.9	11.14	41.2	42.04	2.04
121.2	11.16	39.64	40.95	3.3
132.1	11.28	37.07	41.71	12.52
123.4	11.21	42.39	39.70	6.35
136.3	11.13	48.57	42.53	12.44
130.7	11.2	36.82	41.38	12.38
118.9	11.29	34.83	38.92	11.75

values. The first group of data in the table are the algorithm training data, whereas the second group includes both the predicted data versus the actual. It can be noticed that the minimum difference between the predicted and actual energy consumption ΔEC is 2.04% whereas the maximum reached 12.52% where:

$$\Delta EC = |\frac{EC_p - EC_a}{EC_a}| * 100$$

As it can be seen from the previous results, it is possible for the system developer in the design phase to identify and test the machine functionality (visualised) and to adjust the parameters that control sustainability and productivity before the physical machine is built. It is also possible to test different operation scenarios at the WDT without the physical machine disturbance.

Regarding the limitations of the current work, one drawback of the previous application is that it does not take into account the welding quality as there is a following inspection process. Once the digital twin of the inspection station is implemented and combined with the current one of the welding station, the quality inspection outcome will be quantified as an influencing parameter, and the influencing parameters vector X can be extended. Also, no optimised solution is put forward as this is not the scope of the work, but rather validating the proposed concept.

V. CONCLUSION AND OUTLOOK

The research work reported in this article corresponds to the shift to digitalising and distributing manufacturing resources by embedding them in the digital twin, then enabling the accessibility to their values through a web browser to achieve WDT. Using the proposed architecture, WDT could access the PLC code to read and write the values of cycle time and the welding current which constituted the starting point of creating meaningful analysis along with verifying machine operability in the design phase. Furthermore, the proposed architecture enables the “intelligence” element of DT as a computational algorithm could be deployed successfully.

Future work will look into including more manufacturing resources (e.g. materials) and linking the outcomes of multiple stations to reach optimised sustainability in terms of energy and material consumption. It is also intended to utilise more advanced artificial intelligence algorithms to achieve optimised sustainability solutions and business models.

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