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Digital Twin for Plastic Recycling

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Abstract - The various types of plastic waste produced for recycling include HDPE, LDPE, PP, HIPS, etc. However, the plastic recycling industry is facing significant difficulties due to a diverse workforce, a lack of product knowledge, a lack of communication between the supply chain and the product chain, and so forth. On the other hand, modern information and communication technology (ICT) offers new approaches and opportunities for managing and operating industrial processes. As a result, the research presented here introduces the plastic manufacturing industry to digital twins and Industry 4.0 enablers. The objective is to offer a comprehensive and trustworthy digital representation of each recycling facility, creating a customised service system. The innovative digital twin-based system for plastic recycling, which supports recycling operations across a product's life cycle, from design to recovery, is the key contribution made in this report. Meanwhile, machine learning models are created using the data from the digital twin to enable plastic recycling services and refine presumptions with high data interoperability. During system implementations, the feasibility of the proposed system and techniques are validated and assessed.

Keywords: Plastic recycling; HDPE; LDPE; PP; HIPS; Machine learning; digital twin; Industry 4.0

Table of Contents

Table of Tables

Table of Figures

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I. Introduction

Growing environmental issues, particularly those linked to the use of plastics, have developed into serious problem. The majority of researchers are focused on effective and environmentally friendly plastic recycling and use. However, a sizable percentage of recycled plastic remains untapped. It might occur as a result of the traditional manual processes, such as grinding, washing, separating, drying, granulation, and compounding (Huang et al., 2022). However, excessive and frequent use of plastics poses a risk to both human and animal lives. Currently, 367 million tons of plastics are produced globally each year for various applications, and a survey predicts that this number will double by the year 2050 (Published by Ian Tiseo,2022). These figures are alarming and are only due to the fact that plastics are used in almost every aspect of plastic life.

To address this issue engineers and researchers have created techniques and tools for the digital factory to address certain issues in the recycling and manufacturing industries. These instruments are entirely computer-based due to the digitalization of the production sector. Computer-aided design and product data management are two examples of product development that are used frequently. Engineers use techniques like virtual commissioning and computer-aided manufacturing for virtual design and validation that is based on a digital representation of reality (Dashtimanesh et al., 2022). Over the upcoming years, it is anticipated that these virtual methods and technologies will become even more significant with the aim of achieving a complete 1:1 mapping between actual systems and virtual systems, or the so-called digital twin.

The remainder of this paper is organized as follows. Section 2 describes the problem statement and the research question we are trying to address. Section 3 contains the literature review of digital twins, circular economy, and blockchain. Section 4 covers the research methodology used in this project. In sections 5 and 6 we state the requirements needed for this project and the implementation of the project. Section 7 covers the price estimate for developing a digital twin. 8 covers the results and answers to our research questions.

II. Background & Research Question

One of the key driving forces behind building the project is to increase the plastic recycling rate and reduce the use of plastic production. A study taken in Australia stated that from 2015 to 2019 the national average of plastic recycling for the above 4 years was only 11.5% despite the sharp exponential growth in consumption of plastics (3.5 million tonnes (Mt) in 2018–19) and Germany produce 1 million tons of plastic waste which are worth of 254 million euros, which is more than any other country in EU and 66% of their plastics produce are recycled which is quite impressive amongst other countries. China on the hand produces roughly seven million metric tons of plastic products every month. Since January 2020, the highest monthly output of plastic products was recorded in December 2021, at 7.95 million metric tons (Hossain et al., 2022) but only recycling 30% of the plastics produced. Table 1 depicts the plastic waste recycling rate for per capita GDP and per capita plastic waste in a few selected countries. Though the above-mentioned countries are developed countries we can see a contrasting number. Even though Germany has a good percentage of plastic being recycled there is still room for improvement However, doing so requires new technological innovation.

Table 1

PW recycling rate, per capita GDP, and capita PW generation in selected countries (Envirotech online, 2020, Hossain et al., 2022).

Country	Recycling rate (%)	Per capita GDP (USD)	Per capita plastic waste generation (kg)
Germany	56.10	46,445.25	81
Austria	53.80	50,137.66	34.1
Wales -United Kingdom(UK)[a]	52.20	32,980	40
Switzerland	49.70	81,993.73	100
South Korea	53.70	31,846.22	98.2
Australia	11.50	55,060.33	53

[an] Average value of the UK generation was used.

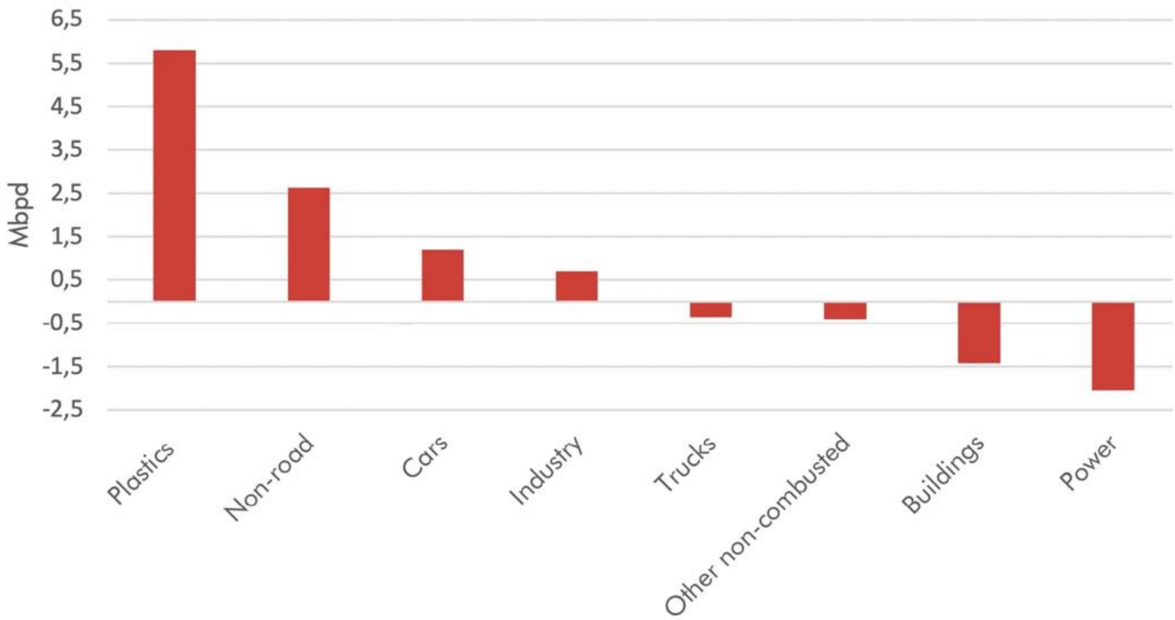
[b] Defined as recovery rate rather recycling rate.

Plastic bags are made from petroleum, which means plastic bags are one way we are depleting our oil supply. Plastic bags and petroleum are intrinsically linked. (“Plastic Bags & The Petroleum Link | 1 Bag at a Time”) About 8% to 10% of our total oil supply goes to making plastic. This can be further reduced by encouraging people to collect plastics for recycling. We discuss in detail the later stages of the report. An article (froav, 2019) states that around 359 million tons of plastics entered markets across the world in the year 2018 and it was also found that all the plastics were made from crude oil.

Figure 1

Oil Demand Growth from 2018 -2040

(Roberts, 2020)

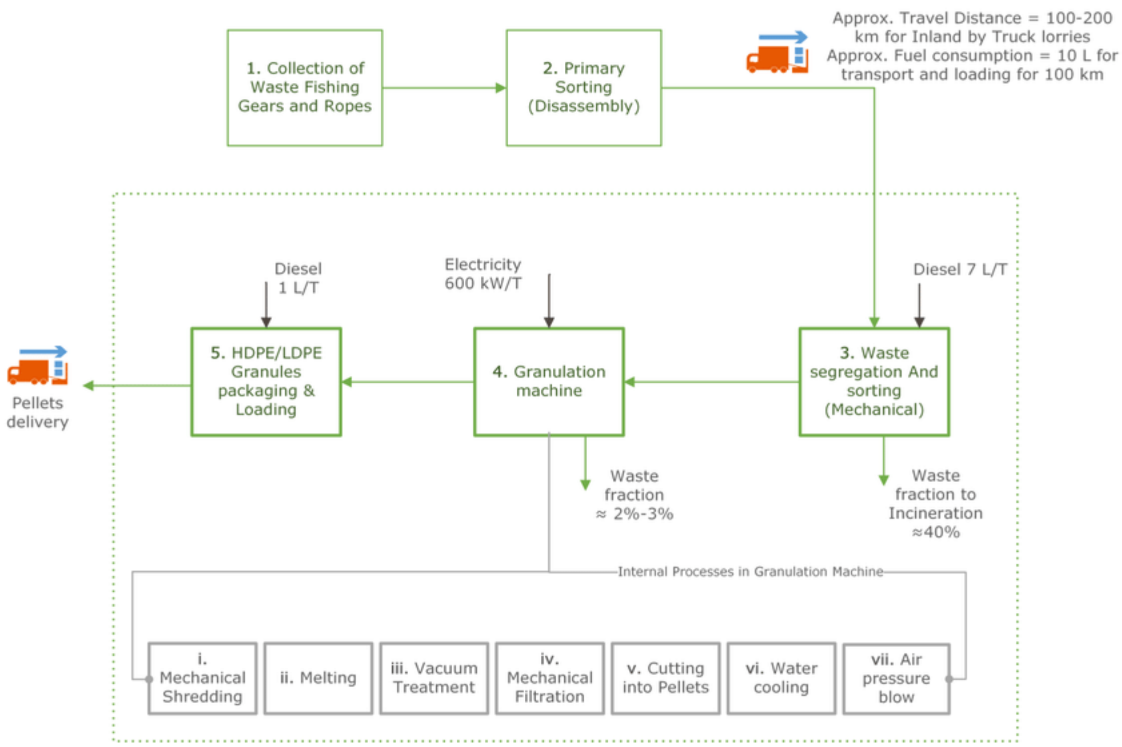


The above graph indicates plastics manufacturing would require the most crude oil to produce plastics. The numbers can be decreased by encouraging people to collect plastics and recycle them.

A major issue we are intending to solve is to design a recycling plant that doesn't interfere with your production processes and is eco-friendly. Designing an optimal recycling plant based on the location can be beneficial to the stakeholders and plastic recycling, structure of a standard recycling plant is shown in Figure 2. Considering the number of plastics, a country produces a recycling plant can be designed by the type of waste which is collected which leads to less investment in recycling equipment and recycling plastics. Having a track of the product is necessarian in the manufacturing and recycling industries. Another area the project focuses on is the inside of the recycling plant. We intend to monitor every stage of the process and the machines involved in the recycling plant. This will be achieved by creating digital twins from every single machine used for recycling by monitoring the telemetry values like temperature, fan speed, and blade speed to name a few. These values are collected stored and constantly monitored by human supervision there any changes in the machine will be indicated and logged. Constant monitoring of equipment will be helpful in troubleshooting, and service and maintenance can be performed before anything escalates. With the rich data knowledge of recycling plants, many things can be achieved which brings us to the next stage.

Figure 2

Typical Plastics recycling plant Architecture (Deshpande et al., 2020)



Product optimization and refining assumptions are very instrumental they can be in manufacturing or recycling. Product optimization can be very

Labor intensive and time-consuming a study taken in siemens show that having a digital twin for testing a product optimization has reduced their testing time by 6 months and has reduced cost and materials by 70%. Eventually, it takes teamwork to make real change, not just between the company and its clients but also among manufacturers, subcontractors, and suppliers of raw materials. For instance, this kind of cooperation already occurs in the steel sector but not in the plastics sector. The supply chain and the production chain should have a clear line of communication. Poor communication between the supply chain and product chain can cause delays in delivery, rising logistics costs, long production cycles, increasing risks, poor customer experience, non-compliance, and poor inventory management.

2.1 Research Questions

In this project, we focus on developing the technology to solve the problems in a plastic recycling plant. We also choose to conduct our study in Australia due to the availability of data compared with other countries. with that said the problems we are trying to address are as follows

RQ1: What are the categories of waste currently generated in Australia and the amount of waste generation (quantitative assessment of plastic waste generation in terms of polymer types, sector, and state-level of generation)?

RQ2: Is there a way to actively monitor and log the data of a plastic recycling plant?

RQ3: Is it possible to build relationships between the supply chain and product chain?

RQ4: Can we use machine learning and data analytics to refine our assumption and product testing?

RQ5: What will be the estimated cost of building a twin system for a recycling plant?

RQ6: What are the prospects of implementing digital twin technology in Australia?

III. Literature Review

This section elaborates on the concepts of international authors and their perspectives on digital twins and the circular economy. We plan to examine published papers from the past to the present in order to identify research gaps and determine where authors agree and differ; this will allow us to comprehend the benefits and downsides of the technology. The section is categorized by the topic of the papers; the first few articles examine digital twins and their use cases, while the second section will discuss blockchain technology and its contribution to material monitoring and tracing in the manufacturing business. Finally, we will discuss papers relevant to the circular economy and how the technology we have previously discussed can help us better the circular economy and plastic recycling.

1) Digital twin literature review

The origins of the concepts of digital twin came from research taken by (Glaessgen & Stargel, 2012) have used digital twin technology for U.S military fleets and vehicles the authors have pointed out the importance of design verification, testing, monitoring, health management and prediction of service and maintenance by improvising reality and safety. (Tuegel et al. 2011, 2012) Have taken the study to the next stage by implementing digital twins for aerospace missions. The authors have monitored the vibration, temperature, sand and trees to structurally monitor and predict the damages and health of the aircraft aiming for high reliability. The concept of digital twins in for originally tossed for space experiments. In the past few years, the concept of other digital twins was extended into the manufacturing and recycling domain.

A paper published in Germany regarding digital twins describes the importance of digital twins, also known as "industry 4.0." The authors stress the necessity of autonomous systems in the manufacturing industries, where they describe autonomous systems as systems without comprehensive programming or human oversight that can do complex tasks. Autonomous systems are intelligent machines that carry out complex responsibilities and are aware of their capabilities. To create extremely accurate simulations of the current state of the process, autonomous systems will require the ability to access alternative actions, organize, and execute. To do this, autonomous systems will require access to realistic simulations of the current state of the process and the real world (Rosen et al., 2015). The methodology has been tossed back to the days when NASA was developing their Apollo mission; since then, several use cases and research have been conducted on this topic. One of the examples shown in the paper intends to create a digital twin for a milling machine. The example required all the external and internal inputs to create a precise digital twin, like temperature, heat, rotating speed, etc. Although the concept of a digital twin in manufacturing is fascinating and could revolutionise manufacturing industries, the authors think there are a few challenges. Building a digital twin of all the products and their lifecycles can be very time-consuming, and storing all the data in a storage unit can cost the manufacturers a lot. Upon successful implementation, the risk of cyber hacking and information theft is sky-high, which will put stakeholders and investors at risk. This can be addressed by employing a powerful, decentralised technology known as blockchain.

Another paper published in the year 2018 have suggest that with the advancement of machine learning algorithms and digital twin environments it is possible to solve problems which usually take several domain experts from various domains and costs and be cut down by several times. The authors also suggest the increase in demand for time efficiency and profitability has led to this development. The method used by the authors has still used a known data-driven method by fusing data from different layers of the autonomous pyramid. Throughout the production process, data is continuously created in the system state or by the relevant sensors. In the framework of industry 4.0, manufacturing technology connectivity is quickly expanding. The integration of control systems with cloud-based technologies enables the storage of vast quantities of production-related data. Communication standards to address the rising need for connection are a prominent issue of discussion in the field of industrial control technology (Jaensch et al., Nov 2018). One of the major advantages of creating a digital twin for manufacturing industries is autonomous problem solving A manufacturing system's engineering process is a step-by-step technique for solving problems. The criteria that are gathered and developed into a problem description determine each engineering process. The problem description can be viewed as an input for a problem-solving stage that leads to the subsequent engineering phase in the lifecycle. In the creation of machines and manufacturing systems, engineers from several fields work together to solve specific issues. As a visual representation, the digital twin facilitates collaboration across multiple domains. Another benefit of the digital twin is that the majority of problem-solving and optimization may be automated. Earlier stages allow for the execution of actions. The authors have suggested that an optimized and secure environment like the Azure cloud service can be used to develop this technology. Although the authors have not discussed any negative aspects of digital twins.

(Wang & Wang, 2019) have proposed that digital twins can be very vital when it comes to tracking raw materials in WEEE manufacturing and recycling the authors have suggested that creating an RFID tag or a QR code for each product can help in tracking all the materials from raw material collection to production, the authors have also suggested that digital twins can be a bridge to the physical world to the cyber world all the information collected from the physical world can be stored in the cyber world and the corresponding data can be used to optimize the manufacturing. (Rüßmann et al., 2015) have suggested that the development of industry 4.0 can revolutionise automobile manufacturing, and the insights provided by the digital twins can be drastically optimised in car design manufacturing. Digital twins were also put in use in manufacturing industries for product lifecycle management (PLM) this was achieved by connecting different digital twins with a connection string to monitor PLM (Boschert & Rosen, 2016).

To recap, The industrial industries require significant development, and industry 4.0 can be utilised in a variety of contexts. In our scenario, a digital twin will be utilised for a recycling plant and its supply chain components. We do not yet have a record of the plastics entering and leaving the recycling sector. Using digital twins, this may be closely supervised. Continuous monitoring of the recycling equipment can be utilised to predict servicing and repair. Despite the fact that there are numerous benefits to using digital twins, the aforementioned authors have also emphasised the challenges of applying them in the real world. The necessity for a massive storage unit to keep all the data collected from digital twins is one of the primary limitations. Numerous stakeholders must be considered, hence a conventional digital twin typically consists of a single processing system per stakeholder. However Digital twins must be shared among numerous application systems engaging multiple stakeholders in the recycling sector. This can be addressed by developing a domain-specific system architecture and a standardised data model in order to create a digital twin environment for recycling plants. Digitalization and security might be crucial in the manufacturing industry. Even if digital copies can be created, we must protect the data from hackers and rivals. This issue can be resolved by incorporating blockchain technology into our digital twin concept, which takes us to the following section of the literature review.

2) Blockchain literature review

Blockchain technology was proposed in the year 2008 by a group of researchers whose intention is to create a secure online transaction. This was achieved by creating a decentralized system which enables peer-to-peer transactions intern eliminates the third-party transaction fee. Security was ensured by connecting long chains of blocks containing the information of the transactions. The longest chain serves as proof of the sequence of events witnessed which makes it extremely difficult for the hackers to outpace (Nakamoto, 2017). Blockchain technology overcomes regulatory and technical issues by integrating smart contracts technology which is capable of being self-verifying, self-executing and tamper-resistant. The authors suggest blockchain technology can perform real-time tasks at a very minimal cost and provide a great degree of security (Mohanta et al., 2018).

Although the concept of blockchain and smart contracts are majorly used in the field of cryptocurrency, there have been several studies connecting blockchain technology to manufacturing and supply chains. A paper published (Francisco, 2018) suggests that there is minimal transparency through the supply chain and the goods are passed from one actor to another they are subjected to theft and counterfeiting. The goods can be protected by creating digital tokens for each physical item the item's end recipient can then authenticate the token, which can trace the item's history to its point of origin. Since no entity or collection of entities may arbitrarily alter the information contained within the blockchain, end users have increased confidence in the information they receive. At this point, there is research on how blockchain technology can re-engineer plastic recycling, one such article published by researchers in tailbone point out that the primary issue which arises from a recycling plant is a lack of optimization in the supply chain management. The authors have also stated that manual segregation is outdated and AI and blockchain help increase efficiency and accuracy in the segregation process (Verma et al., 2022). Another paper published in Taiwan points out four major issues in the terdiurnal supply chain namely traceability and transparency, stakeholder participation and collaboration, supply chain integration and digitalization, and shared frameworks on blockchain-based platforms are essential for the future. Traditional supply chain operations involve a multitude of intermediates, issues of trust, and performance concerns. Utilizing blockchain's ability to disrupt supply chain processes for improved performance, and distributed governance (Chang & Chen, 2020).

3) Plastic and circular economy literature review

A paper published by researchers from the University of Hannover states that mechanical recycling requires little to less energy to recycle plastic and claims mechanical recycling is the most well-developed recycling approach in terms of industrial feasibility. The authors also point out the importance of separating high-impact polystyrene (rHIPS) and low-density polystyrene (rLHIPS) which leads to grinding the plastic multiple times (Shamsuyeva & Endres, 2021). Another study taken place in Australia show the amount of plastic consumed and the authors have also discussed the various methods to improve plastic recycling plants. The authors agree with (Shamsuyeva & Endres, 2021) that mechanical recycling is a viable method to go ahead with recycling. The authors also agree that the separation of polystyrene is important to create a circular economy (Hossain et al., 2022).

All the aforementioned authors agree that a digital twin can serve as a bridge between the real and cyber worlds. This technology can be utilised in industries where physical machines can be monitored at the push of a button. Despite the fact that blockchain technology has been demonstrated to be secure, it may be used to develop smart contracts that can generate incentives for plastic collectors. Blockchain technology can be utilised to safeguard data from tampering. The authors have also stated that blockchain technology can be utilised to track and trace products from sourcing to manufacture to the final consumer. This is precisely what we intend to accomplish with this project.

IV. Research Methodology

This project has made use of several research databases. These include online publications, google scholar, articles, and YouTube. The PW data on plastic consumption and recovery were mainly taken from government reports published by the Australian Government. The author has used keywords such as “Plastic recycling”, “ digital twins and plastic recycling” AND ” circular economy” which were utilised to retrieve information from websites like IEEE and google scholar.

4.1 Choosing a Cloud service provider

Settling on a cloud service provider is vital in developing a project like this. Although there are copious numbers of service providers we were looking for a service provider with clear and concise documentation of their services, video tutorial, accessibility, and transparency. We are also looking to get the best service on a low budget. We trickled down to two providers IBM and Azure cloud. We finally landed on Azure cloud services because they offer up to 200$ for students.

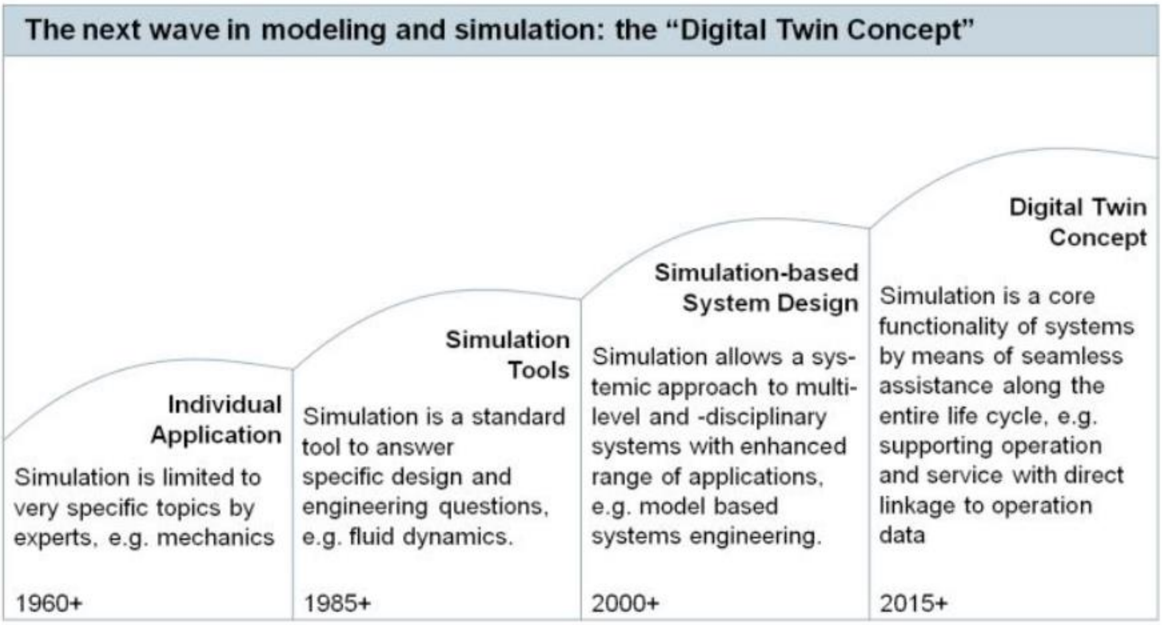
With that said Azure allows open modelling languages which are used to create customised domain models of any connected environment. They also provide a live execution environment to bring your digital twins to live in a live graph representation. Input from IoT and business systems to connect assets, including IoT devices, using Azure IoT Hub, Logic Apps, and REST APIs, Output twin change events to Azure Data Explorer, Azure Synapse Analytics, Event Hubs and other downstream services (“Digital Twins – Modelling and Simulations | Microsoft Azure)

4.2 Digital twins for plastic recycling

The "digital twin" technique is the newest development in modelling, simulation, and optimization technologies from the perspective of simulation (see Figure). Over the past few decades, simulation has transformed from a technology that was exclusively available to computer and mathematical experts to a routine tool that engineers use daily to address specific design and engineering challenges. Today, simulation serves as the foundation for design choices as well as component and system validation and testing. The fundamental idea of model-based systems engineering (MBSE), a new development in the field of systems engineering, is "communication by simulation (Rosen et al., 2015)." However, simulation is still mostly viewed as a tool for R&D departments. The next important thing in simulation is to extend the simulation to later life cycle phases as a key product or system functionality.

Figure 2

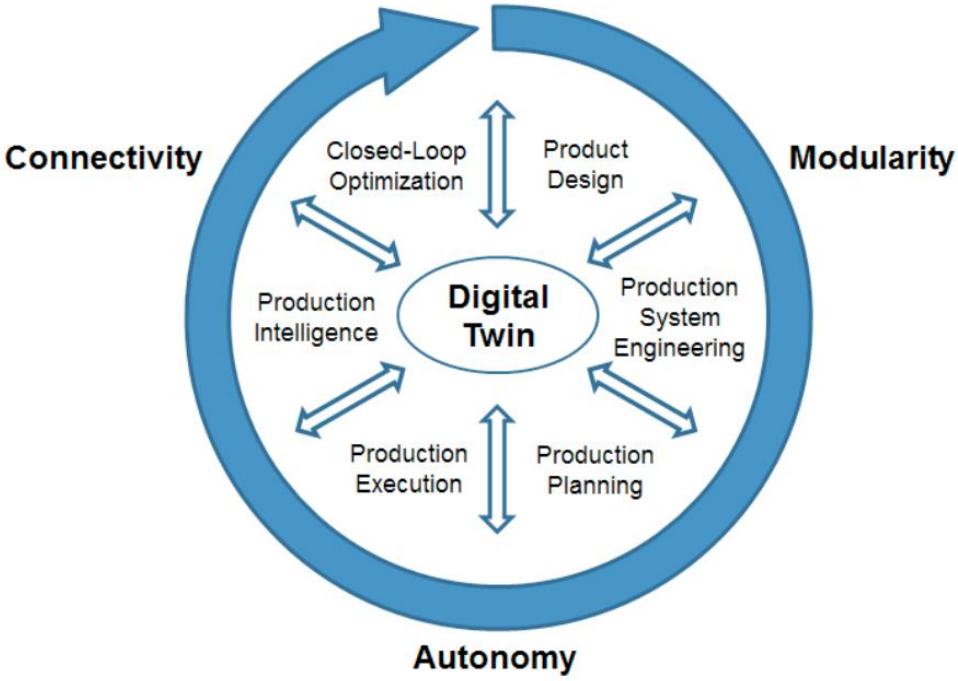
Digital Twins – the next generation for simulation (Rosen et al., 2015)



With such developments in simulation technology product life cycle monitoring can be achieved (figure) depicts the notion of digital twins in a life cycle of a product is to get seamless access to data that is generated in every stage of production.

Figure 3

The notion of Digital Twin in product lifecycle (Rosen et al., 2015)



As the research suggests digital twins can be utilised to monitor stages of recycling from BOL to EOL which answers our second research question. In addition to answering our second research question, we cloud also monitor and log information from all the equipment that comprises the recycling plant. But Doig this is extremely difficult since the make and manufacture are very different which makes connecting all the device data can be very difficult. To tackle this we utilise a Digital twin environment where all the equipment's data are collected in one place and relationships are created between the equipment. Now That all the devices are put in a single location it is very easy to access the data of all the equipment in a single environment. W

To successfully implement digital twins technology in a recycling plant it is vital to have some domain knowledge. In this project, we have focused on building Digital for recycling. The recycling stages were broken down to create digital models for each type of equipment. The required telemetry data were assigned to the twin models see (table). Taking such telemetry values as inputs can mimic the physical equipment. DTDL documentation from Microsoft (Baanders DTDL models - azure digital twins) was used to develop the below twin models

Table 2

Digital twin uses and telemetry values

Digital Twin Model	Recorded Parameters	Description
Collection Point	Distance from the facility, capacity, current capacity, location	This is where the plastics are collected before they get to be recycled. This is the starting point of the supply chain
Transportation	capacity, longitude, latitude, fuel capacity, load,	How the plastics get from the collection point to the facility, or from the packaging unit to the storage
Recycling Facility	Location	This is where recycling takes place. It holds the equipment and personnel required for the recycling process
Sorter	speed, temperature	This machine sorts the plastics into different types as required. It also sorts out undesirable waste

Trommels sorter	Rotating speed, temperature, vibration	Trommels are used to separate materials, mainly in the mineral and solid-waste processing industries ("Trommel screen - Wikipedia")
Eddy current sorter	Eddy current, magnetic field, temperature	"The Eddy Current Separator is used widely in the recycling industry to either recover or remove non-ferrous metals from non-metallic materials." ("Eddy Current Systems | Bunting - Redditch")
Ballistic sorter	Speed, temperature, vibration	Ballistic Separators are used in sorting plants that process DMR, commercial waste, containers, solid waste, or for fuel preparation.
Magnetic sorter	Magnetic strength	Recyclable metals such as aluminium are easy to identify because they aren't magnetic. Magnets are also used in recycling to collect

		fine metallic particles on the recycling line.
Optic sorter	Vibration, wavelength	"optical sorting machines are used to discard plastics, glass, wood, and other non-needed metals." (“Optical sorting - Wikipedia”)
Sink flow	Temperature, water level	By removing the heaviest minerals as a sink product and adding adequate diluting media, such as carbon tetrachloride to acetylene tetrabromide, the necessary lower gravity can be achieved. This will permit the subsequent heavier minerals to settle as a sink product.
OCC Sorter	Rotating speed, temperature, vibration	A screen perfectly suited for the separation of large cardboard from the material flow.

Washer	temperature	This machine is responsible for cleaning the plastics
Friction washer	Kinetic energy, pressure	A friction washer or friction separator is a water high-speed cleaning machine for mixed plastics with high contamination or persistent dirt ("What is friction in the laundry? – Short-Fact")
Rotary washer	Temperature	Used to wash away any excess lead particles in the plastics
Shredder	Blade speed, electricity consumption, Batch code, shredding count	Responsible for shredding the plastics into flakes for melting
Extruder	temperature	Responsible for melting and forming (extruding) the recycled plastic into pellets
Conveyor	speed	This is used to transport the plastics between machines
Packaging Point	amount of recycled plastic (either in	The recycled plastics pellets are collected and packaged here

	tonnes or in number of packages)	
Storage Point	available plastic	Storage

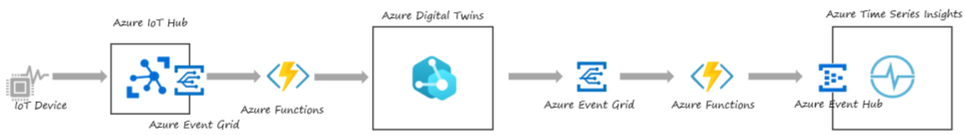
4.3 Data creation and Storage

Without the data the digital twins would be meaningless since we weren't able to get our hands on the real data produced from a recycling plant, we decided to simulate data that replicated the data which are produced from the real equipment. with the simulated date, we will be able to give life to the DTs. The data was randomly generated by going through documentation from Microsoft (Azure-Samples) and documents provided by C# programing language.

The simulated data needs to be stored so that we could use the data in the future. Azure provides storage accounts and blob storage which can hold our data based on the rate of data generation.

Figure 4

Simple Digital twin architecture (Azure-Samples)



The above architecture represents a basic structure to build an effective digital twin. We will need an IoT hub to store all the IoT devices which in our case the simulated client. We use the azure function app to inject the simulated data into the digital twins. The event grid triggers the events and changes that take place while generating data and we will visually see our twin models in our digital twin environment. Since we have created twins, we cloud use that data to provide time series insights by connecting DTs to an even gid and a function app to send data from the devices to the event hub. The time series environment uses the even hub data to show insights into the twin models.

4.4 Machine Learning

Machine learning is worldly used method of supervised learning and unsupervised learning for regression and classification (Holman et al., 2014). Supervised learning construes a hypothesis function $\mathrm{h}(x)$ based on the training dataset. The training dataset consists of N number of vectors which consist of an input vector $X = \{x_1,\ldots.. x_n\}$ and the corresponding target vector $Y = \{y, \ldots., y\}$ to generate input and 1n output pairs $\{(x_i\, y_i)$, $i = 1 \ldots N\}$ the supervised learning model uses the training data to learn which intern builds an approximate model h. to evaluate the model h we use the testing data which was not given to building the model to test the model and estimate predictions, $\hat{y}(x)$ which are then compared with the ground truth (i.e., actual data). There are several statistical methods to validate the predicted outputs in the case of regression, RMSE, R squared error and MSE that can be used to determine the efficiency of the model h (Holman et al., 2014). We focus on two machine learning algorithms which we think will be suitable to get good predictions.

4.4.1Decision Tree

Decision tree algorithms are one of the most popular algorithms for supervised learning. Decision trees can be used for both regression and classification. ("A Dive Into Decision Trees - Towards Data Science")

It is a model that uses a certain set of rules to classify something. The decision tree is very useful in binary classification and regression to run a decision tree we will need to understand the impurities in the dataset this can be achieved by two main methods first by calculating Entropy. Entropy can be defined as the amount of information required to precisely characterise a sample. If the sample is homogeneous, meaning all the elements are alike, then the entropy is zero, however, if the sample is evenly distributed, the entropy is at its maximum of one. The formula for calculating entropy is represented by

$$Entropy = -\sum_{i=1}^{n} Pi * log(p_i) \tag{1}$$

Another method to calculate impurities is the Gini index. The Gini index is a measure of sample inequality. Its value ranges from 0 to 1. A Gini score of 0 indicates that the sample is homogeneous and all items are similar, whereas a Gini index of 1 indicates the greatest inequality between elements. It is the sum of the squares of each class's probabilities (MLMath.io, 2019). The formula for determining the Gini index can be represented as follows

$$Gini\ Index = 1 - \sum_{i=1}^{n} P_i^2 \tag{2}$$

The impurity measures the homogeneity of the data. If the sample is homogeneous then the sample is from the same class. The decision tree algorithm is a tree where the nodes represent a feature and the branch represents a decision and the leaf nodes represent outcomes. Usually, the decision tree decision is based on yes/no conditions.

4.4.2 Gaussian processes

Regarding gaussian regression, the posterior predictive distribution must be considered. A posterior predictive distribution can typically be stated as

$$P(y|x\ D) = \int_h P(y|x\ , h)\ P(h|D)dw \tag{3}$$

Where y is the label for the given data, which we do not yet know for the test point x, and x is the given data for the test point. The probability of label y given x is depicted in equation (3). Using Bayes' rule, we may modify the same equation, marginalise it, and assign it a prior.

$$\frac{P(D|h) *\ p(h)}{Z} \tag{4}$$

If we take the prior P(h), which is gaussian on its own, and multiply it by the P(D|h), which is also gaussian, the marginalized distribution will be Gaussian. Multiplying equations (3) and (4) produces the resulting Gaussian distribution, P(y|x D) (4). ("Gaussian Process", 2022)

With that said formula for the gaussian processes can be represented as the probability of label y given data point x with the respective the dataset

$$P(y|x, D) \sim \mathcal{N}(\mu, k) \tag{5}$$

In the preceding equation (5), mu is the mean of the dataset and k is the covariant function; by determining the mean and the covariant matrix, we can get the predictions and gaussian distribution of all the data points. This takes us to the most crucial stage in performing Gaussian processes: calculating the covariant matrix.

If we consider covariates metrics for one training point and one test point

$$p\left(\begin{bmatrix} y_1 \\ y \\ y_n \end{bmatrix} \begin{bmatrix} x_1 & x & x_2 \end{bmatrix}\right) \sim \mathrm{N}(\mu, k)$$

(6)

where K can look something like this

$$\mathrm{K} = \Sigma = \begin{bmatrix} \delta_1^2 & 3 \\ 3 & \delta_2^2 \end{bmatrix}$$

The δ delta diagonal depicts the variations, whereas the opposite diagonals represent the correlation between two data points. Positive values indicate a high correlation between the two data points in the preceding example. If the diagonals of a Gaussian are 0, it indicates that the data points do not influence one another.

When building a covariant Metrix for a dataset the general form of the matrix can be represented as

$$\sum \begin{bmatrix} K & K_* \\ K_*^T & K_{**} \end{bmatrix}$$

(8 **)**

Where the K represents the training dataK_*^T is the test points and K** Is the variants of the test points and k* represents the variation of the training data.

Based on the above information on determining the mean of the dataset and the covariance matrix we can come up with predictions. The formula for producing predictions can be written as

$$P(y)(y_1 \ldots . y_n \,,\; x_1 \ldots . x_n) \sim \mathrm{N}(k_*^T\, k_y^{-1}, k_{**} \;-\; k^{-1} k_y) \tag{3}$$

Therefore for predictions, we can use the posterior mean and then use the predictive variants for measuring the confidence intervals ("Gaussian Process", 2022).

V. Requirements

To successfully implement this project there is some prerequisite base on the hardware. It is recommended to use Linux or windows to execute the project because of fewer restrictions. If new apple silicon is used to build this project, there are some difficulties and errors which are briefly discussed in this implementation section.

Azure Subscription – first and foremost we will need to create an azure cloud account in order to get access to their services. For students, azure provides 200$ for one full month.

Admin Access to Azure AD Tenant & Azure Subscription

Mac OS: PowerShell for Mac - PowerShell is a cross-platform task automation system comprised of a command-line shell, a scripting language, and a framework for configuration management. ("PowerShell 7.3 on Windows Server 2022 with support by AskforCloud LLC") PowerShell is compatible with Windows, Linux, and macOS. We used homebrew to install a power shell on Mac because homebrew is the preferred package manager for macOS.

Windows OS: PowerShell for Windows – it is built-in for windows, therefore, windows users don't have to worry about installing a power shell instead they could open the terminal and type "pwsh" to open PowerShell. Do not recommend using the Azure Cloud Shell as it will timeout due to the length of the lab.

.NET Core 3.1 – .NET is a free, cross-platform, open-source platform that allows developers to create a variety of applications. With .NET, you can create applications for the web, mobile, desktop, gaming, IoT, and other platforms using a variety of programming languages, editors, and libraries.
.NET applications can be written in C#, F#, or Visual Basic.

• C# is a straightforward, contemporary, object-oriented, type-safe programming language(What is .net? an open-source developer platform.).

• .NET programmes share a uniform set of basic class libraries and application programming interfaces (APIs).

• Each app model may expose extra APIs that are unique to the operating systems it supports or the features it offers. ASP.NET, for instance, is a cross-platform web framework that offers additional APIs for developing online applications that operate on Linux or Windows.

• To expand capabilities, Microsoft and others maintain a healthy.NET package ecosystem.

Our function apps will be built with(What is .net? an open-source developer platform.).Net and the necessary NuGet packages will be covered in the implementation section. We will be using C# to write our functions.

Visual Studio Code – Visual studio code or vs code is a source code editor, it is necessary to download VS code and connect it with Azure cloud by signing in with the Azure account. VS code will be used to edit function apps and publish the function to the Digital twin environment. We highly recommend using Visual Studio to publish functions since most require packages are pre-installed.

C# VS Code extension – C# extensions will be discussed in detail in the implementation section.

Node.js – Node js will be required to produce event-driven programming to web servers, allowing for the creation of quick web servers. We will run our JavaScript file on node js to send simulated client data.

NOTE: The above-mentioned are prerequisites before creating twins all the above-mentioned should be installed with their stable versions if not the programs won't run and will require to downgrade.

In the next section of the report, we will be focusing on the design and implementation of the digital twins, and we check if we can answer our research questions.

VI. Implementation

In this section of the report, we will go through the step-by-step process of implementing digital twins. We will go through creating the models, uploading the models, assigning relationships, assigning telemetry values, uploading models to the Azure DT environment, creating simulated clients, injecting telemetry values and finally connecting DTs to the Time series environment. To develop this project Apple M1 MacBook Pro with 8 gab ram was used.

7.1 Creating an Azure account

This project was entirely developed in the azure cloud environment since they provide good documentation and azure also provides sub-services which will be very useful in developing the project. If not, azure cloud services we cloud have worked on IBM cloud services. But developing digital from scratch without 3rd party will require a lot of time and will be out of the scope of the project.

We start by creating a Microsoft azure account by going to the website. after creating an account, we can log in from our local machine by going to the power shell terminal and typing the code.

```
az login
```

7.2 Creating a digital twin environment

After entering Microsoft azure choose to **create a resource -> search for digital twins -> create digital twins**

The next step in creating DT environments is to give a name to your resource group. It is important to have all the resources we create for DTs under the same subscription finally choose a region and click **Review +create** on the bottom left. Now the azure DT instance will be up and running.

7.2.1 Assigning Data owner

In order to access and manage DTs and their data we need to assign a data owner in this instance it is ourselves to do so go to the digital twin instance on the left-hand side click **Access control (IAM) -> Add -> Add role assignment -> set the role to Azure digital twin owner and select your Microsoft account which you normally -> Save**

Note: To work with an azure digital twin, we will be using Microsoft API/SDK

However, Microsoft has created a simple node.js client app which is called Azure digital twin explorer which allows us to use its graphical interface to interact with the DTs and to do things like uploading and creating models, creating relationships, running queries, and visualizing twin graphs.

7.2 Creating Twin models

To create twin models, we will need to go through Microsoft digital twin definition language (DTDL)documentation (DTDL models - azure digital twins). There are a few problems while developing twin models. sample code for a single model is shown in Appendix -A. In developing the model we need to be sure if these things are right first being **@id** should always be unique second the **@type** should be set to **interface in**

the beginning and **@context** should always be set as **"dtmi: did:context;2". The display name** can be changed based on our requirements. The **contents** will have all the telemetry parameters we are defining for each model and always set @**type** to **"property"** inside the contents for telemetry values**.** To build relationships when can either define it in the JSON file or do it manually on the azure DTs environment.

Some errors encounter in this phase were typo errors, and setting the same id (if the models have the same Id they won't upload to the DT environment). Always capital P for property and capital R for relationship.

7.3 Uploading Twin models

After creating the model for all the equipment in our case the equipment inside the recycling plant we can now upload it to the Digital twin environment. There are a few steps to follow in order to do so, first and foremost we need to enter into the digital twin environment and **go to the azure main page to search for azure digital twin which was created -> open azure digital twin explorer.** Azure should automatically identify your account subscription if not copy the **hostname from the DT instance go inside the digital twin explorer -> and paste the hostname if and only if asked.**

Now that we have set up our environment and created our twin models it's time to upload our models click the **upload icon on the left-hand side -> choose all the models -> select open**. This uploads all the models inside the DT environment. See Appendix -B

7.4 Creating Relationships

This is one of the easy ways to create relationships in a DT environment. **Go to the DT environment and choose any two models in which you would want to create a relationship -> right chick -> add Relationship -> save.** After defining relationships the final output should be similar to see Appendix- B

7.5 Setting up IoT Hub

An IoT hub will hold all our devices. Go to the Azure portal click **Create a resource -> search IoT Hub and press create -> define the same resource group which was provided for the digital twin -> select region -> Name The IoT hub -> select review and create -> create a go-to resource.**

Now that we have successfully created IoT also need to create devices for our IoT hub which should correlate with the twin models which we have created. On the left-hand side **click IoT devices -> device Id should be the same name as our digital twin -> Save**

This needs to be done for all the models created for our digital twin. After the creation of our devices, we can use the primary connection string to send data to the cloud see Appendix – C

7.6 Setting up function app and storage account

The function app is used to give instructions to the cloud locally and the storage account will store our simulated data. In order to create a function app **go To Visual studio (preferred) -> sign into the Microsoft account -> click create new project -> search for azure functions-> select -> next -> name the function app -> create -> choose event trigger.**

Now for the function to interact with the azure digital twins we need to use azure digital twin SDK to do that we include some NuGet packages **Right click on the project -> Manage NuGet packages -> search for azure.digitaltwin.core, Azure.Identity, system.Net.Http, Azure.core , Microsoft.Azure.WebJobs -> install.**

Go to the function app.cs and replace the existing code with the code given In Appendix -D

After replacing the code **save -> right click on the project -> click Publish -> choose Azure -> choose Azure Function App(windows) -> click the "+" to create a new function -> make sure the correct subscription is selected -> make sure the correct resource group is set -> finish -> click Publish**

We can go to the cloud and check if our function app is running. **Microsoft Azure portal -> search for the function app created by name -> function on the left-hand side-> click ->** we should see our function app

Another way to check errors in the function is by going to **Log steam** on the function app in the digital twin portal. We can see if we have errors in our code. See Appendix- E

Note: IoT hub configuration may vary based on the requirements for this project we have chosen the base configuration.

7.7 Creating simulated clients device

For every device created we will simulate telemetry values by using connection string code for one simulated device is shown in Appendix -F

Figure 5

Code for the simulated device

```
const deviceConnectionString = "HostName=plastic-iot-hub.azure-devices.net;DeviceId=OCC_Sorte
let sendInterval;
```

The device connection string should be replaced with the devices created in the IoT hub. Copy the primary key from the device and paste it into the simulated device .js file. This will create a connection between the local and the cloud

Now to run the simulated device. Js file now needs to open the terminal In Visual Studio and type

```
Node ./Sensor.js
```

At this point, the sensor file will start to send telemetry values to the azure digital twin and the values will be visible in the digital twin environment see Appendix - G

Some errors faced in this phase of the project are: the telemetry values were not visible though we have done everything correctly. The solution for this problem is we need to save the twin models in the DT environment and press run quarry see Appendix- H

7.7 Time series insights

To connect the digital twin environment to the TSI environment we will need another function app and we also need to create an event route. As previously discussed create a function app on visual code and define the ATD endpoint and set the event route creating the function app replace the code with the code shown in Appendix - I

7.8 Machine learning

To run machine learning with the data produced from digital twin we need to get access to the Azure blob storage where our data is stored. **Create a new resource -> Machine learning lab -> Create new ML workspace mention the resource group -> Review + create** To perform Machine learning we need to set some parameters if it regression we need to mention the test size or the validation split, also select the dependent and the independent variables to perform regression. Finally, we need to choose a consumer for us to run a machine learning algorithm we used 3 cores and 7 GB ram but this comes with a certain cost. Microsoft also provides various consumers with GPUs. See the results section for regression outputs.

With the successful implementation of the digital twin system, we also intend to find the cost estimate to deploy this system in a recycling plant which brings us to the next section of the report.

VII. Pricing Estimate

In this section of the report, we intend to calculate a tentative cost for implementing digital twins for a plastic recycling plant. We have provided a clear explanation of the below tables. We have also divided the manufacturing unit into small, medium, and large-scale industries. This estimate was made for recycling plants in Australia due to the availability of data however this estimate can also be used for other countries for references.

8.1 Small-scale Recycling plant

A small-scale recycling plant in this case can be defined as a recycling plant with an output capacity of 2500 tons/year Since this is a small-scale plant there might be some missing equipment and some might not be required, with that in mind, we have estimated a base price for digital twin for a recycling plant.

Note: we have calculated everything in dollars ($) since it is universal

Table 3

Cost estimation for – Small scale industries

Microsoft Azure Estimate					
Service category	**Service type**	**Region**	**Description**	**Estimated monthly cost**	**Estimated upfront cost**
Internet of Things	Azure Digital Twins	UK South	1 Million messages, 1 Million operation, 1 Query unit	$5.00	$0.00
Storage	Storage Accounts	Australia Central	Block Blob Storage, General Purpose V2, LRS Redundancy, Hot Access Tier, 1,000 GB Capacity - Pay	$21.15	$0.00

			as you go, 10 x 10,000 Write operations, 10 x 10,000 List and Create Container Operations, 10 x 10,000 Read operations, 100,000 Archive High Priority Read, 1 x 10,000 Other operations. 1,000 GB Data Retrieval, 1,000 GB Archive High Priority Retrieval, 1,000 GB Data Write		
Compute	Azure Functions	West US	Consumption tier, Pay as you go, 128 MB memory, 100 milliseconds execution time, 10,000,000 executions/mo	$1.80	$0.00
Internet of Things	Azure IoT Hub	East US	Standard Tier, Free: 500 devices, 8,000 msgs/day, $0.00/mo, 1 IoT Hub Unit; IoT Hub Device Update: Free Tier, 1 Instance, 10 Devices	$0.00	$0.00
Internet of Things	Azure Time Series Insights	West US	S1 tier: 1 unit(s)	$150.00	$0.00
Internet of Things	Event Grid	West US 2	1,000,000 operations per month	$0.54	$0.00
Compute	Azure Functions	West US	Consumption tier, Pay as you go, 128 MB	$1.80	$0.00

			memory, 100 milliseconds execution time, 10,000,000 executions/mo		
Analytics	Azure Machine Learning	East US 2	1 D2 (2 Core(s), 7 GB RAM) x 149 Hours, Pay as you go	$19.97	$0.00
Analytics	Event Hubs	East US	Basic tier: 1 Throughput unit(s) x 150 Hours, 0 million Ingress events	$2.25	$0.00
Support		Support	0	$0.00	
		Total	$202.499379	$0.00	

The region mentioned in the table can be changed based on the nearest server to the country. This will change the cost estimate based on the location. The messages mentioned in the above table mean that every time the device sends a message to twin models it will be counted. The quarry operation is counted every time we write a quarry in the twin environment for retrieval of information. Since it's a small scale we have set the base option for 1 million messages and 1 million quarry operations. As for the storage we have also selected the base option since we want to be monitoring a lot of devices, therefore, fewer messages and less storage are required. The function app plays a major role in updating the twins since we have fewer devices, we will be needing at least 128 MB of memory which is the base memory offered by azure.

IoT Hub serves as a location where we can have all the devices in one location azure allows up to 500 devices in their base pack, in our case, we won't be needing 500 devices, but we will be needing a lot of messages a day. Our IoT hub allows 4000 messages per day which are good for a small-scale plant.

Azure Time series Environment is used to give insights into the connected devices it will give us insights of devices. Azure Machine learning is where we can run our machine learning models, we have chosen the base model with 2 codes and 7GB of ram.

8.2 Medium scale

A medium-scale recycling plant can be defined as a plant with an output capacity of 8000 to 15000 tons/ year. With that in mind, we figured out a mid-scale plant will have a few more pieces of equipment compared to a small scale, therefore, we have increased the configuration based on the requirements see (Table 4)

Table 4

Cost estimation for – Medium scale industries

Microsoft Azure Estimate					
Service category	**Service type**	**Region**	**Description**	**Estimated monthly cost**	**Estimated upfront cost**
Internet of Things	Azure Digital Twins	UK South	3 Million messages, 3 Million operations, 1 Query unit	$13.74	$0.00
Storage	Storage Accounts	Australia Central	Block Blob Storage, Blob Storage, LRS Redundancy, Hot Access Tier, 1,000 GB Capacity - Pay as you go, 10 x 10,000 Write operations, 10 x	$21.17	$0.00

			10,000 List and Create Container Operations, 10 x 10,000 Read operations, 100,000 Archive High Priority Read, 5 x 10,000 Other operations. 1,000 GB Data Retrieval, 1,000 GB Archive High Priority Retrieval, 1,000 GB Data Write		
Compute	Azure Functions	West US	Consumption tier, Pay as you go, 256 MB memory, 100 milliseconds execution time, 10,000,000 executions/mo	$1.80	$0.00
Internet of Things	Azure IoT Hub	East US	Standard Tier, S1: Unlimited devices, 400,000 msgs/day, $25.00/mo, 1 IoT Hub Units; IoT Hub Device Update: Free Tier, 1 Instances, 10 Devices	$25.00	$0.00
Internet of Things	Azure Time Series Insights	West US	S1 tier: 1 unit(s)	$150.00	$0.00
Internet of Things	Event Grid	West US 2	1,000,000 operations per month	$0.54	$0.00

Compute	Azure Functions	West US	Consumption tier, Pay as you go, 256 MB memory, 100 milliseconds execution time, 10,000,000 executions/mo	$1.80	$0.00
Analytics	Azure Machine Learning	East US 2	1 NC4as T4 v3 (4 Core(s), 28 GB RAM) x 149 Hours, Pay as you go	$78.37	$0.00
Analytics	Event Hubs	East US	Basic tier: 1 Throughput unit(s) x 150 Hours, 1 million Ingress events	$2.28	$0.00
Support		Support	0	$0.00	
		Total	$294.692979	$0.00	

We have increased the number of messages the twins will be receiving and increased the number of quarry operations as well. We have set the same storage as the small scale because we think it will be more than sufficient. It is also vital to understand that not all devices send messages at the same rate some might be high, and some might be low e.g., a sorter may send messages every two seconds, but a conveyor doesn't need to send messages every two seconds. We have also increased the memory of our function app to 256MB since we are dealing with a good number of devices. In the case of the IoT Hub, we have changed the base plan to a plan which allows having unlimited devices and 800000 messages per day which we think will be sufficient.

8.3 Large scale

We consider any plastic recycling plant that has an output capacity of more than 15000 – 70000 tons is considered as large scale. In a large-scale plant, we will have more equipment therefore a huge amount of data generation and more querying. Which leads to an increase in our Machine learning configuration and, function app configuration see table

Table 5

Cost estimation for – Large scale industries

Microsoft Azure Estimate					
Service category	**Service type**	**Region**	**Description**	**Estimated monthly cost**	**Estimated upfront cost**
Internet of Things	Azure Digital Twins	UK South	5 Million messages, 5 Million operations, 5 Query units	$24.98	$0.00
Storage	Storage Accounts	Australia Central	Block Blob Storage, Blob Storage, LRS Redundancy, Hot Access Tier, 3 TB Capacity - Pay as you go, 30 x 10,000 Write operations, 10 x 10,000 List and Create Container Operations, 10 x 10,000 Read operations, 100,000 Archive High Priority Read, 5 x 10,000 Other operations. 1,000 GB Data	$63.71	$0.00

			Retrieval, 1,000 GB Archive High Priority Retrieval, 1,000 GB Data Write		
Compute	Azure Functions	West US	Consumption tier, Pay as you go, 512 MB memory, 999 milliseconds execution time, 10,000,000 executions/mo	$75.32	$0.00
Internet of Things	Azure IoT Hub	East US	Standard Tier, S1: Unlimited devices, 400,000 msgs/day, $25.00/mo, 1 IoT Hub Units; IoT Hub Device Update: Free Tier, 1 Instances, 10 Devices	$25.00	$0.00
Internet of Things	Azure Time Series Insights	West US	S1 tier: 1 unit(s)	$150.00	$0.00
Internet of Things	Event Grid	West US 2	1,000,000 operations per month	$0.54	$0.00
Compute	Azure Functions	West US	Consumption tier, Pay as you go, 256 MB memory, 1,000 milliseconds execution time, 10,000,000 executions/mo	$35.40	$0.00
Analytics	Azure Machine Learning	East US 2	1 NC4as T4 v3 (4 Core(s), 28 GB RAM) x	$157.80	$0.00

			300 Hours, Pay as you go		
Analytics	Event Hubs	East US	Basic tier: 1 Throughput unit(s) x 300 Hours, 1 million Ingress events	$4.53	$0.00
Support		Support	0	$0.00	
		Total	$537.268979	$0.00	

We have increased the messages and quarry operation to 5 million. We have also increased the storage to match the amount of data revived from the digital twins. We have included GPU and increased the cores and RAM for machine learning to improve performance.

Note: The above three tables are an estimate of employing digital twins in a recycling plant.

VIII. Results

Table 6

Recycling plants based on states in Australia and their capacity and polymer type (2018-19 Australian Plastics Recycling Survey - National Report – DCCEEW, Shamsuyeva & Endres, 2021, Hossain et al., 2022)

Industry	State	Type of plastic recycled	Main Processing	Specific features	Recycling materials	Processing capacity
Polymer Processors	Victoria	PP, HDPE, LDPE, LLDPE, ABS, HIPS	Not specified	Not specified	Pell Granules	2500
Advanced Circular Polymers	Victoria	PET, PP, HDPE	Not specified	Sorting and shredding/granulation (polymer identification and flake manufacture plant)	Flakes	up to 70,000
Advanced Plastic Recycling	South Australia	HDPE	Mechanical recycling	Extrusion	Granules/ pellets	–
Astron Sustainability	Victoria	PET, PP, HDPE, LDPE, LLDPE	Mechanical recycling	Sorting, shredding/granulation, and pelletising (extrusion, injection	Granules/ pellets	30,000

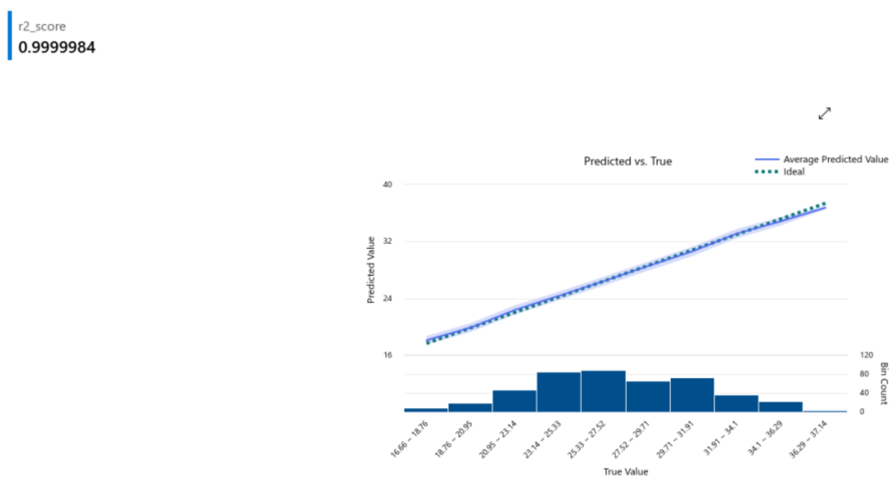
				and washing equipment)		
Australian Recycled Plastics Pty Ltd	NSW	PET, PP, PS, PVC, HDPE, LDPE	Mechanical recycling	Not specified	Flakes	–
CLAW Environmental	Western Australia	PP, HDPE, EPS, PS	Mechanical recycling	Shredding, granulating, washing and pelletising	Granules/ pellets	–
Corex Recycling Pty Ltd	Victoria	HDPE, LDPE, PP and HIPS, ABS, GPPS	Mechanical recycling	Extrusion, filtration systems, contamination detection	Granules/ pellets	–
GT Recycling	Victoria	PP, HDPE	Mechanical recycling	Decontamination and size reduction process	Granules/ pellets	1500 (flexible PP packaging), overall, ≥ 2500
iQRenew Pty Ltd	NSW	PET, HDPE and mixed plastic (residues of PET, HDPE and soft plastics and multilayer packaging)	Mechanical and chemical recycling	Optical sorting and processing for physical recycling and (Cat-HTR™ platform – catalytic hydrothermal reaction	Flakes, fuels, chemicals and new plastics	–
Olima Fibre Processors Pty Ltd	Victoria	PET, PP, PA, PS, PC, HDPE, MDPE, LDPE, ABS, HIPS	Mechanical recycling	Granulation lines	Granules/ pellets	–
Olympic Polymers	Victoria	Post-industrial plastic	Mechanical recycling	Film extrusion, profile extrusion and injection moulding, granulation	Granules/ Pellets	≥2500
Plastic Forests Pty Ltd	NSW	Soft plastics (food industry films, agricultural films, woven PP, post-industrial film)	Not specified	Dry-Cleaning Technology	–	–
Poly Pipe Recyclers	Western Australia	LLDPE	Not specified	Not specified	Granules/ pellets	–
Recyclecare Pty Ltd	NSW	HDPE	Not specified	Not specified	Granules/ pellets, Flakes	–
Repeat Pty Ltd	NSW	PP, HDPE, LDPE	Mechanical recycling	"Injection moulding, blow moulding, film and other extrusion processes, as well as rotational moulding applications	Granules/ pellets	–
Valera Recycling Pty Ltd	NSW	PP, PVC, HDPE, LDPE, LLDPE	Mechanical recycling	Not specified	Flakes	–
JK Plastics Pty Ltd	NSW	PP, PE	Mechanical recycling	–	Flakes	–
Martogg Group of Companies	Victoria	PET, HDPE, LDPE	Mechanical recycling	Sorting, shredding/granulation and pelletising (bottle-to-bottle recycling – 'Vacurema' processing line)	Granules/ pellets	10,000–20,000
Resitech Industries Pty Ltd	Queensland	PP, HDPE, LDPE	Not specified	Not specified	Granules/ pellets shredded	8000
YCA Recycling	South Australia	PET, PP, PA, PS, PC, PVC, HDPE, LDPE, ABS, POM	Not specified	Not specified	Not specified	–
Dunlop Flooring	Victoria	Foam underlay	Not specified	Not specified	Not specified	≥2500
Cryogrind	Victoria	PVC	Not specified	compounding and melt filtration equipment, Cryogenic processing technology (reagent - liquid nitrogen)	Not specified	≥2500
Action Products	Queensland	Not specified	Not specified	Not specified	Not specified	≥2500
Visy Recycling	New South Wales	PET and HDPE	Mechanical recycling	Sorting, shredding/granulation and pelletising and bottle production	Granules/ pellets	101,000
Recycled Plastics Australia	South Australia	Not specified	Mechanical recycling	Sorting, shredding/granulation, and pelletising	Granules/ pellets	40,000
Microfactories™	New South Wales	E-waste plastics	Microrecycling	Sorting, shredding/granulation, pelletising, high-	3D plastic filaments	–

The above table represents various plastic recycling plants with their capacity and type of plastics they recycle, the table gives us a good idea about the type of plastic recycling done. With this information, we will be able to build a digital twin based on the capacity and based on the type of plastic recycling. Some of the information was not found on the internet therefore they are left blank. The above table also addresses our first research question.

To answer the 4th research question, we have performed some machine learning algorithms and the results are shown below check figures (6) and (7)

Figure 6

(A) Decision tree algorithm to predict fuel consumption



(B) Gaussian processes to predict current consumption

The above two diagrams indicate the inconsistency in the data therefore algorithms were not able to learn anything from the given data. This was the result of generating data randomly, since we have generated data in a random fashion for the digital twins the prediction is not accurate. However, sympathizing data which matches the real data will certainly give better predictions.

Overall, the entire system built in this project can be utilized in real recycling or a manufacturing plant. The system is capable of connecting various equipment to a single environment and it does build good connections between the product chain and supply chain. As suggested the prediction outputs can be very well improved when with accurate data.

To answer research question 6 employing digital twins in Australia can be a huge step-up regarding recycling and manufacturing. Since Australia has the best systems for meteoritical monitoring. This technology can be used to make models simulation and improve climate change predictions like forest fires and floods. Another major industry digital twins can be employed in is the iron ore mining industry.

IX. Project Management

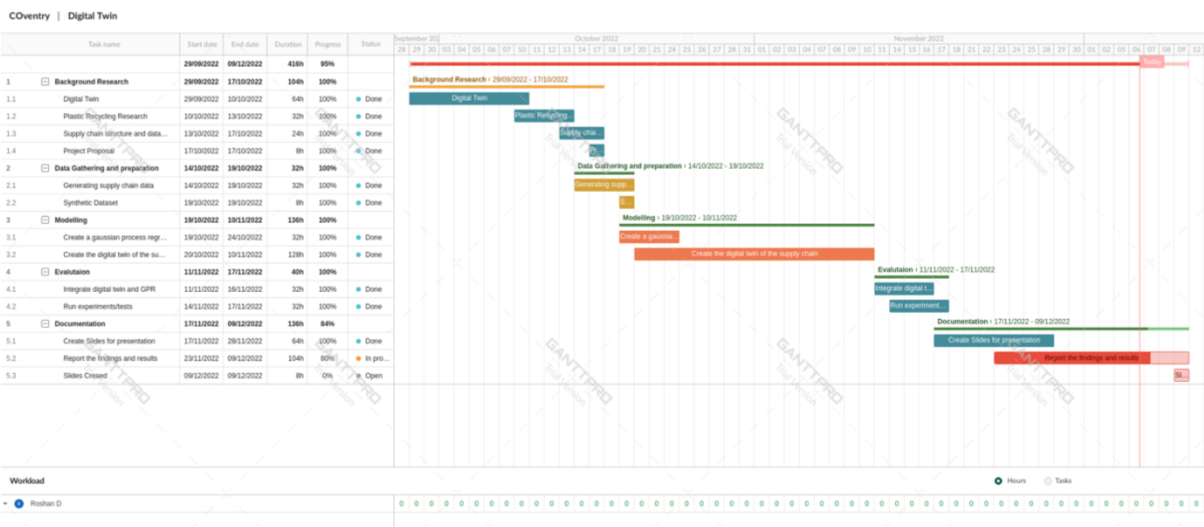
Project management is vital to keep the project on track and ensure successful outcomes. In this section of the report, we will discuss how this project was developed. We also disuses the ethical constraints on developing the project.

10.1 Project Schedule

Project timeline and steps to transparency are key factors to successfully building and project. All the required work is broken down and each work is assigned a date. All the works were performed in the mentioned time see figure () The Gantt was developed using an online tool called GanttPro.

Figure 7

Gantt chart for project Scheduling



10.2 Social Legal Ethical and Professional Consideration

Digital Twins must operate ethically. They offer a chance to transform industries because, if they live up to their potential, they will alter how we interact with, utilize, and benefit from infrastructure and services. However, we must acknowledge that digital twins come with ethical advantages and concerns that, if we do not address them, would limit their ability to help business and society (Guest blog: Ethics, Digital Twins, and the Gemini principles).

Trustworthy digital twins are essential. To do this, they must promote an "ethics by design" methodology that incorporates basic principles of data ethics. Maintaining privacy, particularly when dealing with sensitive information, while promoting a policy of openness to data and insights is one important consideration in this. To hold digital twins responsible for factors like privacy, data minimization, data ethics, and security, a shared strategy is necessary (Guest blog: Ethics, Digital Twins, and the Gemini principles).

In the context of plastic recycling, we can use digital twins but the data, which is generated, and stored must be safe and transparent to all the stakeholders. By developing digital twins for plastic recycling apart from data there are no ethical or legal constraints on conducting these experiments and the dataset used in this in this experiment was synthetically generated therefore no human or animal was harmed while conducting this experiment. On the other hand, creating a digital twin can be very useful in waste management manufacturing and research its benefits outweigh the cons.

X. Discussion

For this project, we have developed digital twins for a recycling plant which is a generic model. Though there are other ways to implement digital twins with services from General Electric, IBM, Bosh, and Cisco Systems. We felt Microsoft documentation and support were better. The twin models created in this project are based on assumptions therefore the telemetry values do not exactly correlate with the real equipment. This was because of the lack of accessibility to real equipment.

When performing machine learning with the randomly generated data it was very difficult to generate data for variables like vibration, rotation speed, flux density, and magnetic field. Although we were able to generate data for simple variables like vehicle id, vehicle type, load, distance travelled, trip length and fuel consumption. Though data was randomly generated there was no correlation between variables which makes the prediction meaningless Therefore predictions for fuel consumption were made but not for calculating energy consumption. But it proves that our system can work in a real scenario.

The cost estimate provided in this report was created based on the implementation of digital twins. We were able to identify the components required for building DTs for the recycling plant. With that said the cost varies based on the size of the recycling plant capacity and the number of devices. On top of building a digital twin, we will need engineers to handle and monitor twins and fix bugs and errors.

In terms of sustainability digital twins can be implemented in several domains like air pollution and MSW management, designing cars, and testing in manufacturing. When compared with the state-of-the-art papers on digital twins our paper fares well as this technology is in its developing stage therefore there are not many states of art implementations. However, siemens have developed digital technology for their plastic tub manufacturing where they have employed DTs for every stage of plastic tub production and the product is optimized with generic algorithms to get the best plastic tub possible with 95 % recycled plastic and 5 % of other materials.

Data storage and data security can be a huge problem with technology. Fishing and cyber hacks can be done to steal data from a certain plant this limitation needs to be addressed in future works.

Given Australia's reliance on food production and gold mining, plastic recycling and metrology all the states can greatly benefit from this Technology. The aforementioned forecast and uncertainty can provide them with an estimate which can assist many manufacturers in recycling.

XI. Conclusion

In conclusion, digital twin technology can be extremely valuable in plastic recycling and aids in the resolution of numerous sustainability concerns, such as industrial cable reels. The technology offers enormous manufacturing, testing, and growing possibilities. Although the technology has many advantages, the cost of deploying it is surprisingly low, making it accessible to industries in various fields. However, generating twins is time-consuming.

XII. Future Works

Using blockchain technology, future work on this project can be accomplished. As previously described, digital twin technology has a security issue since all the data is held in a centralised system. Blockchain technology can aid in the development of a decentralised storage system that is tamper-proof.

Several studies have examined the use of blockchain in tracing and tracking products. This can be achieved by generating tokens for each product. Having tokens for all goods enables us to divide items based on their polymer type, hence resolving the segmentation difficulties. We believed we would find a solution for plastic segregation. Blockchain was outside the scope of our study.

Another excellent component of blockchain technology is smart contracts. Creating smart contracts can motivate individuals to collect plastics and deliver them to the nearest plastic collection site for recycling by providing them with an incentive. This eliminates the need for middlemen, allowing for the automation of the entire process. In addition to plastic recycling, smart contracts can be utilised for regulatory compliance in manufacturing and recycling as a whole.

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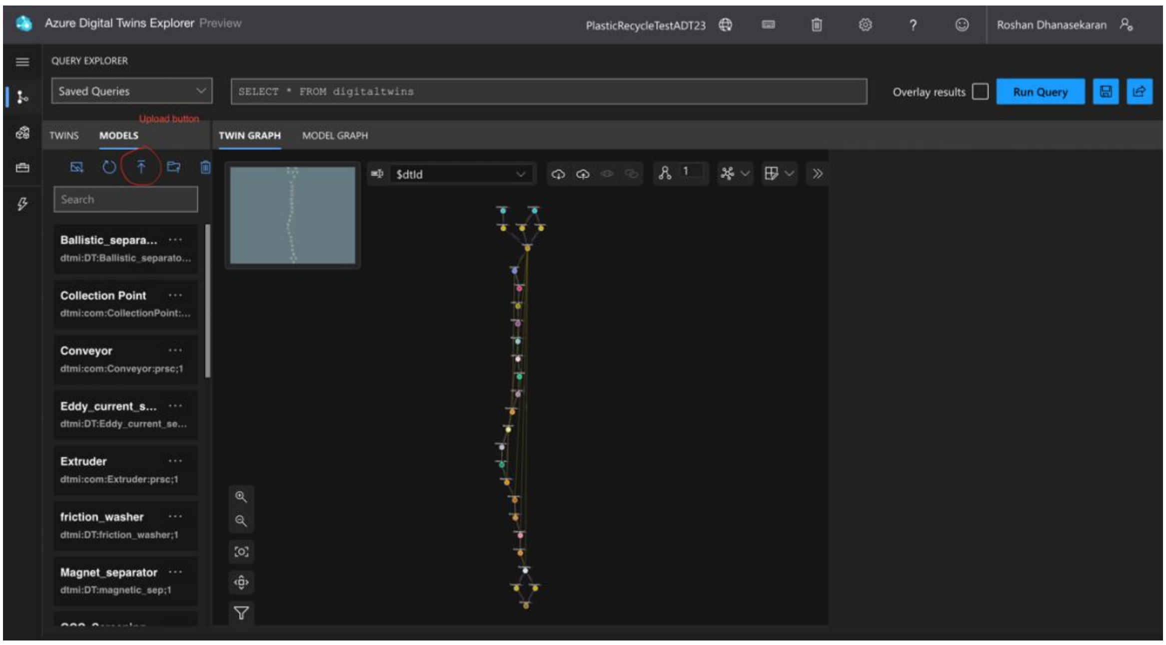
Appendix – A – code for creating a model

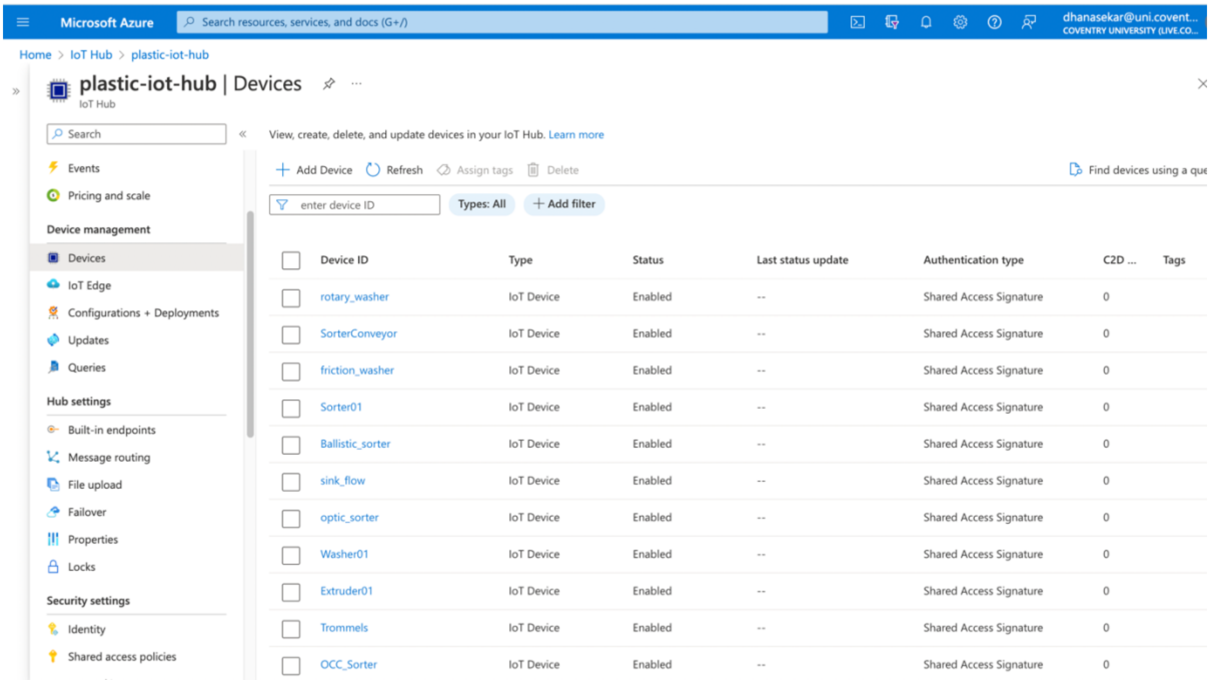
```
{
    "@id":"dtmi:DT:OCC_Screening;1",
    "@type":"Interface",
    "@context": "dtmi:dtdl:context;2",
   "displayName": "OCC_Screening",
    "contents":[
            {
            "@type":"Relationship",
            "name":"contains",
            "displayName":"contains"
            },
```

```
            {
            "@type":"Property",
            "name": "rotating_speed",
            "schema":"double"
            },
            {
            "@type": "Property",
            "name": "temperature",
            "schema" :"double"
            },
            {
            "@type":"Property",
            "name":"vibration",
            "schema":"double"
            },
            {
            "@type":"Property",
            "name":"weight",
            "schema":"double"
            },
            {
            "@type":"Property",
            "name":"humidity",
            "schema":"double"
            }
        ]
    }
```

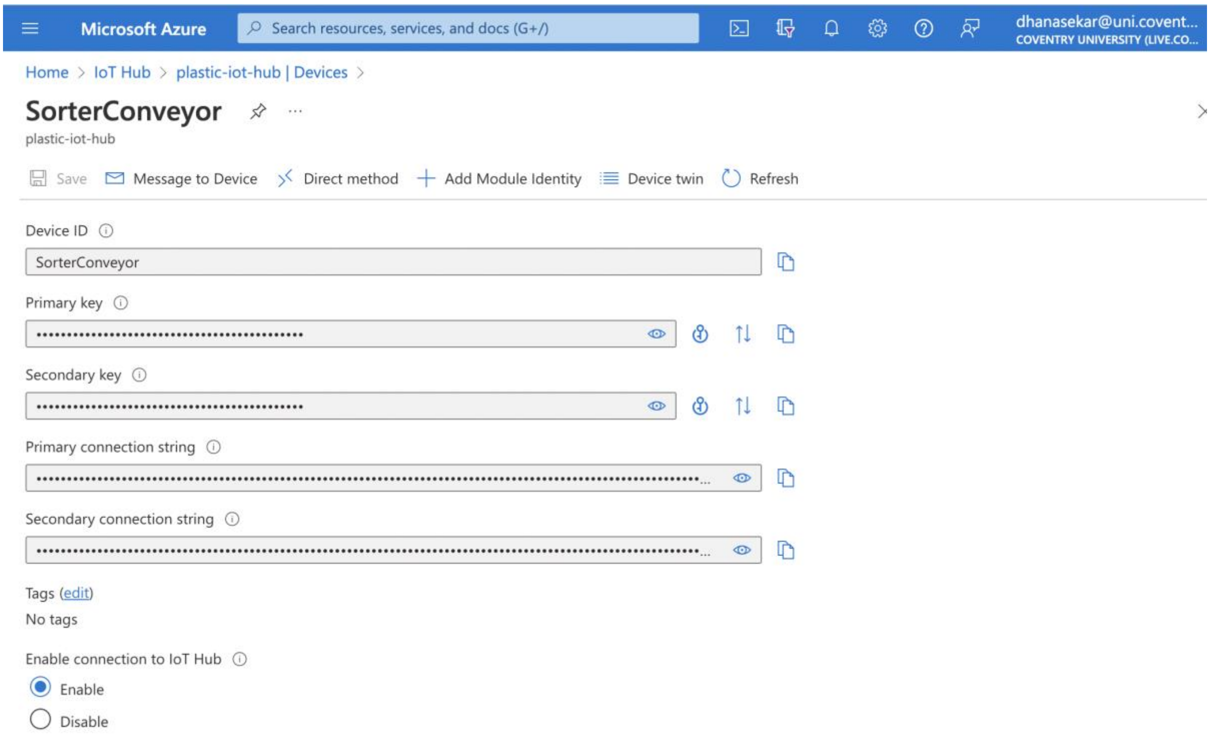
Appendix -B- Digital twin graph



Appendix – C -IoT hub and devices



Devices for IoT hub



Connection string for a device

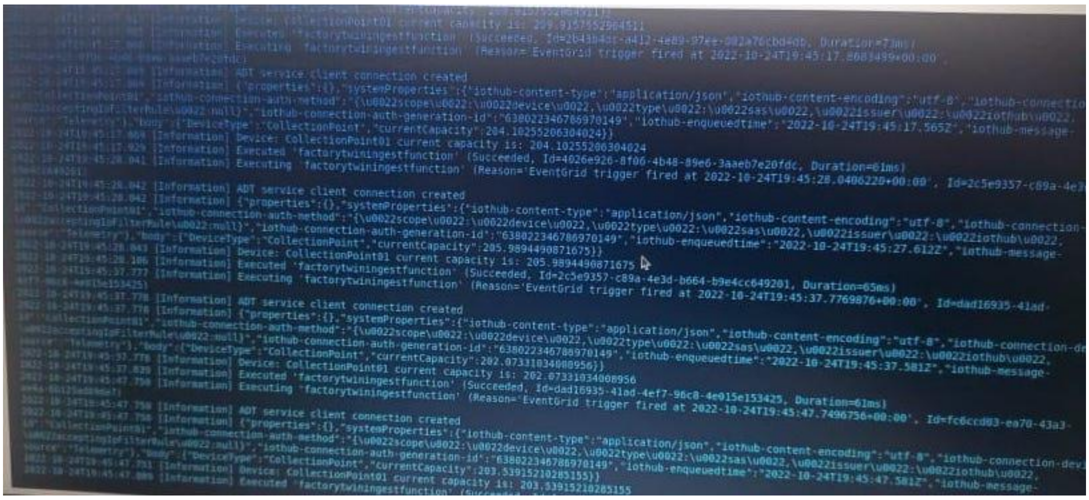
Appendix- D – code for function app

```
// Default URL for triggering event grid function in the local environment.
// http://localhost:7071/runtime/webhooks/EventGrid?functionName={functionname}
using System;
using Microsoft.Azure.WebJobs;
using Microsoft.Azure.WebJobs.Host;
using Microsoft.Azure.EventGrid.Models;
using Microsoft.Azure.WebJobs.Extensions.EventGrid;
using Microsoft.Extensions.Logging;
using Azure.Messaging.EventGrid;
using Azure.DigitalTwins.Core;
using Azure.Identity;
using System.Net.Http;
using Azure.Core.Pipeline;
using Newtonsoft.Json.Linq;
using Newtonsoft.Json;
using System.Threading.Tasks;
using Azure;


using JsonPatchDocument = Azure.JsonPatchDocument;
using EventGridEvent = Azure.Messaging.EventGrid.EventGridEvent;

namespace plastic_EventGridTrigger_plastic
{
    public static class plastic_EventGridTrigger_plastic
    {
        private const string Variable = "ADT_SERVICE_URL";
        private static readonly string adtInstanceUrl = Environment.GetEnvironmentVariable(Variable
        private static readonly HttpClient singletonHttpClientInstance = new HttpClient();

        [FunctionName("plastic_EventGridTrigger_plastic")]
        public static async Task Run([EventGridTrigger] EventGridEvent eventGridEvent, ILogger log)
        {
            if (adtInstanceUrl == null) log.LogError("Application setting \"ADT_SERVICE_URL\" not_s
            try
            {
                /*var cred = new ManagedIdentityCredential("https://digitaltwins.azure.net");

                 var client = new DigitalTwinsClient(
                 new Uri(adtInstanceUrl),
                 cred,
                 new DigitalTwinsClientOptions
                 {
                      Transport = new HttpClientTransport(singletonHttpClientInstance)
                 });*/
                var cred = new DefaultAzureCredential();
                var client = new DigitalTwinsClient(new Uri(adtInstanceUrl), cred);

                log.LogInformation($"ADT service client connection is created.");

                if (eventGridEvent != null && eventGridEvent.Data != null)
                {
                    log.LogInformation(eventGridEvent.Data.ToString());
                    //convert device message into json object
                    JObject deviceMessage = (JObject)JsonConvert.DeserializeObject(eventGridEvent.D

                    string deviceId = (string)deviceMessage["systemProperties"]["iothub-connection-
                    string deviceType = (string)deviceMessage["body"]["DeviceType"];
                    var Temperature = deviceMessage["body"]["Temperature"];
                    var speed = deviceMessage["body"]["speed"];
                    var rotating_speed = deviceMessage["body"]["rotating_speed"];
```

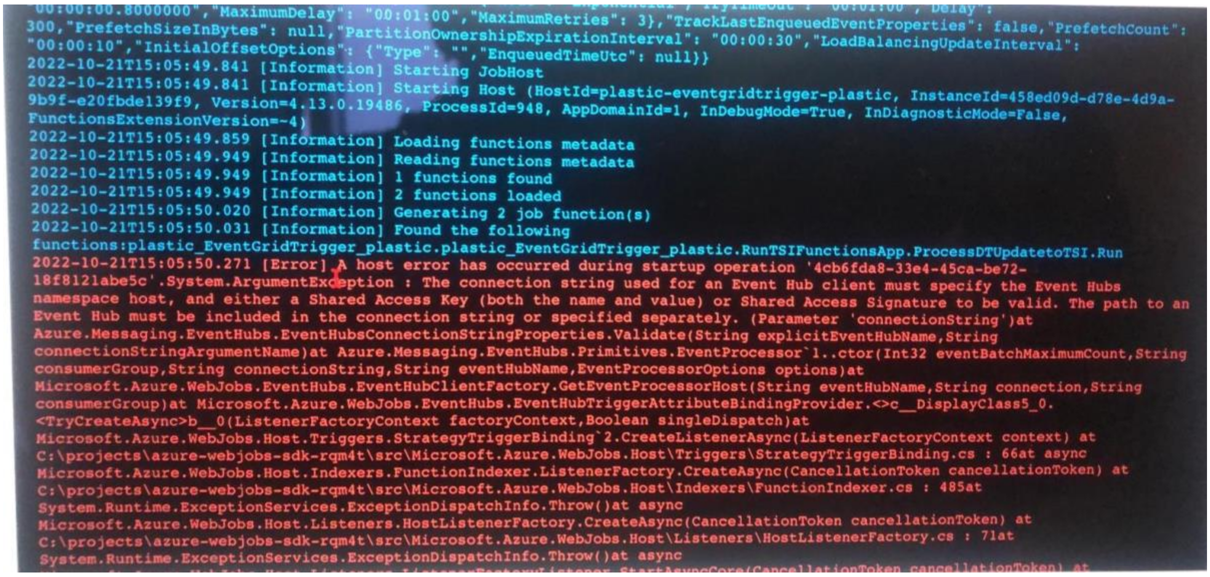
```
            var vibration = deviceMessage["body"]["vibration"];
            var eddy_current = deviceMessage["body"]["eddy_current"];
            var magnatic_field = deviceMessage["body"]["magnatic_field"];
            var weight = deviceMessage["body"]["weight"];
            var magnatic_flux_dencity = deviceMessage["body"]["magnatic_flux_dencity"];
            var magnatic_strength = deviceMessage["body"]["magnatic_strength"];
            var wavelength = deviceMessage["body"]["wavelength"];
            var water_level = deviceMessage["body"]["water_level"];
            var humidity = deviceMessage["body"]["humidity"];
            var health = deviceMessage["body"]["health"];
            var waterTemp = deviceMessage["body"]["waterTemp"];
            var kinetic_energy = deviceMessage["body"]["kinetic_energy"];
            var pressure = deviceMessage["body"]["pressure"];
            var bladeSpeed = deviceMessage["body"]["bladeSpeed"];
            var furnaceTemp = deviceMessage["body"]["furnaceTemp"];

            log.LogInformation($"Device:{deviceId} speed is:{speed} Temperature is:{Tempera


            var updateTwinData = new JsonPatchDocument();
            switch (deviceType)
            {
                case "Sorter01":
                    updateTwinData.AppendReplace("/speed", speed.Value<double>());
                    updateTwinData.AppendReplace("/temperature", Temperature.Value<double>(
                    await client.UpdateDigitalTwinAsync(deviceId, updateTwinData);
                break;
                case "Trommels":
                    updateTwinData.AppendReplace("/rotating_speed", rotating_speed.Value<do
                    updateTwinData.AppendReplace("/temperature", Temperature.Value<double>(
                    updateTwinData.AppendReplace("/vibration", vibration.Value<double>());
                    await client.UpdateDigitalTwinAsync(deviceId, updateTwinData);
                break;
                case "eddy_current":
                    updateTwinData.AppendReplace("/eddy_current", eddy_current.Value<double
                    updateTwinData.AppendReplace("/magnatic_field", magnatic_field.Value<do
                    updateTwinData.AppendReplace("/temperature", Temperature.Value<double>(
                    await client.UpdateDigitalTwinAsync(deviceId, updateTwinData);
                           break;
                       case "Ballistic_sorter":
                           updateTwinData.AppendReplace("/speed", speed.Value<double>());
                           updateTwinData.AppendReplace("/vibration", vibration.Value<doub
                           updateTwinData.AppendReplace("/temperature", Temperature.Value<
                           updateTwinData.AppendReplace("/weight", weight.Value<double>())
                           await client.UpdateDigitalTwinAsync(deviceId, updateTwinData);
                           break;
                       case "Magnetic_sorter":
                           updateTwinData.AppendReplace("/magnatic_flux_dencity", magnatic_
                           updateTwinData.AppendReplace("/magnatic_strength", magnatic_str
                           updateTwinData.AppendReplace("/Temperature", Temperature.Value<
                           await client.UpdateDigitalTwinAsync(deviceId, updateTwinData);
                           break;
                       case "optic_sensor":
                           updateTwinData.AppendReplace("/vibration", vibration.Value<doub
                           updateTwinData.AppendReplace("/wavelength", wavelength.Value<do
                           await client.UpdateDigitalTwinAsync(deviceId, updateTwinData);
                           break;
                       case "sink_flow":
                           updateTwinData.AppendReplace("/temperature", Temperature.Value<
                           updateTwinData.AppendReplace("/water_level", water_level.Value<
                           await client.UpdateDigitalTwinAsync(deviceId, updateTwinData);
                           break;
                       case "OCC_Sorter":
                           updateTwinData.AppendReplace("/humidity", humidity.Value<double
                           updateTwinData.AppendReplace("/rotating_speed", rotating_speed.
                           updateTwinData.AppendReplace("/temperature", Temperature.Value<
```

```
                                updateTwinData.AppendReplace("/vibration", vibration.Value<doub
                                updateTwinData.AppendReplace("/weight", weight.Value<double>())
                                await client.UpdateDigitalTwinAsync(deviceId, updateTwinData);
                                break;
                            case "SorterConveyor":
                                updateTwinData.AppendReplace("/health", health.Value<double>())
                                updateTwinData.AppendReplace("/speed", speed.Value<double>());
                                await client.UpdateDigitalTwinAsync(deviceId, updateTwinData);
                                break;
                            case "Washer01":
                                updateTwinData.AppendReplace("/waterTemp", waterTemp.Value<doub
                                await client.UpdateDigitalTwinAsync(deviceId, updateTwinData);
                                break;
                            case "friction_washer":
                                updateTwinData.AppendReplace("/kinetic_energy", kinetic_energy.
                                updateTwinData.AppendReplace("/pressure", pressure.Value<double
                                await client.UpdateDigitalTwinAsync(deviceId, updateTwinData);
                                break;
                            case "rotart_washer":
                                updateTwinData.AppendReplace("/humidity", humidity.Value<double
                                updateTwinData.AppendReplace("/temperature", Temperature.Value<
                                await client.UpdateDigitalTwinAsync(deviceId, updateTwinData);
                                break;
                            case "WasherConveyor":
                                updateTwinData.AppendReplace("/health", health.Value<double>())
                                updateTwinData.AppendReplace("/speed", speed.Value<double>());
                                await client.UpdateDigitalTwinAsync(deviceId, updateTwinData);
                                break;
                            case "Shredder01":
                                updateTwinData.AppendReplace("/bladeSpeed",bladeSpeed.Value<dou
                                await client.UpdateDigitalTwinAsync(deviceId, updateTwinData);
                                break;
                            case "Extruder01":
                                updateTwinData.AppendReplace("/furnaceTemp",furnaceTemp.Value<d
                                await client.UpdateDigitalTwinAsync(deviceId, updateTwinData);
                                break;





                        }

                    }

                }
                catch (Exception ex)
                {
                    log.LogError($"Error is ingest function: {ex.Message}");
                }

            }
        }
    }
```

Appendix – E – Log stream



Log stream without errors



Log screen with errors

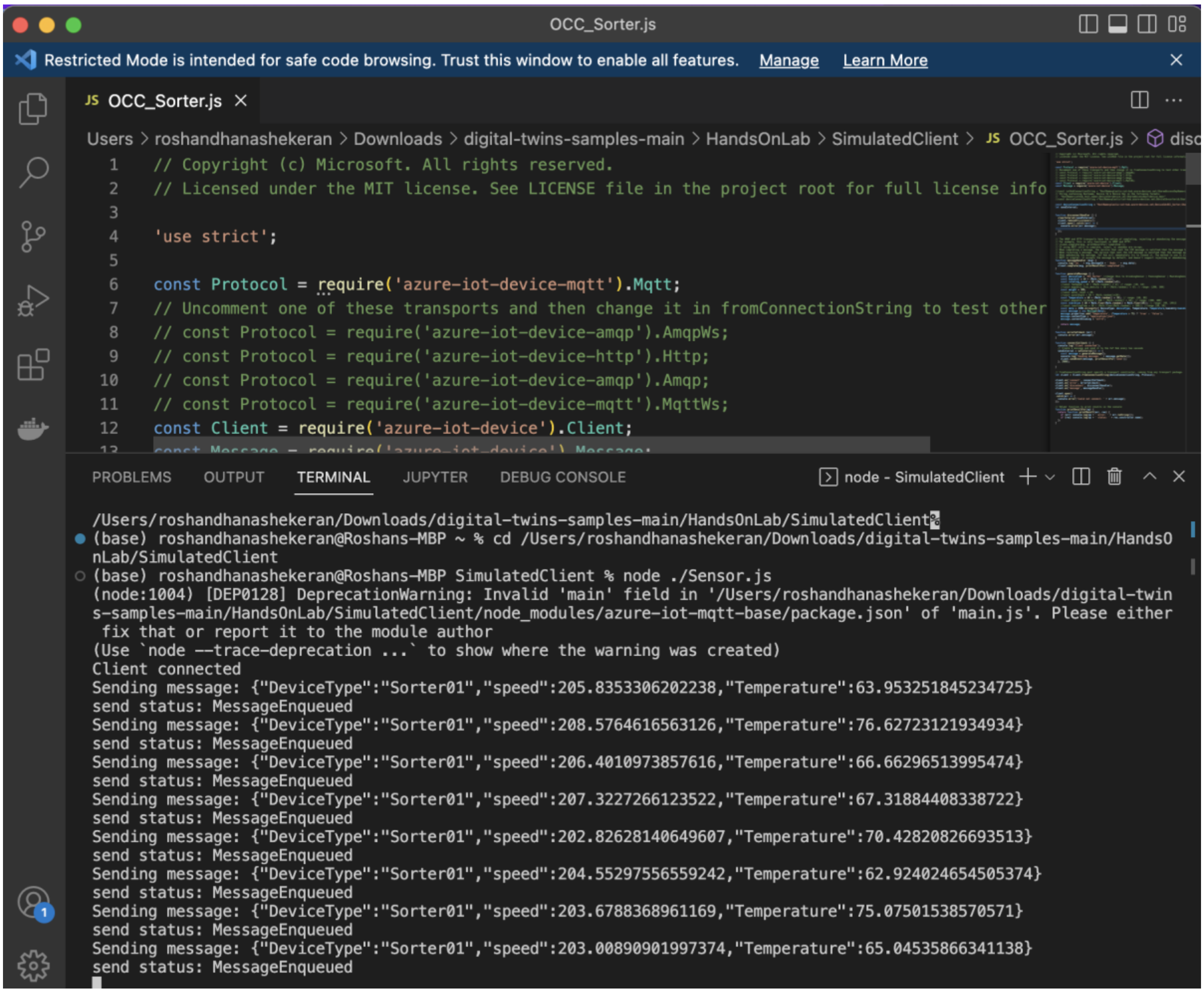
Appendix – F – code for one simulated device

```
// Copyright (c) Microsoft. All rights reserved.
// Licensed under the MIT license. See LICENSE file in the project root for full license information.

'use strict';

const Protocol = require('azure-iot-device-mqtt').Mqtt;
// Uncomment one of these transports and then change it in fromConnectionString to test other transports
// const Protocol = require('azure-iot-device-amqp').AmqpWs;
// const Protocol = require('azure-iot-device-http').Http;
```

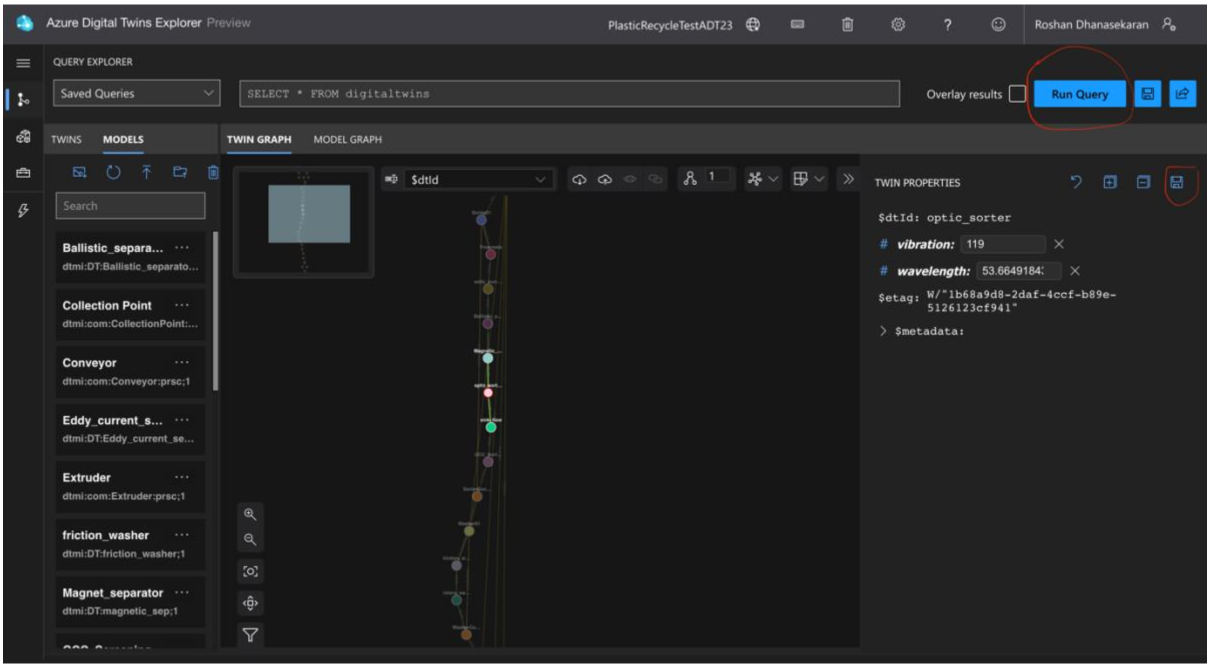
```
// const Protocol = require('azure-iot-device-amqp').Amqp;
// const Protocol = require('azure-iot-device-mqtt').MqttWs;
const Client = require('azure-iot-device').Client;
const Message = require('azure-iot-device').Message;

//const iotHubConnectionString = "HostName=plastic-iot-hub.azure-devices.net;SharedAccessKeyName=iothubowner;SharedAccessKey=Y1yZ5/qllORKoZ2CFhYq+VE2wrh4jL9wt6l5d0hCvlc=";
// String containing Hostname, Device Id & Device Key in the following formats:
//  "HostName=<iothub_host_name>;DeviceId=<device_id>;SharedAccessKey=<device_key>"
//const deviceConnectionString ="HostName=plastic-iot-hub.azure-devices.net;DeviceId=sorterid;SharedAccessKey=AygdfWZPMwHRwSjyUUyd2Jsa/J/bvp+iEau1noMeOgY=";

const deviceConnectionString = "HostName=plastic-iot-hub.azure-devices.net;DeviceId=OCC_Sorter;SharedAccessKey=dslhjdTq72j723bax8tnkGyUG8X4AnC8Ft/t6qSi+uQ=";
let sendInterval;


function disconnectHandler () {
  clearInterval(sendInterval);
  client.removeAllListeners();
  client.open().catch((err) => {
    console.error(err.message);
  });
}

// The AMQP and HTTP transports have the notion of completing, rejecting or abandoning the message.
// For example, this is only functional in AMQP and HTTP:
// client.complete(msg, printResultFor('completed'));
// If using MQTT calls to complete, reject, or abandon are no-ops.
// When completing a message, the service that sent the C2D message is notified that the message has been processed.
// When rejecting a message, the service that sent the C2D message is notified that the message won't be processed by the device. the method to use is client.reject(msg, callback).
// When abandoning the message, IoT Hub will immediately try to resend it. The method to use is client.abandon(msg, callback).
// MQTT is simpler: it accepts the message by default, and doesn't support rejecting or abandoning a message.
function messageHandler (msg) {
  console.log('Id: ' + msg.messageId + ' Body: ' + msg.data);
  client.complete(msg, printResultFor('completed'));
}

function generateMessage () {
    const deviceType = 'OCC_Sorter' //change this to GrindingSensor | FanningSensor | MouldingSensor
    const humidity = 40 + (Math.random()*2);
    const rotating_speed = 40 +(Math.random()*5);
    //const fanSpeed = 10 + (Math.random() * 4); // range: [10, 14]
    //const magnatic_flux_dencity = 30 + (Math.random() * 4); // range: [200, 300]
    const weight = 300;
    //const water_level = 20;
    //const wavelength = 50 + (Math.random()*10);
    const Temperature = 60 + (Math.random() * 20); // range: [60, 80]
    //const magnatic_strength = 100 + (Math.random() * 10); // range: [300, 400]
    const vibration = 80 + Math.floor(Math.random() * Math.floor(80)); // range: [99, 199],
    //const roastingTime = 30 + (Math.floor(Math.random() * 100)); //range [30, 50]
    const data = JSON.stringify({ DeviceType: deviceType, Temperature: Temperature,humidity:humidity, rotating_speed:rotating_speed, weight:weight, vibration:vibration});
    const message = new Message(data);
```

```
    message.properties.add('Temperature', (Temperature > 75) ? 'true' : 'false');
    message.contentType = "application/json";
    message.contentEncoding = "utf-8";

    return message;
  }

function errorCallback (err) {
  console.error(err.message);
}

function connectCallback () {
  console.log('Client connected');
  // Create a message and send it to the IoT Hub every two seconds
  sendInterval = setInterval(() => {
    const message = generateMessage();
    console.log('Sending message: ' + message.getData());
    client.sendEvent(message, printResultFor('send'));
  }, 2000);

}

// fromConnectionString must specify a transport constructor, coming from any transport package.
let client = Client.fromConnectionString(deviceConnectionString, Protocol);

client.on('connect', connectCallback);
client.on('error', errorCallback);
client.on('disconnect', disconnectHandler);
client.on('message', messageHandler);

client.open()
.catch(err => {
  console.error('Could not connect: ' + err.message);
});

// Helper function to print results in the console
function printResultFor(op) {
  return function printResult(err, res) {
    if (err) console.log(op + ' error: ' + err.toString());
    if (res) console.log(op + ' status: ' + res.constructor.name);
    };
  }
```

Appendix – G – simulated client



Appendix – H – inject function Error solution



Appendix – I – TDSI function app code

```csharp
using Microsoft.Azure.EventHubs;
using Microsoft.Azure.WebJobs;
using Microsoft.Extensions.Logging;
using Newtonsoft.Json;
using Newtonsoft.Json.Linq;
using System.Threading.Tasks;
using System.Text;
using System.Collections.Generic;


namespace TSIFunctionsApp
{
    public static class ProcessDTUpdatetoTSI
    {
        [FunctionName("ProcessDTUpdatetoTSI")]
        public static async Task Run(
            [EventHubTrigger("twins-event-hub", Connection = "EventHubAppSetting-Twins")] EventData myEventHubMessage,
            [EventHub("tsi-event-hub", Connection = "EventHubAppSetting-TSI")] IAsyncCollector<string> outputEvents,
            ILogger log)
        {
            JObject message = (JObject)JsonConvert.DeserializeObject(Encoding.UTF8.GetString(myEventHubMessage.Body));
            log.LogInformation("Reading event:" + message.ToString());

            // Read values that are replaced or added
            Dictionary<string, object> tsiUpdate = new Dictionary<string, object>();
            foreach (var operation in message["patch"])
            {
                if (operation["op"].ToString() == "replace" || operation["op"].ToString() == "add")
                {
                    //Convert from JSON patch path to a flattened property for TSI
                    //Example input: /Front/Temperature
                    //        output: Front.Temperature
                    string path = operation["path"].ToString().Substring(1);
                    path = path.Replace("/", ".");
                    tsiUpdate.Add(path, operation["value"]);
                }
            }
            //Send an update if updates exist
            if (tsiUpdate.Count > 0)
            {
                tsiUpdate.Add("$dtId", myEventHubMessage.Properties["cloudEvents:subject"]);
                await outputEvents.AddAsync(JsonConvert.SerializeObject(tsiUpdate));
            }
        }
    }
}
```

Appendix – J – Code files for implementation

https://livecoventryac-my.sharepoint.com/:f:/g/personal/dhanasekar_uni_coventry_ac_uk/EsR3GZtVIjtGohjIavQgKqEBkeeGS-4aCddiQ19wQNDxRQ?e=YJGqfl