Master Dissertation in Mechanical Engineering

Simulation of a production order duration using Digital Twins

Author:
Gonçalo Campos Carvalho Varela

Coordinator:
António Pessoa de Magalhães
Supervisor:
Miguel Bastos Gomes

Master in Mechanical Engineering
Automation Branch

July, 2022

"Automation is cost cutting by tightening the corners and not cutting them."

Haresh Sippy

Acknowledgements

First I would like to thank my family. For the freedom that allowed me to make mistakes and the responsibility that compelled me to correct them. To my friends, because without them, this adventure would not have felt the same. We are all about to embark on a journey without a destination, but I hope we never forget where it all started.

To Chloé Gac, whom I eternalize in this text, for the patience, comfort and unconditional support. For what we lived and what is still to come.

A special acknowledgement to my coordinator, António de Pessoa Magalhães, professor at FEUP, for not giving up on me and insisting on improving my work. To my supervisor at Sonae Arauco, Miguel Bastos Gomes, for guiding my work, accepting my ideas and making me feel integrated into the company, to which I am also thankful for the given opportunity. I want to thank Diogo Correia for his patience in assisting me unconditionally and Nuno Abrantes for making an effort to give me the best virtual tour of the factory.

Thank you.

Abstract

A Digital Twin (DT) is a virtual representation of an object or system. It is updated with real-time data, and uses simulation and artificial intelligence to help on the decision-making process. It is a growing topic on the manufacturing industry, being associated with continuous improvement.

Using this technology, Sonae Arauco aims to centralise in a unique location the description of all their factories. They have a cloud-based architecture so, with this centralisation, they intend to take advantage of all the synergies the Azure Digital Twins (ADT) and the Microsoft cloud services offer. Ultimately, this solution will help to significantly increase production efficiency, and reduce costs.

However, the DT is not a generally accepted topic and its concept does not have sufficient proofs on the production industry to be accepted without a thorough investigation. This dissertation follows that objective: to give a proof of concept of this innovative technology in the company's sector of activity. For that, a DT solution was implemented and its benefits tested in the context of a practical use case.

In order to accomplish this objective, a study of the state-of-the-art of DT and familiarity with the Azure products was required. Following that, and after the use case selection, the conditions to develop the project were met. Using ADT and Azure services like Azure Functions, Event Hubs, Time Series Insights, and others, an application was developed to simulate the duration of a production order. This development has the objective of testing the DT range of capabilities and evaluate its performance.

Finally, the results obtained are shown and discussed and the conclusions taken from them are described in detail. The future work that can be performed to improve the implemented solution is also presented.

Resumo

Um Gémeo Digital (DT) é uma representação virtual de um objecto ou sistema. Este é atualizado com dados em tempo real, e utiliza o poder de simulações e inteligência artificial para ajudar no processo de tomada de decisão. É um tema associado a melhoria contínua em crescimento na indústria de manufatura.

Utilizando esta tecnologia, a Sonae Arauco pretende centralizar num único local a descrição de todas as suas fábricas. A empresa possui uma arquitectura baseada na nuvem, pelo que, com esta centralização, pretendem tirar partido de todas as sinergias que os Gémeos Digital do Azure (ADT) e os serviços da nuvem da Microsoft oferecem. Em última análise, esta solução ajudará a aumentar significativamente a eficiência da produção, e a reduzir os custos.

No entanto, o DT não é um tópico geralmente aceite e o seu conceito não tem provas suficientes sobre a indústria de manufatura para ser aceite sem uma investigação exaustiva. Esta dissertação tem esse objectivo: dar uma prova de conceito desta tecnologia inovadora no sector de actividade da empresa. Para tal, foi implementada uma solução de DT e os seus benefícios testados em função de um caso de uso prático.

Para alcançar este objectivo, foi necessário um estudo do estado da arte do DT e familiaridade com os produtos Azure. Em seguida, e após a selecção do caso de uso, foram cumpridas as condições para desenvolver o projecto. Utilizando serviços do Azure como Azure Functions, Event Hubs, Time Series Insights, entre outros, foi desenvolvida uma aplicação para simular a duração de uma ordem de produção. Este desenvolvimento tem o objectivo de testar as funcionalidades do DT e avaliar o seu desempenho.

Finalmente, os resultados obtidos são mostrados e discutidos e as conclusões tiradas são descritas em pormenor. É também apresentado o trabalho futuro que pode ser realizado para melhorar a solução implementada.

Contents

Acronyms

AAS	Asset Administration Shell
ADT	Azure Digital Twins
AF	Azure Functions
CPS	Cyber Physical Systems
DT	Digital Twin
DTDL	Digital Twin Definition Language
IoT	Internet of Things
IT	Information Technology
JSON-LD	JavaScript Object Notation for Linked Data
KPI	Key Performance Indicator
MDF	Medium Density Boards
PB	Particle Boards
TSI	Time Series Insights

List of Figures

List of Tables

Chapter 1

Introduction

The constant development of new technologies is crucial to any business's success. It is the key to being competitive and profitable throughout the years, and Sonae Arauco is no exception. The company seeks to stay up-to-date, being the IT department where the most significant efforts and resources are applied. This investment is easily understood because digital applications are advancing and upgrading faster. Moreover, they can potentially improve all the other processes, namely in the manufacturing industry, by reducing the production times, avoiding unnecessary breaks and enhancing the quality of the final products. All of this positively impacts production, so although the investment in such applications may be considerable, the return can be far greater.

Manufacturing companies face everyday challenges related to maintenance, line automation, quality assurance, and many other aspects that make this industry so complex. Technology plays a vital role in dealing with such problems. However, the more a business grows, the more problems begin to occur, making technology advances increasingly important to deal with them more efficiently. A company must study the new market trends to stay up-to-date and seek the best possible outcomes.

Therefore, investing in a "Digital Twin" of their plant is a logical step on the company's route of continuous improvement. More than being the digital representation of the physical entities in their factories, which is advantageous from a visualisation point of view, it offers the possibility of simultaneously simulating operations with historical and real-time data. Thus, allowing for preventing problems before their occurrence or improving a production plan, for example, without wasting vital resources, such as time and money, with the outdated but typical trial and error method.

Nevertheless, Digital Twins (DTs) are a topic in rapid expansion, appealing for what they offer yet, more complex than they appear to be, at first sight, making it challenging to use their full potential and obtain good enough results to justify the required investment.

1.1 The host company: Sonae Arauco

Sonae Arauco is one of the world's largest manufacturers of wood-based panels. The company constantly aims to improve its methods and encourages innovation in the furniture, interior design and construction industries by enhancing the design and quality of its products.

The company's core started way back in 1959 with a single location in Maia, where it has its current head office and where the development of this project took place. Throughout the years, the shareholders focused on expansion and internationalisation by acquiring several companies in Portugal and spreading around the globe.

The industrial sector where the company locates itself is sensible from an environmental point of view since the raw material to produce its products is wood. However, from the very start, efforts were made to use the natural resources available sustainably, maintaining their ecological footprint the less significant possible.

The partnership with Arauco, a global manufacturer of forest products, started only six years ago. However, Sonae has produced the same products for decades, having to go through multiple evolutions to follow the market trends, product and technological wise, while increasing efficiency, profitability and keeping competitive prices to be a market leader.

The need for digital advancements comes from the company's continuous improvement mentality. Currently, they have deployed SCADA and visualisation interfaces in the factories to help in the monitorisation of the production processes in real-time. Such applications do not solve the full extent of existing problems, even though they provide key performance indicators (KPI) to the operators and allow the visualisation of all the processes in the same place. The company has a growing need to know why problems occur, not only their existence. Evaluating the possible benefits of DTs is therefore included in the company's strategies.

Yet, DTs are seen as very innovative in manufacturing because there are not many industry-related proofs of concept. Therefore, this dissertation emerges to assess the implementation of a DT instance. For this occasion, this development needs to be associated with a real industry use case that reflects the company's needs. Initially, the proposed project is focused on a production line where the availability is considerably lower than in the remaining, implying a higher accumulation of downtimes. However, further on, the company intends to give it continuity, increasing its importance, as the work done will be used as a model for future developments.

This project's success is not assured since DTs are an open topic in the technology world, and their interest is too recent to have been extensively investigated and evaluated. Some leading companies in the manufacturing industry take this concept seriously and believe it will be one of the most critical developments in recent years. Nonetheless, there are still doubts about the viability and profitability of DTs since the potential lies not just in the visualisation possibilities it provides but also in the synergy with data ingestion and services such as AI and predictive models.

1.2 Starting point and objectives

The main objective of the project developed in this dissertation is to implement a DT and test its benefits in the context of a practical use case. More specifically, it involves the implementation of the DT of a melamine production line in Sonae Arauco's plant in the city of "Oliveira do Hospital" to simulate the duration of production orders.

The company is focused on continuous improvement and has already developed a software application named Connected Factory or Digital Plant, which is the live digital representation of what happens in their physical plants in different countries and continents, allowing for long-distance supervision anywhere and at any time. Equally to the supplied DT application, this software is cloud-based and both ingest many signals and metadata in the same way, which serves as a helpful starting point. Even though the data and attributes to define a DT instance unavoidably coincide with the Connected Factory, its development, visualisation, and purpose are significantly different. In addition, its implementation is innovative within the company.

The first step involves extensive research on the topic of DTs. More specifically, it is needed to know how to implement a DT, integrate with cloud functionalities and services, which software can be used in parallel and how other companies are using the same technology. In other words, reviewing the state-of-the-art is crucial to begin the project in the most efficient way possible. The connectivity with the cloud is essential since Sonae Arauco has a well-defined IT strategy based on cloud computing technologies. Needless to say, the DT or any emerging solution has to be aligned with the business model.

During the development and before the creation of twins, models must be appropriately deployed to fit the manufacturing industry and the existing physical assets. DTs are brought to life from these physical models and are prepared to receive real-time telemetry data from the factory through the cloud. This implementation is heavily connected to the cloud. In the case of this project supported by Microsoft Azure, so one of its main goals is to study how the different instances are related and which are the best Azure services to use to obtain the best results while requiring less computational power.

The codding of Azure custom functions in C# is mandatory to integrate different Azure services and simulate production orders. More specifically, there is the need to ingest data from Azure IoT Hub to the Digital Twin Explorer, process this data into simulated outputs and, lastly, supply the outputs into Time Series Insights (an Azure service used to collect, process, store, query and visualise data). Once the simulated results are obtained, they will be compared with the predicted and real-time results. Their differences must be discussed, and consequently, the success of DTs for the selected use case.

This use case must be previously defined and important to the company's needs. Its implementation aims to improve the production process efficiency regarding the melamine line by running simulations of the production plan in the digital twin environment to measure its feasibility and identify potential bottlenecks to be posteriorly solved. The use case definition is the starting point of the entire project, so it is undoubtfully vital to be well thought out considering the company's needs. At the same time, an adequate balance between complexity and feasibility within the project's expected duration must be achieved.

At the end of the project, the expected results are not meant to immediately improve the company's processes but to validate the DT concept and technology, taking into consideration not only its advantages and what it brought new but also the costs associated, which include the hours spent on its implementation and computational costs.

1.3 Dissertation outline

The dissertation unfolds in this way:

The second chapter briefly mentions the final board produced in the line this project is built on and describes the melamine production process in the BP9 line, which is necessary for understanding the work to be developed. It is also where the company's problems and implemented use cases are defined. The selected use case is highlighted.

The third chapter explores the digital twin topic, starting with a brief history and concept definition. After, its types and industrial applications are investigated. After this theoretical review, the software and support services are presented, raising the question: Are the sufficient conditions reunited for the project's development? The question is answered throughout chapter four and discussed in chapter five.

The fourth chapter explains the implementation and productive deployment processes with the help of fundamental images and graphics. It includes the system architecture, extended models, DT creation, functions developed, and the final simulation results and output.

The fifth chapter contains the result analysis and discussion, comparing the expected with the values obtained. This discussion is accompanied by graphics that assist in visualising and comparing such values.

The sixth and final chapter contains the most relevant conclusions of the dissertation. It suggests further development and optimisation of the DT solution created while giving a detailed assessment of the value of the technology.

Chapter 2

Problem statement and fundamental concepts

Before presenting the problem on which this dissertation lays, some essential notions and knowledge must be obtained to understand it better. The project is focused on a melamine production line. There are different raw products being processed on this line, yet their characteristics do not influence its behaviour, so they are not presented in detail.

The problem has to be previously defined and an appropriate use case selected for the solution to be implemented. This use case is not the main focus of this dissertation. It serves as a proof of concept for the DT. Bearing this in mind, a specific production line had to be carefully chosen. Its composition, operations and issues are described to demonstrate where the DT will be experimented with.

Thus, this chapter provides detailed but concise information about the BP9 line, justifying its choice, and deepening into the problem discussed throughout this dissertation. The company's needs are reviewed, and the use case is presented in detail.

2.1 Production process of melamine surfaced boards

A brief description of the final product is necessary to provide context; however, the functioning of its production line is the real focus. In this section, the most important information to retain is the procedures and operations of a specific melamine production line so that the problems and project development can be understood.

2.1.1 Melamine surfaced boards

Melamine surfaced boards are composed of a raw board, Particleboard (PB) or Medium Density Fiberboard (MDF), and 1 or 2 sheets of impregnated decorative paper, as illustrated in Figure 2.1. The melamine resin works as the connector to the board, activated by a heated pressing process.

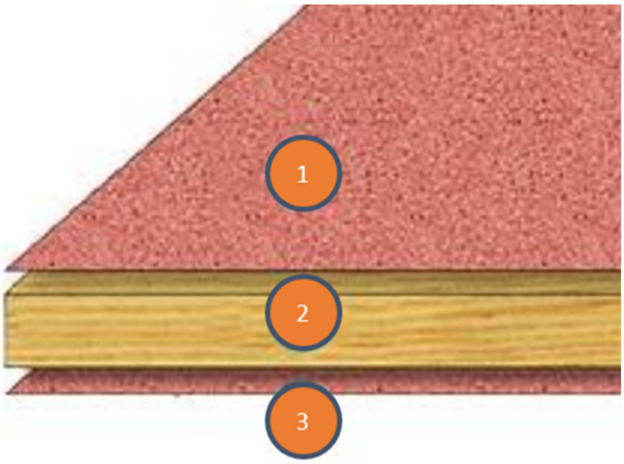

Figure 2.1: Melamine surfaced board layer composition. 1 & 3 - Decorative paper; 2 – Raw board.

The properties of the raw boards are then combined with a specific aspect and texture appropriate to each application or client preference. It is also important to highlight that the paper with which the boards are surfaced, more than a decorative function, also provides optimal scratch, abrasion and stain resistance and allows for easy cleaning.

Thus, impregnated decorative paper is the most particular and defining element of melamine surfaced boards, and its impregnation process is complex and vital for the surface properties of the board. However, this production line does not affect the melamine line directly, so it was not investigated.

2.1.2 BP9 line operations

Sonae Arauco's melamine surfaced boards manufacturing process is divided into multiple stages, schematised in Figure 2.2 and explained in detail later in this subsection.

Yet, from a broad point of view, a melamine production line is composed of key zones. The formation zone, represented in blue, where the raw boards enter the line and the final product is assembled. The press, represented in green, is the most important element of the line as it is the asset where the board's surface finish is provided and, more importantly, where the boards take the longest time, forming the line's unavoidable bottleneck. After the press there are stations that remove the excess paper, cool the boards and cut them. Among these, there is the control station where an operator classifies the quality of the boards. It is the only manually operated zone of the line. At the end, there are five packing tables where the final product is pilled and transported to a warehouse.

This project's development is based on one of the four melamine lines in the "Oliveira do Hospital" plant. The BP9 line is the most modern of the four, and despite being large and complex, it was the line chosen because the

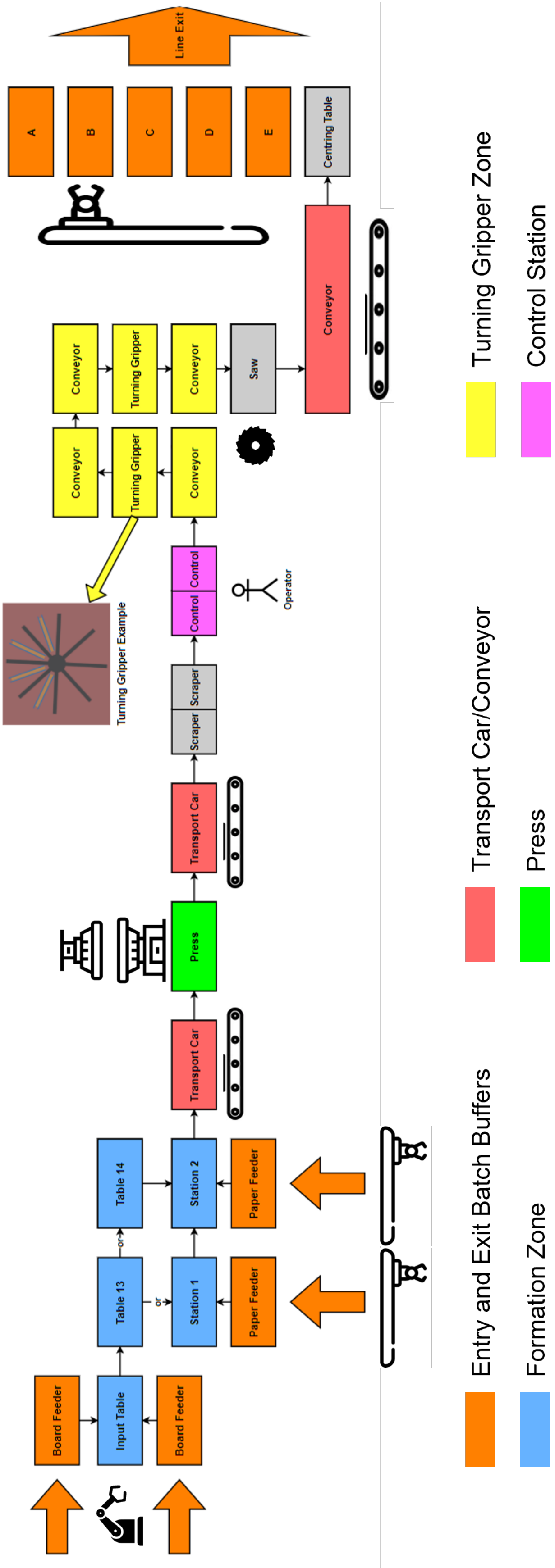

Figure 2.2: BP9 line schema.

processes are more updated and have more IoT devices than on the remaining lines.

The factory runs continuously, so when a production order is complete, the necessary batches for the next order are placed in the feeding buffers. There are two buffers for the boards and two for the sheets of impregnated paper. After each station detects the presence of a batch, the operator can manually start the process by inserting the order code.

Then, boards are picked up by a robotic arm with suction cups and placed on the input table. It can pick up one or two boards simultaneously, depending on their size, determined by the order specification. The press has 5.7 m of length, so the big boards have approximately the same size, and the smalls have half. When there are two small boards in the line simultaneously, they are treated as if they are one, with slight changes throughout the line.

The paper is placed on the boards in the next stage, the formation zone, represented in blue in Figure 2.3. There is the possibility of placing paper on both sides of the boards or only on one. According to this, the line has different behaviours.

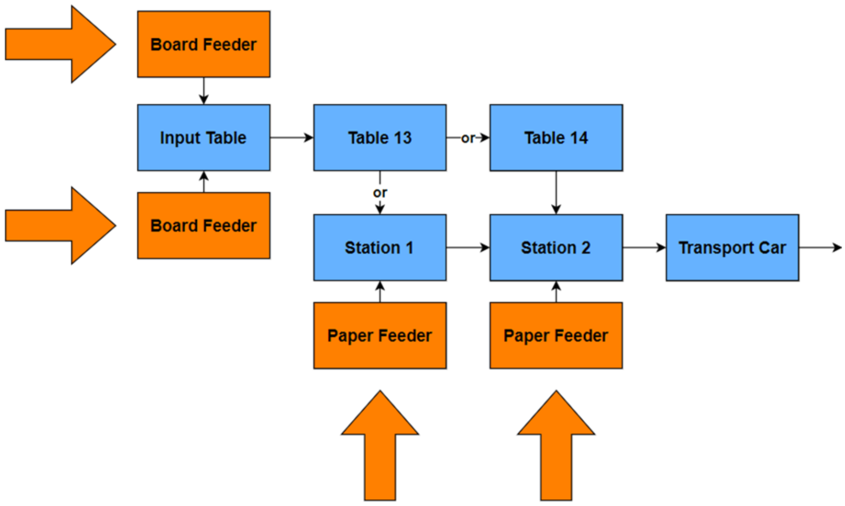

Figure 2.3: BP9 line: Input tables and formation zone.

Paper on both faces: The boards are moved into table 13 and transported by a car into station 1, where paper is placed on the lower face. The board is then transported into station 2, where paper is placed on the upper face.

Paper on one face: After table 13, the boards are moved into table 14 and transported by a car into station 2, where paper is placed on the upper face.

There are other sequencing possibilities related to the existence of paper on the feeders. This prevents the stop times due to lack of feeding material but increases this zone's complexity.

A transportation car then moves the boards into the press, where they will go through two critical cycles. The mechanical cycle corresponds to the closing and opening of the press, and the thermal cycle is the time the press stays closed, during which the press plates heat the board at a predetermined temperature and pressure, making the resins in the paper stick to the board. At the same time, it provides a texture to the surface.

Between two production orders, the press temperature can change and if less than 10 ºC, for each degree Celsius increase, the thermal cycle reduces 1 second of its time. This method prevents the line from stopping.

The press is the central element of the line since the sum of these cycles determines the speed of the entire line if there are no unexpected issues in other stations, making it the main but unavoidable bottleneck of the process.

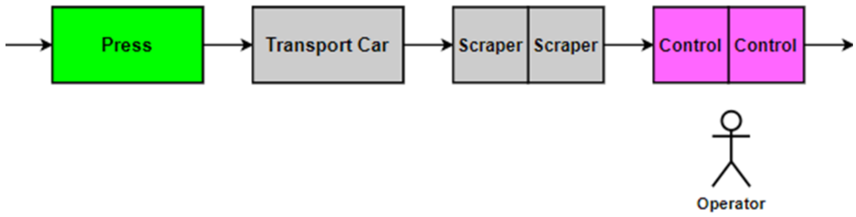

Figure 2.4: BP9 line: Press, scraper and control stations.

While transported to the next station, the boards go through a scrap zone. In the scraper, the excess paper is removed, and, on the occasion of having two small boards, the sheet of paper is cut in half, separating them. However, they still move as one.

Afterwards, they reach the only manually controlled line station, the control zone, where an operator analyses the presence of defects and classifies the boards into three groups: first quality, second quality and third quality. The first and the second are allowed to pass the control zone but are stored in different batches. The third degree fails the control and is removed from the line. The operator has a control panel where he/she inserts the quality degree of the boards after seeing both sides with the help of a lift and sends the boards into the next station.The sequence of stations after the press is represented on Figure 2.4.

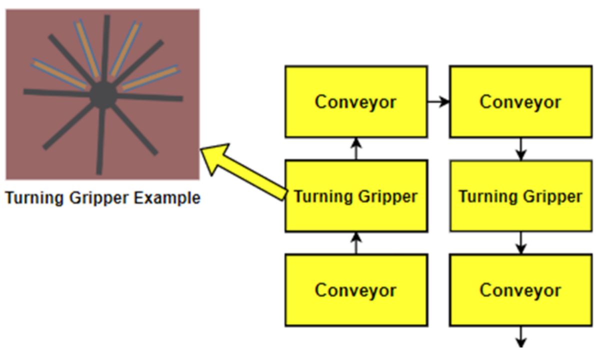

Figure 2.5: BP9 line: turning grippers.

After the indication from the operator, the boards enter a turning gripper, represented in Figure 2.5, where they will slowly cool down. The gripper has two stages and a counter. When a board enters this station, the counter is incremented, and when it leaves is decremented.

At the grippers' exit exists a cutting table with a saw. However, the operation is optional and determined by the order specifications. There the boards can be cut along the length of the board.

Just before the line's exit, the boards enter a centring table to be in the correct position for the packing in batches.

There are five packing tables:

- Table E - first quality boards ;
- Table D - second quality boards;
- Table C - first quality boards;
- Table B - boards of quality defined by the operator (not always used);
- Table A - holds pallets. These are placed on the other tables before they take boards.

The packing is the final stage of the line, and the production order is finished when the number of boards specified in the production plan is reached. The batches are then taken into a specific warehouse, where they are stored before transportation. The final zone of the line is represented in Figure 2.6.

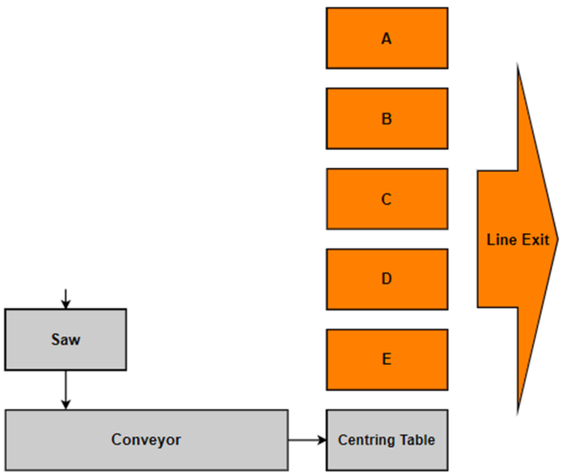

Figure 2.6: BP9 line: Saw, centring table and packing tables.

It is important noting that plants are expected to work 24/7, so there is a significant effort for the lines not to stop as it results in a considerable loss of profit. This requirement forces the company to look for advanced solutions to ensure it does not happen, and it is in the IT department that the most significant efforts are made.

The described production line in the "Oliveira do Hospital" plant is the subject of the proposed practical work; therefore, each mentioned element and stage is meant to be modelled and connected with the appropriate relationships. Understanding its operations, individually and as a whole, is thereby crucial for defining the existing use cases and essential for the correct approach to the presented problem.

2.2 Problem definition

The correct and complete definition of the problem is, or should be, the first approach for any project because it is at this stage that the conceptualisation begins, sometimes indirectly, and also when the outline, objectives, and timeline are defined.

Clarifying these topics is a great deal since it allows for well-balanced management of expectations from the client, which helps the developer build the best solution possible according to the client's needs and restrictions.

Thus, the success of a project, in addition to the results, is also evaluated according to the completion of the objectives defined in its preliminary phase. The following subsections present the problem in detail, from the company's needs and expectations to the proposed solution.

2.2.1 Identified production constraints

Industry 4.0 promotes the interaction of intelligent software, machines, and humans, both inside the factory and over the cloud. This philosophy promotes using cutting-edge information technology and automation to gather and monitor all essential information flows to maximise efficiency, optimise management, and automate tasks.

One of the main goals of the melamine production line is to achieve the ideal recipe, which includes minimal cycle time and stable plate temperature while maintaining the highest level of product quality and production line availability. These targets are essential for ensuring that customers get the best service possible while maintaining low production costs.

This desired goal is not readily achievable since several factors contribute to the added complexity:

- Currently, optimal recipes are obtained by try and error, which has high costs associated;
- External conditions like temperature, humidity, components ware and others influence the process, being difficult to predict;
- Multiple lines are running in parallel, creating the need for different

recipes and, consequently, having an impact on the production setups and line availability;

- Line feeding of boards and impregnated paper is accomplished using the same conveyors, frequently resulting in higher waiting times.

It is known that external and unpredictable factors are an issue in every production line. However, in Sonae Arauco, Melamine lines have the lowest operation efficiency compared with other production lines such as ParticleBoards Press, Sanding lines, Cutting lines or Impregnation lines. The low efficiency is impacted by the three vectors considered in this KPI: availability, performance and quality. As of today, the main problem is availability which is, on average, 70% compared to 98% of quality and 95% of performance. As such, it is Sonae Arauco's objective to boost Melamine production availability.

The above means that the melamine line is, on average, stopped 30% of the time, approximately six times more than the other lines. These stops result in a big production break involving significant losses since melamine surfaced boards are considered an added value product since it is the most profitable product the company produces.

Deep diving into the availability context, it is known that besides the unplanned downtimes, the most significant impact is the changeovers between orders and the accumulated micro stops due to the waiting times in each one of the production line control points.

Empirically, the company knows that having only one warehouse supplying the four melamine lines will generate waiting times for supply issues because the four lines have different cycle times, different lot size typologies, and the plans are not optimised to supply them. In addition, it is known that the operators sometimes increase the cycle time (disrespecting the recipes), which allows them more time for quality inspection, causing unwanted stops.

Thus, there is the need to identify the most critical points within the line to focus on them and find adequate solutions. At an advanced stage, the board and paper feeding together with the four melamine lines must be studied to check for cadence problems.

These problems are currently solved with analytical and probabilistic methods in a much simpler way. However, this dissertation aims to implement a DT solution on the context of a real industry use case that is also valuable for Sonae Arauco. Therefore, the availability problem in the BP9 line was selected to validate the interest and analyse the performance of DTs.

2.2.2 Proposed solutions

The efforts applied to solve the identified problems are significant and not overlooked by the company. However, several issues require more customised methods that produce the most efficient solution with fewer resources. The concept is logical and easy to comprehend; however, it can be contradictory since, in most cases, customised approaches are too specific for an application, creating the need for significant changes and adaptations for other implementations to obtain the desired results. This adaptation implies higher costs in several areas, from the development to the computational and storage costs.

Thus, the manufacturing industry continuously seeks new alternatives and cutting-edge technology to solve their problems or assist in the never-ending search for improvement within the internal processes. The evolution of the internet and available services assisted tremendously in this search for continuous improvement.

DTs, at first sight, have an excellent prospect to be the innovation this and many other industries need. The concept of digitally representing the most accurately possible what happens in reality, is not innovative, but DTs are much more than a visualisation tool. The software offers the possibility of gathering the description of all the company's factories and all of the associated data in the same place, which allows for its integration with other cloud services and merging with DTs from a third party. Moreover, it enhances the outcomes of simulations and gives the user a feeling of real-time proximity to what happens in the physical world.

Even though DTs' potential is undeniable, there are doubts about this software's applicability. The authors of [1] reveal the scepticism a considerable amount of people directly connected with the process industry have shown about the advantages of this technology.

Therefore, the concerned project arose from the need to prove the DT concept and its advantages when connected with Sonae Arauco's already implemented solutions. Integrating with their cloud is fundamental for the company, so the DT implemented must provide interesting outcomes while facilitating the integration between services. These results must be evaluated in parallel with the expenses associated with the software's implementation, and computational power utilised.

Thus, the solution must be developed for a specific use case linked to the company's current needs. Only on this occasion will the results be sufficient to discuss the DT effectiveness in the company's reality properly.

2.2.3 Use case selection

Use cases are approaches and processes utilised to assess and analyse systems, such as software platforms. Their goal is to assist in determining, interpreting, and organising the requirements and features of a system, as well as how they are utilised.

Currently, there are several use cases defined by Sonae Arauco. They represent the needs that the company has identified and are divided into the following five categories:

- Preparation of production orders;
- Execution of production orders;

- Quality control;
- Storage;
- Continuous improvement.

Within these groups, there were countless possibilities to be explored. The production plan compliance check, post-production management, defects prediction or new product testing are possible cases that could have been applied. However, the selected use case to be implemented was the simulation of a production order duration in the BP9 line. This is considered a more generic use case that can fit into the categories of execution of production orders and continuous improvement. The calculations necessary for the implementation of this use case are the time a board takes in each station, which will also allow for the identification of bottlenecks. From this, several outputs can be produced to give important insights on the line behaviour. The approach adopted is described in Chapter 4.

This use case represents a fundamental requirement proving the necessity of implementing the DT. It intends to test its capabilities in a real-world scenario while having future applicability for the company.

2.3 Summary

The description of the production line that the DT will represent was a necessary first step for the development of the entire project, starting with the problem definition and use case selection. Even though secondary for the DT assessment, these decisions are important because they determine the project's path.

Sonae Arauco has a clear interest in exploring DTs for everything they offer. More specifically, the data centralisation, the possibility to connect with multiple cloud services and the integration with other DT developed by external entities. Therefore, this software was proposed as the solution for the identified problems and a use case was selected to test the DT capabilities and prove its concept for future applications.

Before developing the project that seeks to prove the utility of this software, its concept needs to be understood, in particular the one provided by the company: the Azure Digital Twins (ADT). This need led to a thorough investigation of the software capabilities and applications. The outcome of this research provided the necessary knowledge for the project's implementation and assisted in selecting the correct approach to test this technology.

The DT research results and survey of Azure services are presented in the next chapter.

Chapter 3

Azure Digital Twins

This chapter presents the essential knowledge obtained from the investigation before the current project's development. It includes a summary of the state-of-the-art of the DT technology, from its definition to standard applications.

Several other services, presented in this chapter, must be deployed and integrated to get the best outcome of any DT. The ADT software is connected to the Microsoft cloud (Microsoft Azure), facilitating communication and collaboration between different environments.

The supporting software and its preference over the other available options is a debated topic within the company, so the reasons behind their decision are also presented. The most important cloud services are also described.

Finally, the DT applicability in the production industry and development concerns are discussed.

3.1 Digital Twins

The manufacturing industry did not always resemble its current state. It underwent several transformations that the following four significant milestones may summarise:

- The industrial revolution during the 18th and 19th centuries;
- Mass production in the first half of the 20th century;
- Information technology-based automation of production in the second half of the 20th century;
- The ongoing fourth industrial revolution.

The latter, also referred to as Industry 4.0, promotes the cooperation of all the technologies and elements of a process to improve product quality and production efficiency, adaptiveness, sustainability and affordability.

Then, big data acquisition became vital for implementing these promising technologies; however, the information collected by intelligent sensors needs to be filtered into valuable data. Only then does it have the power to enable the connection of factories, supply chains and clients [2].

DTs are displayed as a solution that can integrate the necessary treatment of data and produce viable outputs from it. This view is extremely appealing since it allows for the centralisation of information and services, leading to a continuously increasing cost efficiency [3].

Before exploring the wide range of possibilities it offers, its definition has to be understood. A digital twin is the virtual representation of one object or more, forming a system through establishing relationships and hierarchies between them, mirroring their interactions in reality. The accurate representation of these models is guaranteed through the collection of real-time data from IoT devices and its transmission, analysis and processing through appropriate services integrated with the cloud.

In the manufacturing industry, DTs give manufacturers insights, enabling them to make more accurate predictions, assisting and improving the decision-making process associated with the generated twin. It runs in parallel with simulations, machine learning, and reasoning to predict, identify and avoid possible bottleneck problems while optimising the system's performance, quality and overall efficiency [4]. Thus, the main focus of a DT is to reduce costs, optimise operations and enhance the customer experience in the original physical system.

Digital twins are among the several technologies believed to strongly impact the future of manufacturing through the combination of the cyber and physical dimensions. However, they are not independent technology.

The authors of [5] underline the importance of the cooperation between DT and big data analytics to achieve smart manufacturing. DTs can ingest an impressive volume of data throughout a product lifecycle. Then, by analysing it through advanced analytics, the performance of the product or process in the physical space can be improved.

Almost any system transmitting valuable data can have its digital twin representation, even though the most common applications are complex or rapidly changing environments, from production lines to entire factories or cities. This thesis intends to show how to deploy and take advantage of a DT environment in the manufacturing industry. For that, the concept has first to be understood.

3.1.1 Brief history and concept

Despite being considered an emerging technology, the DT concept was introduced in 2003 by Dr Michael Grieves as "A set of virtual information constructs that fully describes a potential or actual physical manufactured product from the micro atomic level to the macro geometrical level. At its optimum, any information that could be obtained from inspecting a physically manufactured product can be obtained from its Digital Twin" [6] [7]. Physical products, virtual products, and their connections were identified as the three components of DTs' first proposed format.

At this time, the technologies necessary for the development of DTs had severe limitations, preventing its evolution and, unavoidably, the scientific community's interest. From 2003 to 2011, the rapid growth of cloud computing, communication technology, Internet of Things (IoT), sensor technology, big data analytics, and simulation technologies led to the proliferation of DTs.

In 2012, NASA published an article recognising the importance of DTs, defining them as a "multiphysics, multiscale, probabilistic, ultra-fidelity simulation that reflects, in a timely manner, the state of a corresponding twin based on the historical data, real-time sensor data, and physical model" [8].

The interest of such a respected institution accelerated the research on the topic. Several authors reported their interpretation of the concept, yet the main disagreement is related to its composition. The most complete definition states that DTs must include five dimensions: physical part, virtual part, connection, data, and service [9]. Figure 3.1 presents a representation of the DT five dimensions. PE represents the physical entity; VE represents the virtual entity; Ss represents the services for both PE and VE; DD stands for the DT data; and CN means the connection of different parts [9].

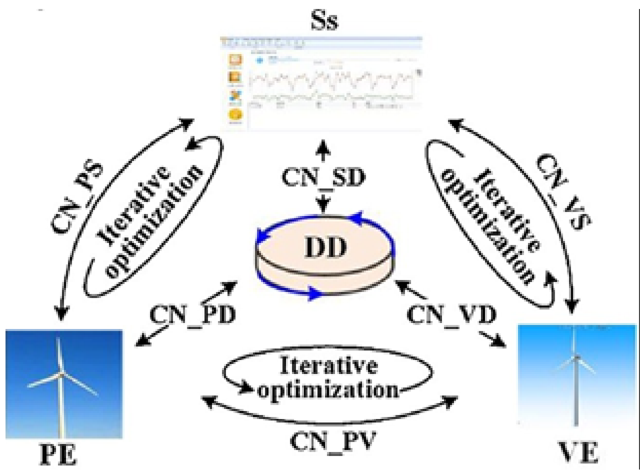

Figure 3.1: Five-dimension model for the DT.

The virtual environment enables simulation while representing the physical system accurately. Integrating sensor and manufacturing data with several services allows for the prediction of production metrics and monitorisation of machine operations [10], improving the system's efficiency, productivity and reliability. Lastly, the connection aggregates all the described components.

Nowadays, DTs are seen as a promising technological trend and are present in several industries due to their vast industrial applications. In order to fully get the possibilities they offer, there is the need to understand their common types and functions.

3.1.2 Types of digital twins

Digital twins are commonly classified according to their application area; however, it does not mean they cannot co-exist. It is essential to know the characteristics of each type and which are more appropriate to the required application so that the results obtained are the best possible when considering all the functionalities of this technology.

The digital twins are therefore divided into four categories with higher levels of importance and complexity, presented as follows. The study of these categories revealed how detailed and exact twin modelling should be.

Component Twins / Parts Twins

Defined as the twin of a single mechanism from the entire system. Components are crucial to the structure's functioning, directly impacting its performance and functionality. The objects defined as parts are similar but with considerable lower importance.

The typical applications at this level are, for example, part design and material deformation.

Asset Twins

Describe the interaction of two or more components as an asset while component twins are developed concerning the stability and durability of an independent object. It allows the user to verify whether the individual parts function correctly as a system and enables the simulation of various hypothetical situations to improve the overall performance of the twin and, consequently, the physical system.

System or Unit Twins

The aggregation of the existing assets facilitates the visualisation of how they work as a group regarding the assets' interactions and ideally identifies room for improvement within their collaboration, with the primary goal of increasing the system's performance.

Process Twins

Reveal how systems or units function as a whole representing an entire production facility. One of the vital factors is the timing in which all systems work together. This higher level of magnification's main objective is synchronising all the existing systems to achieve the best possible overall time and cost-efficiency. The most common applications of digital twins at this level of complexity are sequencing and plant layout. It is important to note that individual units producing too quickly also represent a problem related to higher storage and logistical costs.

This division simplifies the development of the digital twin environment through the representation of smaller models, allowing a better understanding of each component and facilitating modifications in each part. However, the digital twins solely reach their full potential at the process level, when all the components, assets and units function as a whole, fulfilling their purpose.

3.1.3 Industrial applications of DTs

The use of digital twins in the industrial sector can be applied in every stage of production, from the product's design to its end of life, assuring maximum efficiency throughout the whole process [11].

Predictive models supplied with historical data and expected performance outcomes can provide insights that allow the manufacturer to make slight changes or refinements before starting production and, therefore, avoid the traditional try and error method associated with waste and, consequently, unnecessary costs.

When integrated with autonomous systems, DTs can visualise and update the production status in real-time without requiring direct human interaction [12]. The ingestion of environment, operational, and process data allows autonomous systems to respond to unexpected changes during ongoing operations in the physical world or simulation.

During the planning phase, alongside the power of simulations, DTs are widely used to eradicate bottlenecks or verify the feasibility of the production plan [2]. During production, digital twins can monitor the global or specific processes, according to the company's desires and needs, with the continuous aim of achieving and maintaining peak efficiency.

A maintenance prospect is also one of the most utilised functions of a digital twin as it is essential for the final product quality and the machine's lifetime. These indicators can be obtained through historical data, allowing the DT producing warnings about the need to verify the state of a machine or even to change one of its components.

In specific cases, they can also be used to test the efficiency of a factory before its construction. Bosh is currently building a DT environment with thousands of twins to verify the efficiency of processes and factory floor design by ingesting data from other identical factories. This innovative technique can lead to the identification of bottlenecks and overall improvement and integration of several production lines in the digital world, allowing for the most efficient construction possible, reducing the associated costs substantially.

Furthermore, Microsoft provides several building scenarios of manufacturing instances that were used as inspiration to the development procedures explained in Chapter 4. As an example, their developers built a robotic arm assembly line and use simulated telemetry to show the DT capabilities.

All these fields of application show that the technology is evolving and increasing in popularity; however, companies tend to develop their own DTs, making it more challenging to integrate new developments with existing solutions and forcing an assessment of the best available software. This investigation is vital as the best option can differ substantially considering the company's activity, needs and data handling.

3.1.4 Supporting software

DTs interest on a mass scale is considerably recent, yet there are already many available options in the market from trusted institutions, including IBM, Siemens, Microsoft Azure, AWS (Amazon Web Services) and GCP (Google Cloud Platform).

Sonae Arauco has a cloud-based IT strategy, so the DT and any other emerging technology must be aligned with their methods. Therefore, the software used during the development of the concerned project was Microsoft Azure Digital Twins (ADT). Although extensive research was not carried out on defining the best solution, since the company provided the software mentioned, it has excellent advantages, mainly because it is connected with all the services available in Microsoft's cloud.

Microsoft Azure is one of the leading cloud services worldwide, allowing for interoperability between software directed to manufacturing and factory automation. Additionally, they show concern and a will to help the customer by providing extensive and easy-to-understand documentation. For example, they have made the Digital Twin Definition Language (DTDL's) specifications available to expand their open community and establish a standard language for defining DTs and their relationships.

3.2 Microsoft Azure services related to IoT and DTs

Before developing the proposed application, there is the need to understand multiple concepts and services inside the cloud. This research allows for more efficient deployment and integration of the available services, enhancing the DT potential.

The most important information regarding these concepts is presented in the following subsections.

3.2.1 Digital Twin Definition Language

DTDL is based on JSON-LD (JavaScript Object Notation for Linked Data) and is the language used to define executable models for Azure Digital Twins. Although it is programming-language independent and is mainly used for this application, it is not exclusive to ADT, being used in other IoT devices. It was made simple and user-friendly, making Microsoft's documentation extremely helpful in allowing a better understanding.

The models' definition is the foundation of any DT solution since they describe the types of entities in the built environment. When the projected solution is linked to a specific industry, it is more efficient to begin with a set of models previously made and openly shared called ontologies.

3.2.2 Ontologies

Ontologies provide a more immediate start for developing a new DT solution. However, in the exception of particular cases, it is never a perfect match. Many changes can be required to make the solution fully adequate to the considered case. Despite this, they assist developers in focusing on the final objective, like solving business problems.

Microsoft has a good policy to help their customers and supplies ontologies regarding different sectors that are easily extensible and, therefore, highly customisable to the idealised solution.

The usage of ontologies to the detriment of building models from scratch allows for the creation of DT instances with benefits, such as:

- Reduced investment in conceptual modelling and system development;
- Harmonisation of software components and documentation;
- Best practice for the reuse of the adapted models.

Ontology Adopted

The RealEstateCore ontology for smart buildings was the starting point for the model definition. Before presenting this ontology, it is important to state that, as the name suggests, it is an ontology directed to the real estate sector, a completely different sector from the production industry, where the current project locates itself. Figure 3.2 represents the ontology structure.

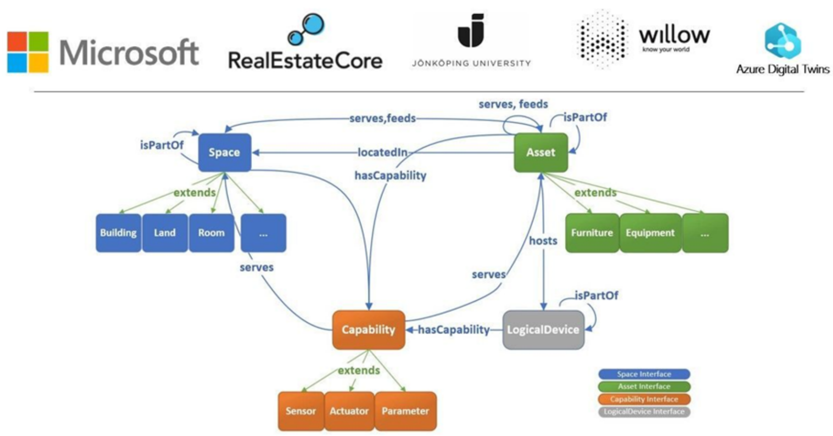

Figure 3.2: RealEstateCore, a smart building ontology for Digital Twins.

Therefore, the ontology was used solely as a structural and organisational guide for developing the model graphic, particularly in defining the relationships between each model. However, the existent models' content was modified to match the production industry and Sonae Araucos's plants.

Before creating the DT associated with these models, it is necessary to understand what each class of models represent. Table 3.1 includes a brief description of each core model. These models have a great deal of importance and form the base of all the remaining models since they can be extended. A model that extends another inherits all of the referenced model's properties, relationships, and components.

Table 3.1: Core models of the RealEstateCore ontology.

Core Model	Description
Agent	Represents any basic types of stakeholder that can have roles or perform activities. For example: people, companies, departments.
Space	Represents a physical structure that has a 3D spatial extent and can contain, or not, sub-spaces. For example: a region can contain a factory, which can contain different production areas.
Asset	Represents an object located inside or outside a space, without being a structural part of such space. For example: equipment and machines.
Logical Device	A piece of equipment or software that communicates and interacts with a digital twin platform. Logical devices can have Capability instances that describe their input/output capabilities.
Capability	Represents the capacity of an entity to produce or ingest data. It is composed by numerous sub-classes, like Sensors that mimic the harvest of data from the real world, Actuators that accept commands from the digital twin platform, and Parameters that are previously defined by the user.

There is an open standard for exchanging information between partners in the manufacturing value chain: the Industry 4.0 Asset Administration Shell (AAS). Studies are trialling the applicability of using the AAS as a base for building an ontology for smart production. This ontology would be more suitable for the current application; however, it is not finalised, so, despite not being the most adequate, the RealEstateCore ontology was used and appropriately modified.

3.2.3 Azure IoT Hub

Azure IoT Hub is a cloud-based service that acts as a central messaging hub for IoT applications and device communications. Millions of devices can be securely linked with their backend solutions. It is a universal service as most devices can be linked to an IoT hub.

3.2.4 Azure Event Hubs

Azure Event Hubs is an event ingestion and big data streaming platform. It has the capability to receive and process millions of events per second. Event

Hubs enables the dissemination of telemetry and event data to multiple stream-processing. This service offers a unified solution for quickly retrieving data for real-time processing.

The Figure 3.3 shows the Event Hubs stream processing architecture:

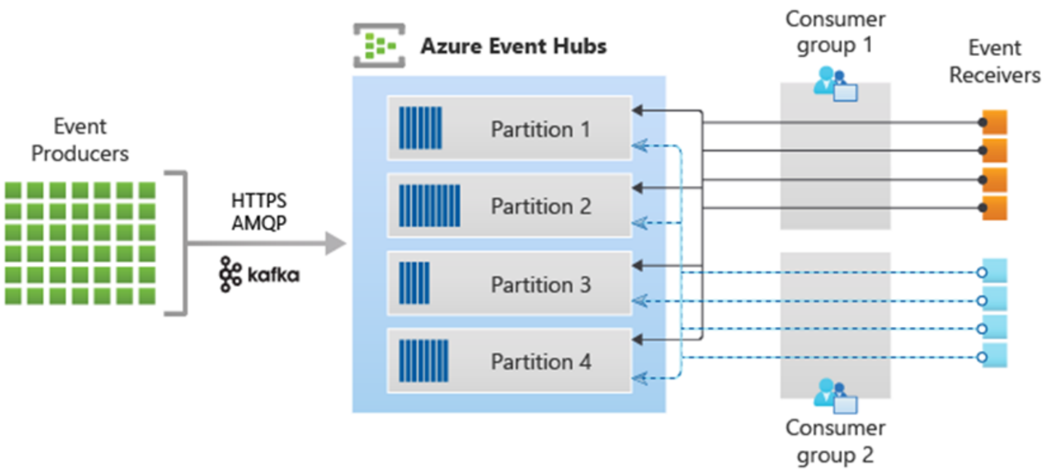

Figure 3.3: Event Hubs stream processing architecture.

3.2.5 Azure Event Grid Topic

Event Grid is a highly scalable, serverless event broker that integrates applications using events. Eliminating the necessity for constant polling, simplifies event consumption and reduces expenses. Event Grid transports events from Azure and non-Azure services efficiently and delivers the events to subscriber endpoints. Event Grid is not a data pipeline and does not provide the updated object itself.

Figure 3.4 displays the most common event sources and event handlers supported by Event Grid.

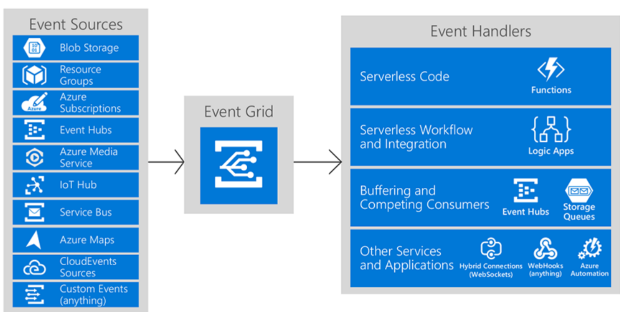

Figure 3.4: List of event sources and event handlers supported By Event Grid.

3.2.6 Endpoints and event routes

An event route enables the transmission of event data from digital twins in Azure Digital Twins to user-defined endpoints. Before an event route can be defined, its destination must be established. Destinations supported include Event Grid custom topics, Event Hubs, and Service Bus.

Each of these three Azure services can be linked to other services and functions as an intermediary, transmitting data to final destinations like Time Series Insights.

3.2.7 Azure Function Apps

Azure Functions is a serverless solution that enables developers to write less code, maintain less infrastructure and, consequently, save money. Instead of building and maintaining servers, the cloud architecture delivers all current resources required to keep the developed apps operational. Figure 3.5 highlights the composition of an Azure Function.

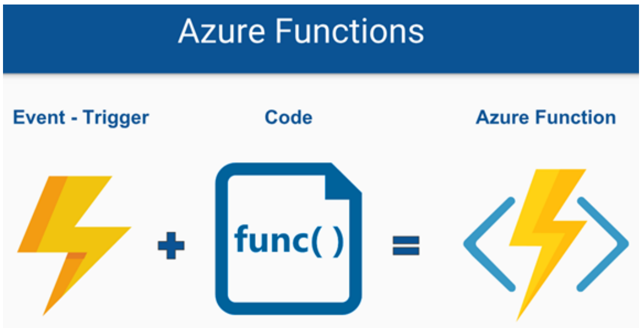

Figure 3.5: composition of an Azure Function.

Every application requires a method to execute code when certain events occur. Therefore, Azure Functions enables the implementation of the system's logic into accessible blocks of code known as "functions".

This service allows using several languages like C#, Java, JavaScript, PowerShell, or Python. Another significant advantage is the debug possibilities it offers. Through the usage of logs, the developer can troubleshoot a function while running it online and solve issues or gain insights into the applications.

3.2.8 ADT 3D scenes studio

Azure Digital Twins 3D Scenes Studio (preview) is a 3D environment in which users may monitor, troubleshoot, and examine operational data in the context of 3D assets. 3D Scenes Studio enables businesses to enhance current 3D models with Azure Digital Twins data.

There, 3D objects can be connected to digital twins, which gives a realistic visual image of the data being ingested. Metrics can also be implemented to change the colour of elements if the ingested signal changes or create alerts.

3D design skills are not mandatory as there are several visualisations available online. Despite this, a 3D environment was not developed in this project since it is a recent application, and there were other priorities. Even so, it is a valuable tool to integrate with digital twins.

3.2.9 Azure Time Series Insights

Azure Time Series Insights is a second-generation end-to-end IoT analytics service. It can capture, analyse, store, query, and display data.

Azure Time Series Insights Gen2 is destined for data exploration and operational examination, enabling users to discover hidden patterns, find irregularities, and investigate the root of an issue. It is an open and adaptable solution that suits the diverse requirements of industrial IoT projects.

Besides, it can filter, clean and prepare data for analysis, serve as a framework to facilitate the comprehension of the data, and store data cost-efficiently.

3.3 Predictable implementation difficulties

DTs have some documented cases of success in their implementation. Nevertheless, as mentioned before, every field of application requires specific methodologies and adequate connection of resources, so it is not guaranteed that the software can be applied in any situation.

Microsoft plays a significant role in this project since almost the whole extent of services and applications utilised are supplied by the software development company and integrated with their cloud.

Therefore, more than the proof of concept of DTs, there is the need to rely on the digital technology supplied. This concern is barely related to the quality of the services available since Microsoft is one of the leading companies in the market. Nevertheless, many questions related to this implementation arise. It is not assured that Azure has all the tools needed or that their integration is as simple as they promise.

It is also unknown whether the software is too complicated to put into practice, creating the possibility of some issues not being overcome. One of the predicted difficulties is to obtain all the attributes necessary to develop a complete simulation, which can negatively impact the outcomes and influence the DT validation.

Thus, after obtaining the results, there is the need to analyse them critically to separate the possible errors or inefficiencies of the simulation from the DT capabilities.

3.4 Summary

The research that led to the writing of this chapter was fundamental for its development. The awareness of the existent DT types, their differences and examples of industrial applications allowed a better development process. The DT technology does not run by itself so the Azure services it can be integrated with were also investigated.

This study advantages were perceived during the implementation of the project presented in Chapter 4. It describes in detail the development process by presenting the methods followed and tasks performed. Their final objective is to create outputs comparable with what happens in reality so that the simulation and, consequentially, the DT can be assessed.

Chapter 4

Project development

After knowing the functionalities and characteristics of the services Azure provides to integrate with the DT, the system design was the logical next step. This knowledge, alongside understanding the production line elements, behaviour and problems, allowed for efficient development of the DT environment, which includes all of the elements presented in the system's architecture.

The numerous parts of the final system and the steps necessary to connect them with ADT are then presented. This process began with the models' extensions, which allowed the twins' creation. For the integration process, two C# functions were developed to ingest the necessary data, run the built simulation and connect with the output.

4.1 System architecture

The definition of the system architecture serves as a guide to the work being developed and allows for a better understanding of it. Thus it is a crucial part of the early stages of the project's development.

The system is almost entirely cloud-based, using the services integrated into the Microsoft cloud (Azure). The diagram in Figure 4.1 shows the architecture from the physical factory to the DT created. The previously existing connections are differentiated from the ones implemented, and the different stages are highlighted.

At the starting point of the development, the totality of the data from the factories was already collected by the IoT Hub. However, it is interesting to understand how the data is routed from the sensor to the cloud. This local path is represented in red. Each factory has an industrial edge server, meaning that more than one edge device can exist in each location as long as a Microsoft component is installed. This component has several functions:

- Module for collecting data from the OPC-UA server;

- Module to read the requested data in real-time that are on the Shop Floor, their Manufacturing Execution System (MES);

- Calculation module to act on the signals that require any transformation in real-time;
- An alarmistic module that crosses the signals against the configuration of alarms present in the cloud (smart notifications);
- Final integration of all the signals in Azure.

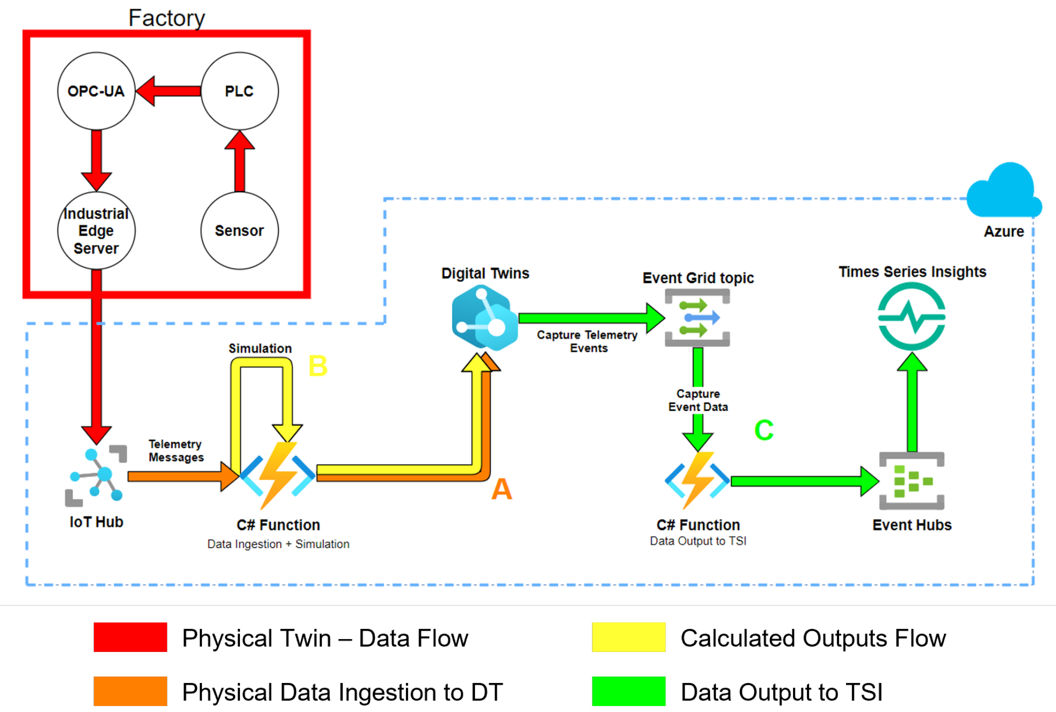

Figure 4.1: System's architecture.

The edge is not an obligatory tool. Nevertheless, it is included in Microsoft's reference architecture, and the company follows their directives. On the cloud, the data consumption is done in several ways through the available web apps: Power BI, TSI, Grafana and Azure Data Explorer. In the current project, TSI was the utilised application.

After understanding the local data flow and how it arrives in the cloud, it is necessary to define a clear path from the starting point to visualising the outputs.

Section A, in orange, represents the ingestion of telemetry data from the IoT Hub to the Digital Twins environment through a C# function. The necessary data is filtered in this function according to the existent twins. This means that if a new twin is created with the proper Id, the function will provide its attributes automatically. This section is described in detail in subsection 4.4.1.

Section B, in yellow, represents the data flow related to the simulation. The necessary calculations are performed in the ingestion function, for reasons explained in Section 4.5, and the outputs are provided to the appropriate twin in the DT environment.

Section C, in green, uses two messaging platforms to supply the outputs to TSI. First, it is necessary to create an endpoint in ADT that connects the instance to the Event Grid topic and set up a route within Azure Digital Twins that sends twin property change events to the endpoint. Then, the Event Grid topic enables data movement between the DT environment and the Function App developed to update the TSI. Before that, the data has to be treated inside the function through a method explained in Subsection 4.4.2, to have the correct structure for its display. Posteriorly, it is supplied to an Event Hubs that streams the DT events to TSI.

The modelling and creation of twins was a crucial stage of the early development of the solution and was executed as follows.

4.2 Models development

In Chapter 3 Subsection 3.2.2, the RealEstateCore ontology for smart buildings was presented. This ontology was the starting point for the model definition, yet, for the reasons stated before, some considerable modifications had to the performed to make the models directed to the manufacturing industry and, more specifically, to Sonae Arauco's plants.

The ontology has a wide range of models; however, 42 models were used for this application. The core models, presented in Subsection 3.2.2, were used, except for the Logical Device since a simpler Output model replaced it. The remaining models were almost all modified or extended.

In Subsection 4.2.1, the extensions and modifications are presented, with the help of some examples for visual comprehension. After defining the models, their hierarchies are represented in a model graphic.

4.2.1 Extensions and modifications

The main modifications were performed regarding the attributes of each model. The Asset model had several properties directly related to the real estate sector that were replaced by others linked to the manufacturing industry. In the example in Figure 4.2, the capacity-related attributes and The Tags and Ids were eliminated for the same Space model, and the area code was added.

Willow, a global technology company with their own DT, recommends "to be as specific as possible when creating twins to provide the most detailed classification. As such, the "child" model which extends the "parent" should always be used". This was the methodology used.

The extensions made were crucial for the most accurate representation of reality. This method helps in the hierarchy definition while transferring properties across models. In the Asset family, many physical devices differ considerably from those represented in the ontology. As it is directed to the real estate business, the assets defined were furniture or cooling devices, and on the melamine production line, there are, for example, a press, conveyors and a saw. This disparity required a thorough assessment of the existing elements and which attributes they possess.

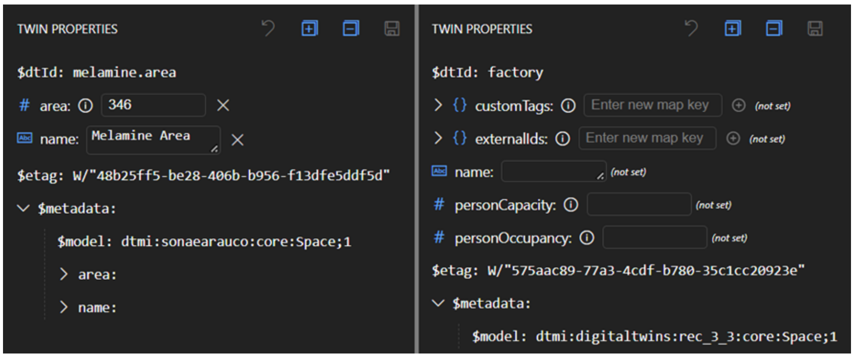

Figure 4.2: Space model modifications.

Within the capabilities, the same process was carried out. On top of that, the type of schema of the ingested data had to be enumerated for posteriorly manual selection upon the twin creation. This allowed the ingestion function to know the type of schema it could provide to each twin and was an essential step for integrating Azure services. In Figure 4.3, it is displayed the example of a twin created from a binary sensor model that extends the attributes of the Capability model.

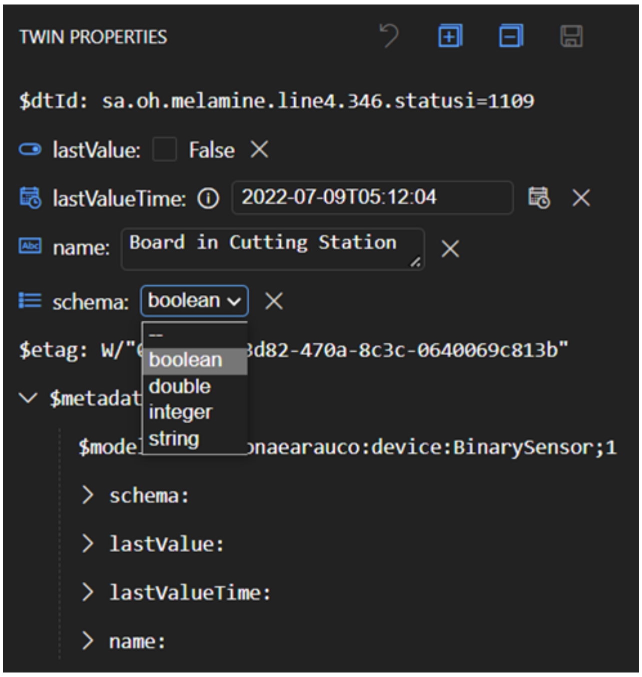

Figure 4.3: Twin created from a binary sensor model extended from the capability model.

4.2.2 Model graph

The model graphic, represented in Figure 4.4, gives a visual insight into the hierarchies and relations between models. The possible relationships between core models are represented in orange, the extensions in green and the link between component and asset in blue.

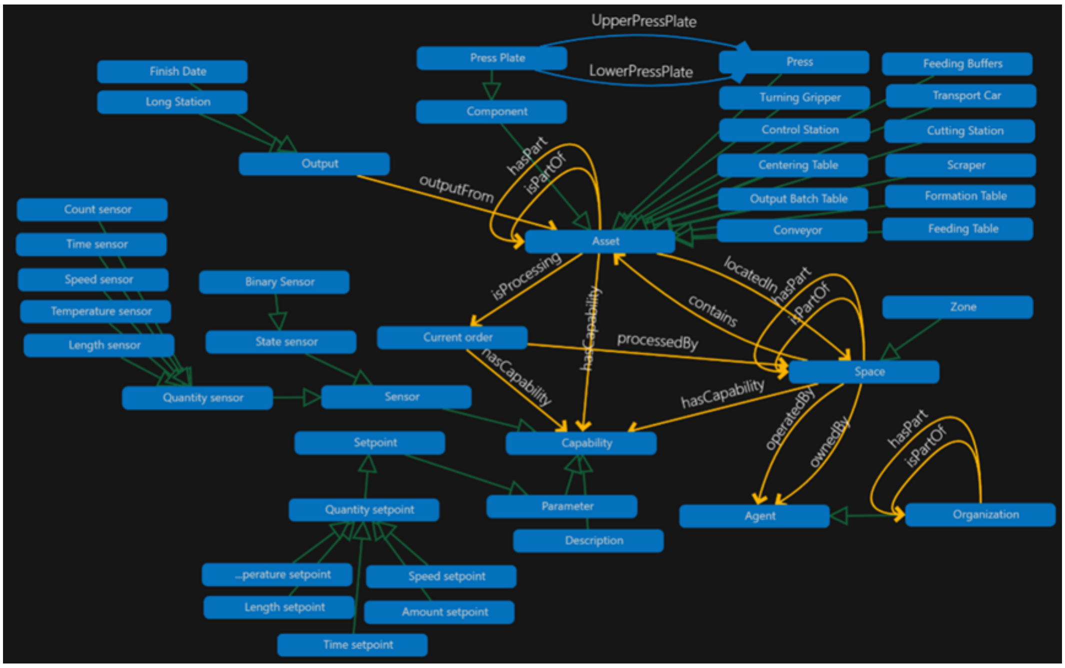

Figure 4.4: Model graphic represented in the ADT.

4.3 DT creation

The twins can be created when all the models are defined and the attributes selected. The process is simple and intuitive. The twins will mirror the behaviour of the physical devices they represent by ingesting its telemetry. The structure of the twin will be provided by the model used for its creation.

After selecting the correct model, a unique twin Id has to be chosen. Apart from a few exceptions, the Id can be anything. In this application, only the name of the capabilities has defined naming rules. Such rules were necessary because it was the most efficient way to relate a property to its designated twin, facilitating the ingestion process. The company catalogues the ingested properties with two codes: the Application Uri and the Node Id. Their combination makes each property unique, making it ideal to name the twins associated with this data.

In total, from the 42 uploaded models, 98 twins were created. The twins that are not correspondent to properties ingested from the cloud are represented in Table 4.1. These twins are related to the Space or Asset models and represent the physical entities that possess the capabilities presented in the following subsection.

Table 4.1: Space and asset Digital Twins, correspondent models and relationships.

Name	Model Id	Twin Id	Relationship (From)	Relationship (To)	Relationship Name
BP9 Melamine Line	dtmi:sonaearauco:core:Asset;1	bp9line			
Sonae Arauco	dtmi:sonaearauco:agents:Organization;1	sonaearauco	ohfactory		ownedBy
Oliveira do Hospital Factory	dtmi:sonaearauco:core:Space;1	ohfactory	melaminearea		isLocationOf
Melamine Area	dtmi:sonaearauco:core:Space;1	melaminearea	bp9line		isPartOf
Press	dtmi:sonaearauco:asset:Press;1	press.bp9		bp9line	isPartOf
Upper Press Plate	dtmi:sonaearauco:asset:PressPlate;1	upperplate.bp9		press.bp9	isPartOf
Bottom Press Plate	dtmi:sonaearauco:asset:PressPlate;1	bottomplate.bp9		press.bp9	isPartOf
Current Production Order	dtmi:sonaearauco:core:CurrentOrder;1	currentorder.bp9	bp9line		isProcessing
Scraper	dtmi:sonaearauco:asset:Scraper;1	scraper.bp9		bp9line	isPartOf
Saw	dtmi:sonaearauco:asset:CuttingStation;1	saw.bp9		bp9line	isPartOf
Control Station	dtmi:sonaearauco:asset:ControlStation;1	station.control.bp9		control.zone.bp9	locatedIn
Car Before Press	dtmi:sonaearauco:asset:TransportCar;1	car.before.press.bp9		bp9line	isPartOf
Car After Press	dtmi:sonaearauco:asset:TransportCar;1	car.after.press.bp9		bp9line	isPartOf
Formation Station 1	dtmi:sonaearauco:asset:FormationTable;1	station1.formation.bp9		formation.zone.bp9	locatedIn
Formation Station 2	dtmi:sonaearauco:asset:FormationTable;1	station2.formation.bp9		formation.zone.bp9	locatedIn
Formation Zone	dtmi:sonaearauco:core:Zone;1	formation.zone.bp9		bp9line	hasPart
Control Zone	dtmi:sonaearauco:core:Zone;1	control.zone.bp9		bp9line	hasPart
Turning Gripper	dtmi:sonaearauco:asset:TurningGripper;1	turning.gripper.bp9		bp9line	hasPart
Conveyor - Saw to Centering	dtmi:sonaearauco:asset:Conveyor;1	conveyor.saw.to.centering.bp9		bp9line	isPartOf
Board Input Table	dtmi:sonaearauco:asset:FeedingTable;1	board.input.table.bp9		board.feeding.zone.bp9	locatedIn
Table 13	dtmi:sonaearauco:asset:FeedingTable;1	table13.bp9		formation.zone.bp9	locatedIn
Table 14	dtmi:sonaearauco:asset:FeedingTable;1	table14.bp9		formation.zone.bp9	locatedIn
Board Feeding Zone	dtmi:sonaearauco:core:Zone;1	board.feeding.zone.bp9		bp9line	hasPart
Centering Table	dtmi:sonaearauco:asset:CenteringTable;1	centering.table.bp9		bp9line	hasPart

4.3.1 Telemetry and properties ingested

The assessment of the telemetry and properties to be ingested had to be performed. This process involved studying the production line while checking for the availability of the needed IoT devices.

For the selected use case, most of the signals desired were the binary position indicators in the multiple stations of the line. These signals are the output of photocells spread throughout the line. However, other properties of specific assets, like the press, are interesting to obtain for a better definition of the asset itself, the process and assistance in the simulation.

Figure 4.5: Analysis of sequence in signals on the cutting saw station.

Most of the required binary signals coming from sensors already existed, but some had to be implemented in the factory. To understand their behaviour and test usability in sequence, TSI was used. In Figure 4.5, an example of this test is used. This particular situation had to be verified, and changes in the simulation were made because of what was discovered. It is noticeable that the sensor on the first column starts before the other, having some time actuated simultaneously. This situation evaluation is justified and discussed in detail in section 4.5.2.

Since the simulation is meant to predict the duration of a production order, many properties related to each production order must be ingested into the DT environment. The properties ingested from the BP9 line are presented in Table 4.2 with their identifying name, twin Id, associated model and relationships.

Table 4.2: Capability Digital Twins, correspondent models and relationships.

Name	Model Id	Twin Id (ApplicationUri + NodeId)	Relationship (From)	Relationship Name
Thermal Cycle Time	dtmi:sonaearauco:device:TimeSensor;1	sa.oh.melamine.line4.346.statusi=1001	press.bp9	hasCapability
Mechanical Cycle Time	dtmi:sonaearauco:device:TimeSensor;1	sa.oh.melamine.line4.346.statusi=1002	press.bp9	hasCapability
Total Cycle Time	dtmi:sonaearauco:device:TimeSensor;1	sa.oh.melamine.line4.346.statusi=1003	press.bp9	hasCapability
Upper Press Plate Temperature	dtmi:sonaearauco:device:TemperatureSensor;1	sa.oh.melamine.line4.346.statusi=1068	upperplate.bp9	hasCapability
Bottom Press Plate Temperature	dtmi:sonaearauco:device:TemperatureSensor;1	sa.oh.melamine.line4.346.statusi=1080	bottomplate.bp9	hasCapability
Target Line Speed press/h	dtmi:sonaearauco:device:SpeedSetpoint;1	sa.oh.melamine.line4.346.statusDynamic#Target#i=1005	bp9line	hasCapability
Line Speed m3/h	dtmi:sonaearauco:device:SpeedSensor;1	sa.oh.melamine.line4.346.statusi=1004	bp9line	hasCapability
Line Speed press/h	dtmi:sonaearauco:device:SpeedSensor;1	sa.oh.melamine.line4.346.statusi=1005	bp9line	hasCapability
Formation Temperature	dtmi:sonaearauco:device:TemperatureSensor;1	sa.oh.melamine.line4.346.statusi=1013	press.bp9	hasCapability
Consumed Boards	dtmi:sonaearauco:device:CountSensor;1	sa.oh.melamine.line4.346.statusi=1025	bp9line	hasCapability
Line Running	dtmi:sonaearauco:device:BinarySensor;1	sa.oh.melamine.line4.346.statusi=1000	bp9line	hasCapability
Press Count	dtmi:sonaearauco:device:CountSensor;1	sa.oh.melamine.line4.346.statusi=1006	press.bp9	hasCapability
Plate Change On	dtmi:sonaearauco:device:BinarySensor;1	sa.oh.melamine.line4.346.statusi=1008	press.bp9	hasCapability
Theoric Thermal Cycle Time	dtmi:sonaearauco:device:TimeSetpoint;1	sa.oh.melamine.line4.346.statusi=1012	press.bp9	hasCapability
Theoric Mechanical Cycle Time	dtmi:sonaearauco:device:TimeSetpoint;1	sa.oh.melamine.line4.346.statusi=1019	press.bp9	hasCapability
Run Time Current Order	dtmi:sonaearauco:device:TimeSensor;1	sa.oh.melamine.line4.346.performance.currentorderi=1010	currentorder.bp9	hasCapability
Short Article Description	dtmi:sonaearauco:device:Description;1	sa.oh.melamine.line4.346.status.currentorderi=1015	currentorder.bp9	hasCapability
Stopped Time Current Order	dtmi:sonaearauco:device:TimeSensor;1	sa.oh.melamine.line4.346.performance.currentorderi=1012	currentorder.bp9	hasCapability
Set Point Upper Temperature	dtmi:soanaearauco:device:TemperatureSetpoint;1	sa.oh.melamine.line4.346.statusi=1069	upperplate.bp9	hasCapability
Cut Length	dtmi:sonaearauco:device:LengthSensor;1	sa.oh.melamine.line4.346.statusi=1070	saw.bp9	hasCapability
Cut Active	dtmi:sonaearauco:device:BinarySensor;1	sa.oh.melamine.line4.346.statusi=1071	saw.bp9	hasCapability
Total Boards CurrentOrder	dtmi:sonaearauco:device:CountSensor;1	sa.oh.melamine.line4.346.output.currentorderi=1006	currentorder.bp9	hasCapability
Set Point Bottom Temperature	dtmi:soanaearauco:device:TemperatureSetpoint;1	sa.oh.melamine.line4.346.statusi=1081	bottomplate.bp9	hasCapability
MicroStops Average	dtmi:sonaearauco:device:TimeSensor;1	sa.oh.melamine.line4.346.statusi=1150	currentorder.bp9	hasCapability
Currentprod (un)	dtmi:sonaearauco:device:CountSensor;1	sa.oh.melamine.line4.346.statusi=1015	currentorder.bp9	hasCapability
Current prod Length	dtmi:sonaearauco:device:LengthSensor;1	sa.oh.melamine.line4.346.statusi=1016	currentorder.bp9	hasCapability
Current prod width	dtmi:sonaearauco:device:LengthSensor;1	sa.oh.melamine.line4.346.statusi=1017	currentorder.bp9	hasCapability
Current prod height	dtmi:sonaearauco:device:LengthSensor;1	sa.oh.melamine.line4.346.statusi=1018	currentorder.bp9	hasCapability
Produced Boards 1 Current Order	dtmi:sonaearauco:device:CountSensor;1	sa.oh.melamine.line4.346.output.currentorderi=1001	currentorder.bp9	hasCapability
Produced Boards 2 Current Order	dtmi:sonaearauco:device:CountSensor;1	sa.oh.melamine.line4.346.output.currentorderi=1002	currentorder.bp9	hasCapability
Article Number	dtmi:sonaearauco:device:Description;1	sa.oh.melamine.line4.346.status.currentorderi=1001	currentorder.bp9	hasCapability
Current Order	dtmi:sonaearauco:device:Description;1	sa.oh.melamine.line4.346.status.currentorderi=1000	currentorder.bp9	hasCapability
New Order Trigger	dtmi:sonaearauco:device:BinarySensor;1	sa.oh.melamine.line4.346.status.currentorderi=1011	currentorder.bp9	hasCapability
Real Start Date	dtmi:sonaearauco:device:TimeSensor;1	sa.oh.melamine.line4.346.status.currentorderi=1017	currentorder.bp9	hasCapability
Planned Qte	dtmi:soanaearauco:device:AmountSetpoint;1	sa.oh.melamine.line4.346.status.currentorderi=1007	currentorder.bp9	hasCapability
Thickness	dtmi:soanaearauco:device:LengthSetpoint;1	sa.oh.melamine.line4.346.status.currentorderi=1004	currentorder.bp9	hasCapability
Width	dtmi:soanaearauco:device:LengthSetpoint;1	sa.oh.melamine.line4.346.status.currentorderi=1002	currentorder.bp9	hasCapability
Length	dtmi:soanaearauco:device:LengthSetpoint;1	sa.oh.melamine.line4.346.status.currentorderi=1003	currentorder.bp9	hasCapability
Board in Control Station 1	dtmi:sonaearauco:device:BinarySensor;1	sa.oh.melamine.line4.346.statusi=1092	station1.control.bp9	hasCapability
Board in Control Station 2	dtmi:sonaearauco:device:BinarySensor;1	sa.oh.melamine.line4.346.statusi=1093	station2.control.bp9	hasCapability
Board in car before press	dtmi:sonaearauco:device:BinarySensor;1	sa.oh.melamine.line4.346.statusi=1089	car.before.press.bp9	hasCapability
Press Not Open	dtmi:sonaearauco:device:BinarySensor;1	sa.oh.melamine.line4.346.statusi=1090	press.bp9	hasCapability
Board in car after press	dtmi:sonaearauco:device:BinarySensor;1	sa.oh.melamine.line4.346.statusi=1091	car.after.press.bp9	hasCapability
Board at station 2	dtmi:sonaearauco:device:BinarySensor;1	sa.oh.melamine.line4.346.statusi=1105	station2.formation.bp9	hasCapability
Board at station 1	dtmi:sonaearauco:device:BinarySensor;1	sa.oh.melamine.line4.346.statusi=1106	station1.formation.bp9	hasCapability
N of boards in the truning gripers	dtmi:sonaearauco:device:CountSensor;1	sa.oh.melamine.line4.346.statusi=1104	turning.gripper.bp9	hasCapability
Board entering turning gripper	dtmi:sonaearauco:device:BinarySensor;1	sa.oh.melamine.line4.346.statusi=1094	turning.gripper.bp9	hasCapability
Board in Cutting Station	dtmi:sonaearauco:device:BinarySensor;1	sa.oh.melamine.line4.346.statusi=1109	saw.bp9	hasCapability
Board leaving Cutting Station	dtmi:sonaearauco:device:BinarySensor;1	sa.oh.melamine.line4.346.statusi=1110	saw.bp9	hasCapability
Board leaving Conveyor to Centering	dtmi:sonaearauco:device:BinarySensor;1	sa.oh.melamine.line4.346.statusi=1112	conveyor.saw.to.centering.bp9	hasCapability
Board at Board Input Table	dtmi:sonaearauco:device:BinarySensor;1	sa.oh.melamine.line4.346.statusi=1083	board.input.table.bp9	hasCapability
Board at Table 13	dtmi:sonaearauco:device:BinarySensor;1	sa.oh.melamine.line4.346.statusi=1085	table13.bp9	hasCapability
Board at Table 14	dtmi:sonaearauco:device:BinarySensor;1	sa.oh.melamine.line4.346.statusi=1086	table14.bp9	hasCapability
Board at Centering Table	dtmi:sonaearauco:device:BinarySensor;1	sa.oh.melamine.line4.346.statusi=1102	centering.table.bp9	hasCapability
Turning tool output boards	dtmi:sonaearauco:device:CountSensor;1	sa.oh.melamine.line4.346.output.currentorderi=1008	turning.gripper.bp9	hasCapability

4.3.2 Relationships between twins

The only step missing to finalise the DT environment is the representation of the relationships between them. This helps visualise the hierarchies and types of connections while organising and allowing for better twin graphic comprehension.

The relationship names may be selected freely. The direction of the relationship is not standardised, yet Willow affirmed that "relationships should be defined on the "children" twins with an outgoing relationship to a common "parent". Apart from the capabilities, this was the procedure followed.

The existing relationships are displayed in Tables 4.1 for the first Asset and Space twins, in Table 4.2 for the Capabilities and in Table 4.3 for the outputs. They have to be defined in the model contents and can be directed to a specific model, selected in the target, or to the general case. Figure 4.6 shows an example of the relationship definition for an Asset model.

```
{
  "@type": "Relationship",
  "description": {
    "en": "The coverage or impact area of a given Asset or Sensor/Actuator."
  },
  "displayName": {
    "en": "serves"
  },
  "name": "serves"
},
{
  "@type": "Relationship",
  "description": {
    "en": "Indicates that an or Asset is served by some Sensor/Actuator or other Asset."
  },
  "displayName": {
    "en": "served by"
  },
  "name": "servedBy"
},
{
  "@type": "Relationship",
  "displayName": {
    "en": "is processing"
  },
  "name": "isProcessing",
  "target": "dtmi:sonaearauco:core:CurrentOrder;1"
},
{
  "@type": "Relationship",
  "description": {
    "en": "Indicates a super-entity of the same base type. Inverse of: hasPart"
  },
  "displayName": {
    "en": "is part of"
  },
  "name": "isPartOf",
  "target": "dtmi:sonaearauco:core:Asset;1"
},
{
  "@type": "Relationship",
  "description": {
    "en": "Points to sub-entities that share the same base type. Inverse of: isPartOf"
  },
  "displayName": {
    "en": "has part"
  },
  "name": "hasPart",
  "target": "dtmi:sonaearauco:core:Asset;1"
},
{
  "@type": "Relationship",
  "displayName": {
    "en": "has capability"
  },
  "name": "hasCapability",
  "target": "dtmi:sonaearauco:core:Capability;1"
},
{
  "@type": "Relationship",
  "displayName": {
    "en": "located in"
  },
  "name": "locatedIn",
  "target": "dtmi:sonaearauco:core:Space;1"
},
```

Figure 4.6: Relationship definition for an asset model.

4.3.3 Twin graph

The twin graphic in Figure 4.7 shows the final result of the DT implementation with the twins created from the models and connected through the given relationships. At first sight, the graphic has a complex aspect due to the high number of twins created yet, when divided by zones, its comprehension becomes easier. The DT software separates the twins developed through the same model by colours, which facilitates graphic reading. The DT graphic is supplied in Appendix A, divided in four parts to allow for a better visualisation.

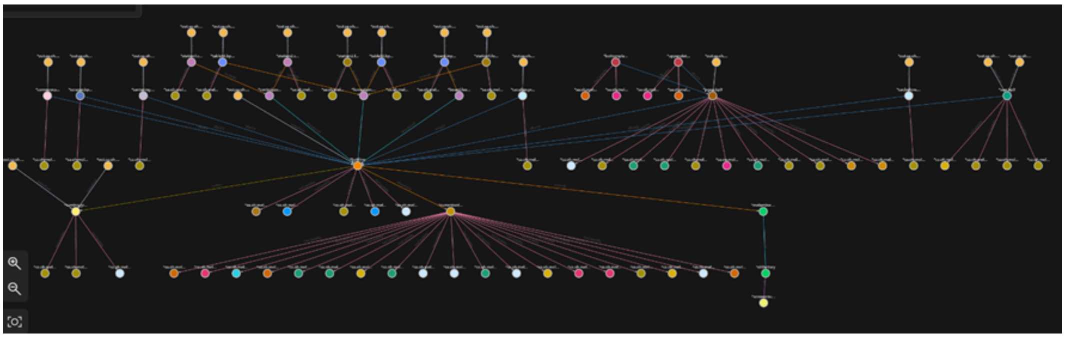

Figure 4.7: Twin graphic.

4.4 C# functions developed

The DT environment collects the data representing reality, gathering all the necessary information in the same place. This, alongside Azure's services, allows data to be used for many distinct applications. However, there is the need for a connection to streamline the stored data. This connection can be made through C# functions. The software used to code these functions was Microsoft Visual Studio 2022.

In Subsections 4.4.1 and 4.4.2, the developed functions are described. Their objectives, trigger type and logic, are presented.

4.4.1 Data ingestion

The data ingestion from the IoT Hub to the DT environment happens in section A of the system's architecture, represented in Figure 4.8.

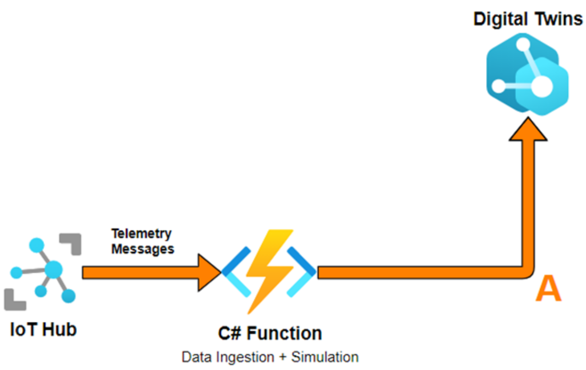

Figure 4.8: Data path from IoT Hub to DT.

The final simulation is done inside this function; however, due to its importance and complexity, it is presented in Section 4.5. The reasons behind this connection are also presented.

The function type is IoT Hub trigger meaning that for each trigger received on the IoT Hub, being it a message or an array of messages, the function receives that message or array and processes it.

In order to be able to code in the most efficient way possible, there is the need to use packages referred to as using systems. In Figure 4.9, the packages utilised in this function are displayed.

```
using IoTHubTrigger = Microsoft.Azure.WebJobs.EventHubTriggerAttribute;
using System;
using Microsoft.Azure.WebJobs;
using Microsoft.Extensions.Logging;
using Newtonsoft.Json.Linq;
using Newtonsoft.Json;
using System.Threading.Tasks;
using System.Net.Http;
using Azure;
using Azure.Core.Pipeline;
using Azure.Identity;
using Azure.DigitalTwins.Core;
using Azure.Messaging.EventHubs;
using System.Collections.Concurrent;
using System.Collections.Generic;
```

Figure 4.9: Using system packages utilised in the data ingestion function.

The logic behind the function is briefly described: First, there is the need to connect with the IoT Hub to receive the messages and with the ADT client to supply those messages.

Then, the following steps will be made only if the event received has content (is not null). This is to avoid the update of twins without data, which could lead to errors in the simulation.

On this occasion:

- If the message starts with "[", "it means it is an array, and it is converted into messages;
- Else messages are deserialised from JSON to a .NET object to be able to be read by the function;

Only then the function can process the intended data. For each object:

- The property Application Uri and Node Id are obtained and joined to create the twin Id. Note: the twins' naming convention does not allow for specials characters like ":" so there is the need to replace ":" with ".";
- Besides, the function saves two properties: the value and the source timestamp;
- Before the twin update, it is necessary to convert the ingested value, saved as a string, to the correct schema, or the twin will not ingest it.
- Then the simulation is updated with the new information ingested;
- Finally, to update the twin, a JSON patch document is created for each property to update. They contain the path and the value the correct twin should be updated with. The properties updated are the last value and the time it was registered.

4.4.2 Data output to TSI

The data output from the IoT Hub to the TSI environment happens in section C of the system's architecture, represented in Figure 4.10. The C# function captures the events from the ADT client, transmitted through the Event Grid topic, and supplies them to the Event Hubs with the necessary format. The remaining path is done through the cloud.

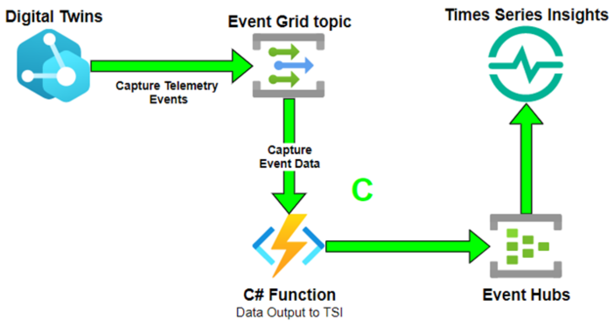

Figure 4.10: Data path from DT to TSI.

The function type is Event Grid trigger meaning that for each trigger received on the Event Grid Topic, the function receives that message and processes it. This messaging service allows filtering messages and selecting the size of the array, among other functionalities. On this occasion, it was used to stream individual messages from the DT to the TSI environments.

As for the Data Ingestion function, there is the need to use packages referred to as using systems. In Figure 4.11, the packages utilised in this function are displayed.

```
using Azure.Core.Pipeline;
using Azure.DigitalTwins.Core;
using Azure.Identity;
using Microsoft.Azure.WebJobs;
using Microsoft.Azure.WebJobs.Extensions.EventGrid;
using Microsoft.Extensions.Logging;
using Newtonsoft.Json;
using Newtonsoft.Json.Linq;
using System;
using System.Net.Http;
using System.Threading.Tasks;
using System.Collections.Generic;
using Azure.Messaging.EventGrid;
```

Figure 4.11: Using system packages utilised in the data output to TSI function.

The logic behind the function is briefly described:

First, there is the need to connect with the ADT client to receive the events and with the Event Hubs to supply those events.

Then, messages are deserialised from JSON to a .NET object to be able to be read by the function. The twin Id is obtained and separated back into the Application Uri and Node Id. Note: the "." is replaced with the original ":" to be coherent with the data already ingested to the TSI environment.

Only then, if the event received corresponds to the update of an output (the rest of the signals coming from the factory are already on the TSI):

- From the message received, the last value and the last value time (time the last value was registered) are saved;
- A list is created with the Application Uri, Node Id, last value and last value time;
- The list is serialised back into a JSON string and outputted into the Event Hub connected to the TSI environment.

The TSI application was crucial to the development of the simulation as it assisted in identifying the line's sequencing and finding errors in the output calculation. Besides, it offers a simple but effective way to visualise the line and outputs behaviours.

4.5 Simulation

The development of the final simulation aims to predict the expected duration of a production order and, knowing the time it started, its finish date. To help identify bottlenecks, the station where boards stay the longest and the correspondent time are also identified.

Even though this calculation produces the outputs, it is integrated with the Data Ingestion function. This merge was not established at first; however, several modifications had to be performed due to data sequencing problems. The solution found was to join both functions and calculate the outputs right after ingesting the telemetry data so that information was not lost or out of order before the critical part of this development. These problems were undermining the final results, which could interfere with the DT assessment. The integration with the data ingestion function also reduced the cloud computing weight, although it increased the function complexity and reduced its comprehension.

This simulation underwent several modifications during its development to get the best outcomes possible. The methodology consisted of separating the line by zones and stations to calculate the time a board stays in each place, which could help identify bottlenecks. After having the time for all stations, the total time is summed to tell the user the duration a board stays in the line. At first, the order's expected duration was calculated with the total time each board stays on the line; however, the line has an undefined number of boards simultaneously, which made this approach invalid.

Therefore, the station where the boards stay the longest had to be identified. This strategy assumes that the main bottleneck dictates the speed of the line. So, the time boards stay in this station multiplied by the planned quantity of boards for that order results in the order's expected duration. For another output, the current board production is subtracted from the planned quantity, and the missing time for the order finish is obtained. The expected finish date is generated by adding the expected duration to the order's start date. The calculated outputs are displayed in Table 4.3. It is noted that the twins that represent the Simulated Finish Date and the Max Time Station are created from different models, extended from the core Output model. This is due to the value being supplied having a different schema.

Table 4.3: Output Digital Twins, correspondent models and relationships.

Name	Model Id	Twin Id	Relationship (To)	Relationship Name
Board Time in Control Station	dtmi:sonaearauco:core:Output;1	out.sa.oh.melamine.line4.346.statusi=1092	station.control.bp9	outputsFrom
Board Time in car before press	dtmi:sonaearauco:core:Output;1	out.sa.oh.melamine.line4.346.statusi=1089	car.before.press.bp9	outputsFrom
Time Press Not Open	dtmi:sonaearauco:core:Output;1	out.sa.oh.melamine.line4.346.statusi=1090	press.bp9	outputsFrom
Board Time in car after press	dtmi:sonaearauco:core:Output;1	out.sa.oh.melamine.line4.346.statusi=1091	car.after.press.bp9	outputsFrom
Board Time at Station 2	dtmi:sonaearauco:core:Output;1	out.sa.oh.melamine.line4.346.statusi=1105	station2.formation.bp9	outputsFrom
Board Time at Station 1	dtmi:sonaearauco:core:Output;1	out.sa.oh.melamine.line4.346.statusi=1106	station1.formation.bp9	outputsFrom
Board Time at Scraper	dtmi:sonaearauco:core:Output;1	out.sa.oh.melamine.line4.346.statusi=1107	scraper.bp9	outputsFrom
Boart Time at the Turning Gripper	dtmi:sonaearauco:core:Output;1	out.sa.oh.melamine.line4.346.statusi=1108	turning.gripper.bp9	outputsFrom
Board Time at Exit of cutting Station	dtmi:sonaearauco:core:Output;1	out.sa.oh.melamine.line4.346.statusi=1110	saw.bp9	outputsFrom
Board Time at Cutting Station	dtmi:sonaearauco:core:Output;1	out.sa.oh.melamine.line4.346.statusi=1109	saw.bp9	outputsFrom
Board Time leaving Conveyor to Centering	dtmi:sonaearauco:core:Output;1	out.sa.oh.melamine.line4.346.statusi=1112	conveyor.saw.to.centering.bp9	outputsFrom
Board Time at Board Input Table	dtmi:sonaearauco:core:Output;1	out.sa.oh.melamine.line4.346.statusi=1083	board.input.table.bp9	outputsFrom
Board Time at Table 13	dtmi:sonaearauco:core:Output;1	out.sa.oh.melamine.line4.346.statusi=1085	table13.bp9	outputsFrom
Board Time at Table 14	dtmi:sonaearauco:core:Output;1	out.sa.oh.melamine.line4.346.statusi=1086	table14.bp9	outputsFrom
Board Time at Centering Table	dtmi:sonaearauco:core:Output;1	out.sa.oh.melamine.line4.346.statusi=1102	centering.table.bp9	outputsFrom
Total Board Time	dtmi:sonaearauco:core:Output;1	out.sa.oh.melamine.line4.346.statusi=1113	bp9line	outputsFrom
Simulated Duration	dtmi:sonaearauco:core:Output;1	out.sa.oh.melamine.line4.346.statusi=1116	bp9line	outputsFrom
Simulated Finish Date	dtmi:sonaearauco:output:FinishDate;1	out.sa.oh.melamine.line4.346.statusi=1117	bp9line	outputsFrom
Max Time Station	dtmi:sonaearauco:output:LongStation;1	out.sa.oh.melamine.line4.346.statusi=1118	bp9line	outputsFrom
Missing Time	dtmi:sonaearauco:core:Output;1	out.sa.oh.melamine.line4.346.statusi=1119	bp9line	outputsFrom

These calculations appear to be simple, yet their integration with the data ingestion proved to be a challenge. The lack of fundamental signals on the line made the math more complex. In Subsection 4.5.1, the necessary steps to achieve a good simulation are presented. The description was intended to be concise, but it was not always possible given the simulation complexity.

4.5.1 Simulation logic

The properties utilised in the simulation were almost entirely binary signals indicating the presence of boards in the stations or zones. The first obstacle was figuring out how to save each signal value and timestamp since many signals are being ingested simultaneously. For this, a dictionary list associated with the Twin Id corresponding to each signal had to be created. In this list, in the most common situation, the saved values were: the time a signal has an upward transition (t0), the time a signal has a descending transition (t1), the difference between the two (tt = t1 − t0) and the last state perceived (lastValue). This list enabled the calculation of several stations' time simultaneously, which is necessary since there are multiple boards in many stations simultaneously.

In Figure 4.12, the utilised signals and their location are represented. It is noticeable that in some stations like the control, in purple, and the turning grippers, in yellow, there is a lack of IoT devices. This unavailability of signals forced structural variations on how each station's time was calculated.

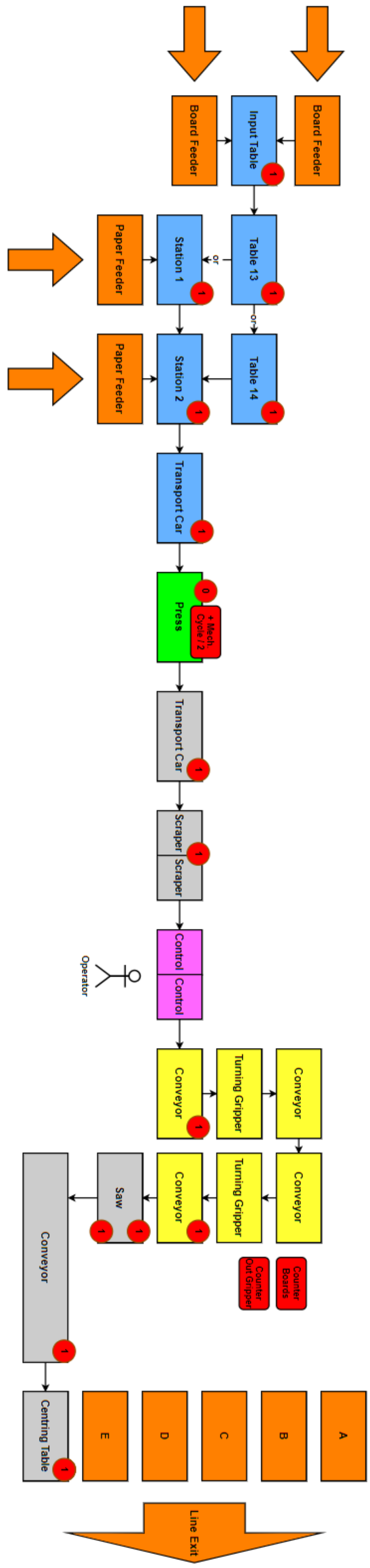

Figure 4.12: BP9 line schema with the location of the utilised signals.

In the formation zone represented in blue, even though there are several board movement possibilities, explained on Subsection 2.1.2, there are photocells in each station, so the time in this zone is the sum of the board duration on every station. If the board does not pass on table 14, for example, the board time is zero, so it does not influence the final result. The same happens on the transport car after the press, the scraper, the conveyor after the saw and the centring table. The flowchart in Figure 4.13 represents the board time calculation in these stations.

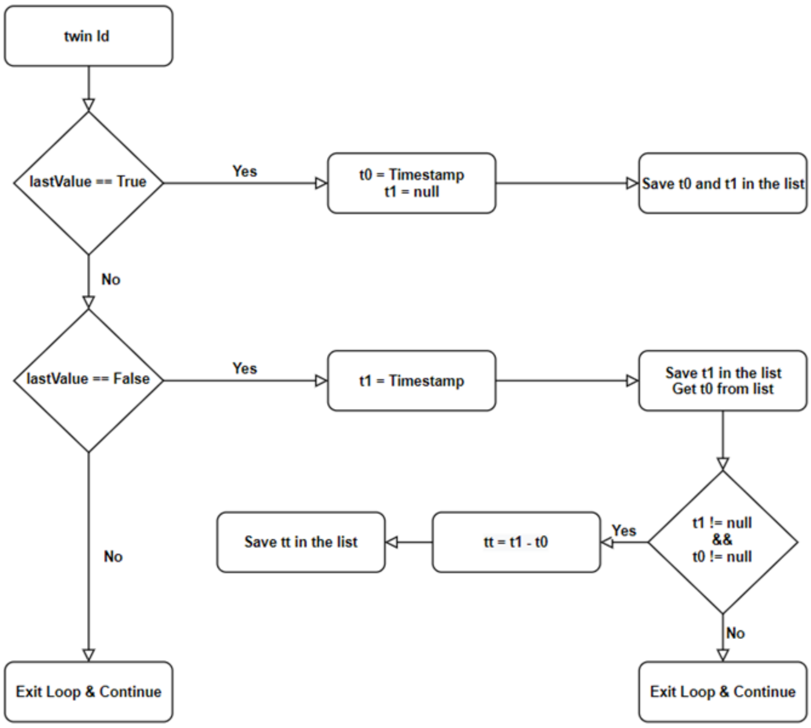

Figure 4.13: Flowchart representing the board time calculation in regular stations.

Some important notes are:

- This loop is only valid for the signals correspondent to the twins mentioned before;
- When lastValue is True, t1 is assigned to null to avoid doing the calculation of tt in case the assignment of t1 fails;
- When none of the conditions are verified, the lastValue is null, so the calculation is not done to avoid errors in the simulation;
- "==" (equal to) and "!=" (not equal to) are relational operators used for comparison of two values.

After calculating the station time (tt), a JSON patch document is created to update the output twin with this value. This output twin Id is formed by adding "out." before the twin Id representing the signal from which the output was created. This allows for a simple connection between signal and output and is also used as a condition to update the TSI.

Finally, the time a board takes in the melamine line is obtained by the sum of all the station times at that moment and updated to the selected twin in the DT environment. The stations' times are compared, and the biggest is saved together with the correspondent twin to identify the main line bottleneck and, multiplied by the planned board quantity, obtain the expected board duration. Other metrics calculated are the missing time and predicted finish date.

This description is a simple way to show the math and methods utilised during the simulation development. However, many factors not mentioned made this development much more complex. For example, the unit conversion was a challenge on some occasions because some values with different schemas had to be related, and the generation of a working list generated multiple problems that forced structural changes on the function and even modifications to the architecture, as explained on the beginning of Section 4.5.

4.5.2 Irregular stations logic modification

The present subsection describes the irregular cases and modifications performed on each one. These alterations are mainly due to the lack of signals on a station. Others resulted from the thorough study of the line behaviour and were implemented to have the closest approximation to reality and, consequently, the best DT representation possible.

Press

On the press, the necessary adjustment was simple. The signal available indicated the press is closed, yet it is saved in a memory, and the state is False when the press is closed, so the time was calculated from the descending to the upward transitions. Apart from this, by viewing the temporal chart of the signals immediately before and after the press and to have a better representation of the time a board spends on the press, half of the mechanical cycle was added. The signals utilised are represented in the schema in Figure 4.14.

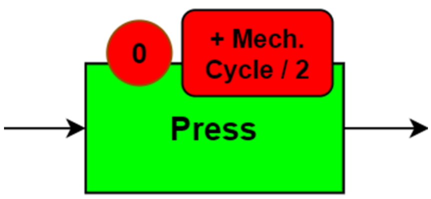

Figure 4.14: Press signals scheme.

Control

On the control station, there are regular photocells; however, they are interrupted when the operator lifts the boards to check for defects on their lower side. This pulse made the signals coming from these IoT devices unusable. To solve this situation, the exit indication from the previous station and the entry indication from the following station were used to calculate the time boards take on the control station.

In Figure 4.15, a graphic from TSI is used to illustrate this situation. The sensor at the first part of the control station is represented in red, and the sensor at the second part of the control station is represented in yellow. The board entry and exit are highlighted, being it is visible on the circumcised section that the signal briefly goes to zero. This corresponds to the lift of the boards.

Figure 4.15: TSI representation of the presence of a board on the control station.

Saw

On the saw station, to have the closest representation of what happens in the physical world, two signals had to be used: the board's presence indicator on the station and the indicator of its exit. The reason behind this is the fact that the saw operation is optional.

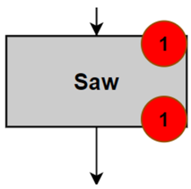

Figure 4.16: Saw signals scheme.

When it is active, the exit signal detects the pulse of the board leaving, but when it is not, the opposite happens since the board does not stop at the station. It can also be detected on the exit for a considerable time if the board is waiting for the next station to be free. Since both signals, represented on

Figure 4.16, are active simultaneously and to avoid errors in the simulation, the upward transition of the entry signal and the descending transition of the exit signal were used to calculate the station time output.

Turning grippers

The turning gripper zone and the signal utilised are represented in Figure 4.17. This was the most challenging sector of the line. Each gripper has a capacity of 70 boards, so there can be up to 140 boards in this area, making it difficult to calculate how long a board takes on this zone only with the supplied entry and exit signals.

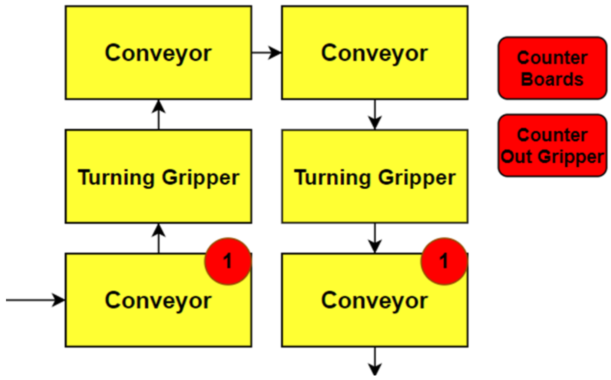

Figure 4.17: Turning gripper zone signals scheme.

Two counters had to be used. One indicates the number of boards on the grippers, and the other counts the number of boards that leave the zone.

When a board enters this area, the timestamp t0 is saved, and both counters values are summed. It is known that the same board exits only when the board exit counter value matches the previous sum and the photocell on the exit detects a board. At this time, the timestamp t1 is saved, and the difference is calculated.

This method is inefficient since a board has to complete an entire cycle on the turning grippers, lasting several minutes, to know how much time a board is taking on the zone; however, given the available data, it was the elected solution.

4.6 Time Series Insights on the development

The function presented in Subsection 4.4.2 transmits the desired data from the outputs to the TSI environment. This software has good visualisation capabilities, which is great for the analysis of the attributes as exemplified in Section 4.3.1 and for the discussion of results since it is where the outputs are presented together with what happens in the physical world in real-time.

During the development, this software was used as a troubleshooting tool. When the output values were not according to what was expected, TSI facilitated the uncovering of the reasons behind such problems. For example, in the event of a station time being excessive, by allowing the analysis of the outputs and real-time signals in the same place, it was possible to discover whether the problem was indeed on the line and a board was stopped in the station or if everything was normal and the problem had to be on the simulation.

In Figure 4.18, a graphic from TSI is used to illustrate this situation. A board enters the centring Table at 12:44:10.301 and leaves at 12:44:20.036, so the time it spends there is 9,735 s. Shortly after, the output related to that station is updated with that value.

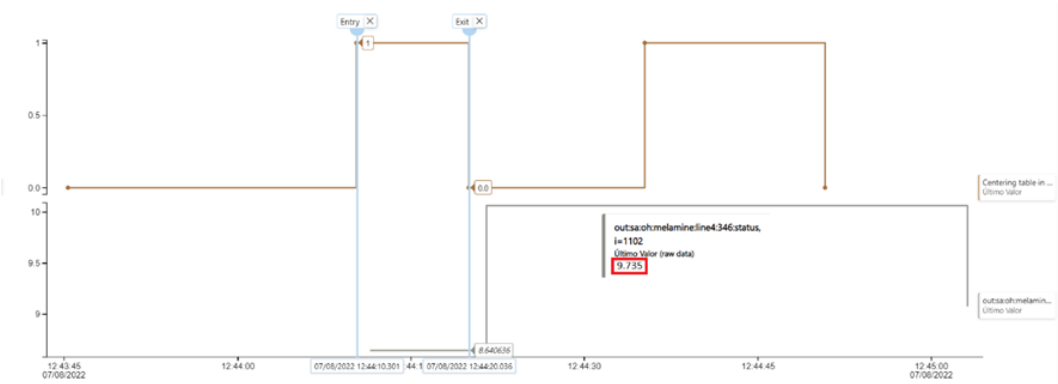

Figure 4.18: Exemplification of the usage of TSI to verify the functioning of the simulation.

4.7 Summary

During the development of the current chapter, many challenges were overcome, yet the calculations were not finalised as it was intended. The simulation was not constructed as envisioned during the project's planning phase. This section presents the expected developments and explains why they were not performed. The developed solution, as it is, simulates production orders in real-time, yet it was desired and advantageous if it allowed for the manual configuration of parameters. This functionality would enable the study of the modified settings' influence on the overall operations of the melamine line. It would widen the range of capabilities of the simulation and allow for more specific enquiries. In addition, it would be beneficial to have an interactive visualisation screen that would display the outputs produced and where the configurable parameters could be changed.

As a result of the lack of available time after the simulation's completion, these enhancements were not implemented. This was due to the challenges encountered throughout its creation. At the time, it was believed that analysing the generated results and evaluating the DT capabilities was more crucial to the success of the dissertation.

In spite of this, the predicted difficulties were overcome and the integration of the Azure services with the DT was simpler than anticipated. This, together with the simulation performed, produced the necessary results to achieve conclusions.

Chapter 5

Discussion of results

In order to make the best conclusions, the results obtained have to be analysed thoroughly and discussed in detail, considering all the eventualities and external factors that could influence or compromise the outcomes.

The platform utilised for the visualisation of those outcomes was the TSI. There, the output values progression, compared with what happens in reality, can be visualised in real-time or historically, making it the perfect data analysis engine to examine the obtained results.

For a complete discussion, multiple production orders were simulated. The outputs were then compared to reality, and its progression with time was analysed. The challenges faced during the development allowed for a deeper perception of the reasons behind certain events, leading to a more critical discussion of the results.

In this chapter, the progression of one production order from start to end and its outputs are displayed, and their meaning debated. It should be noted that the dissertation discussion regarding the DT does not depend entirely on the values obtained from the simulation; however, the result discussion is crucial to prepare the conclusions to be drawn since the DT served as the central engine of the application and, therefore, the existence of outputs and their reliability can participate on the software's assessment.

Other punctual cases are also displayed to justify specific behaviours or demonstrate the simulation's practicality.

5.1 Production order simulation

Ideally, when a production order starts, the codded simulation automatically ingests the necessary parameters to calculate its expected duration, which should be an approximate prediction of the actual duration of the current order. To verify this, once the order is over, the real finish time is registered and the error between the prediction and reality is calculated.

In Figure 5.1, a graphic is presented with the planned quantity of boards in brown, the total boards consumed in the current order in purple and the expected duration output (in seconds) in green. The visualisation of these two system's properties and final output simultaneously assist in assessing whether the simulation is producing acceptable results.

As explained in Section 4.5, the expected duration of a production order is calculated by the multiplication of the planned quantity of boards of a production order with the longest time a board stays in a station. This station should always be the press as, theoretically, is the main bottleneck of the line yet, it is not always the case. When there is an unwanted stop in other stations of the line, there are noticeable but small peaks in the expected duration. The station where boards spend the most time is saved alongside this time, so it is possible to examine the existing bottlenecks.

It is essential to understand that this calculation methodology is not the optimal approach to the given problem yet, as the objective of this dissertation is to scrutinise the capabilities of the DT technology, it was regarded an adequate technique to do so. The selected use case could have been solved in an analytical way much more efficiently yet it would defeat the purpose of this dissertation.

Before further investigation, and through the observation of the graphic in Figure 5.1, the prediction of the production order duration is analysed:

This order, on the 09-07-2022, started at 03:19:36 and finished at 05:36:02.

Its duration was 2,2 h, which is approximately 2 h and 12 min.

Ignoring the unwanted peaks, which reasons are debated ahead, the expected duration is on average 6200 s which is approximately 1,72 h.

The difference between reality and prediction is 29 min, which corresponds to an error of 21,8 %.

It is noted that there were more boards produced than expected so it is important to analyse the error of the predicted duration until the planned quantity. The time span until 280 boards were produced was 2,1 h, which is approximately 2 h and 5 min.

The difference between this instance and the prediction is 22 min, which corresponds to an error of 18 %.

The error values are considerably high for an application that was supposed to be simple which, without the necessity for a thorough examination, reveals that the methodology followed was not correct. Many factors were not considered and the approach itself was inefficient. In the conclusion of this chapter, alternative applications for this solution are suggested.

The additional production is related to the production of defective boards. It is a company policy to exclude boards classified with defects of third degree to maintain their quality standards, as mentioned on Section 2.1.2, while still respecting the planned quantity of boards. This forces the manufacturing of extra boards for the considered order, leading to the need to produce more quantity and, consequently, modifying the duration of the order.

By examining the graphic in Figure 5.1 it is evident that the simulation does not run flawlessly. There are unwanted peaks in the calculated time that can be related to many situations. One known issue is in the failure in the sequencing of data that can lead to the miscalculation of the bottleneck time and, consequently, to bad prediction results. Other verified scenario is the

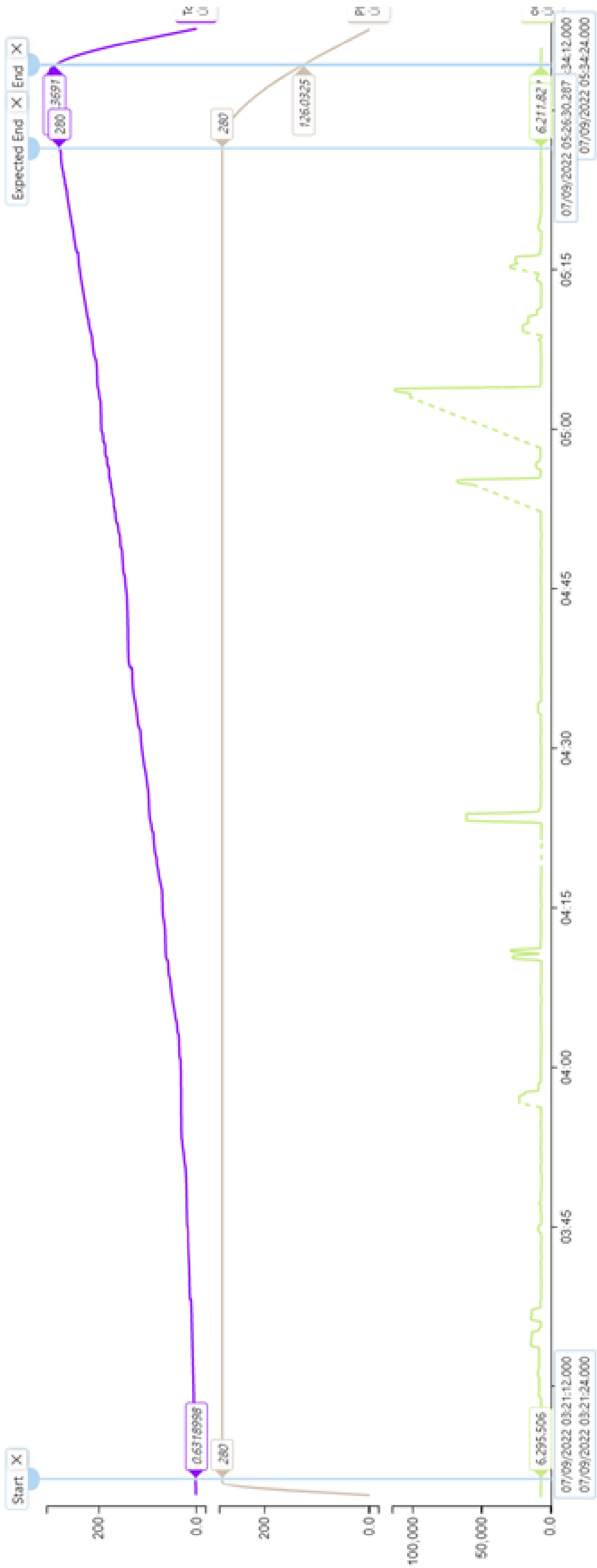

Figure 5.1: Graphic of a production order with a planned quantity of 280 boards.

unwanted activation of the photocells by the robotic arms which can result in the false detection of the presence of a board. In other more common situations, the peaks represent a micro stop on a station. These stops are characterized by small issues on the line or specific zone that cause the line to stop running during brief moments. The identification of these micro stops and where they occur is a efficient way to find bottlenecks.

The graphic in Figure 5.2 is representative of the same production order as in the Figure 5.1 but showing different outputs. The longest time in a station is represented in orange, the time a board stays in the input table is represented in the second row in light blue, the time a board stays in table 13 is represented in the third row in green and the time a board stays in the transport car before the press is represented in the fourth row in blue. The mentioned stations are part of the formation zone. Their location can be consulted in Figure 5.2.

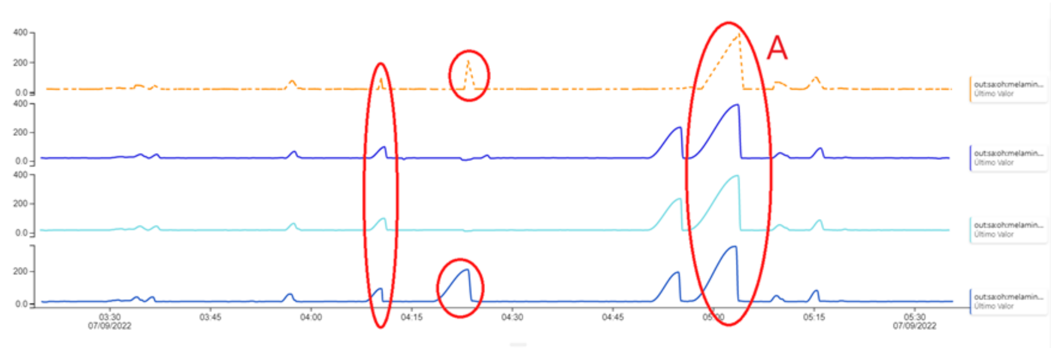

Figure 5.2: Output analysis in the formation zone for the identification of bottlenecks.

As mentioned on Section 4.5 the twin Id related to the station where a board stays the longest at any given time is saved. A display was not developed and this valuable information is not ingested into the TSI. In spite of this, the twin Id is saved on the DT environment, and after retrieving this information it was easier to discover which were the problematic stations created these peaks. At the circled times, it is noticeable that one or more boards were stopped on these stations. This increased the time substantially but was ignored on the calculation of the expected duration because it represent punctual events, serving only to identify the stations were problems occur.

The developed simulation is unable to figure out why most of the problems occur; however, it gives a clear indication of when and where the issues happened, which assist on their identification. On the particular case highlighted in Figure 5.2 by the letter A, the peaks were due a malfunction on the transport car before the press. The situation was handled quickly on site but the line was stopped for about 5 minutes.

In Figure 5.3 the bottleneck identification and how it affects the simulation outcomes is presented in more detail. The longest time in a station is represented in orange, the time a board stays in table 13 is represented in green, the time a board stays in the transport car after the press is represented in yellow.

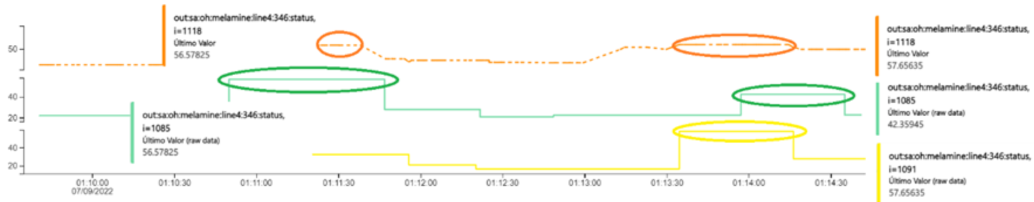

Figure 5.3: Bottlenecks identification process in detail.

On the left side, it is clear that the longest time is spent on table 13 (green) so the output in orange saves the correspondent time. On the right side, the times on the two stations are close but a board stays the longest on the transport car before the press so the output in orange saves the correspondent time. On this particular occasion, the meaning behind this is that a bottleneck occurs on the station right after the mentioned transport car. If this happens currently, it gives insights to the application users and factory operators where to focus on their line examinations to find potential problems more efficiently.

There are other outputs presented in Table 4.3, yet they are secondary and calculated through the expected duration so this is the only one analysed. Before the obtention of values, it was known that the predicted time calculation was not going to be precise, even without external problems. This is due to the existence of many factors that influence the line running and that were not considered on the calculations. There are micro stops in almost every order, the press plates sometimes have to be changed to ensure quality, there can be maintenance issues, machine failure and many other events that affect the line behaviour and, consequently, the simulation's reliability.

Therefore, all of these factors should be taken into consideration to achieve the perfect simulation. On the other hand, as the main objective of this dissertation is to prove the concept of DTs, the calculations made were considered to be sufficient given the time available to produce results. The existence of simulated values close to reality is enough to prove that the developed application works and allows for conclusions to be made about the functionalities of the DT software and its integration with the company's applications.

5.2 Summary

By the values obtained and the situations examined, it is evident that the simulation of the expected duration of a production order, performed in this way, was not optimal. During the result discussion, the simulation capabilities were perceived and other applications for its utilisation are suggested.

Regarding the BP9 melamine production line, the simulation outcomes gave countless insights about the line behaviour which, on its turn, assist on the identification of the factors that negatively impact the line and scenarios that can improve its operations. It is known that the operators' speed on classifying the quality of boards in the control station can impact the line speed if they are slower than the total cycle time of a board in the press. The simulation allows for the comparison of the time a board stays in both stations and, in the case of the operator being too slow, the Id of the worker is saved. This leads on the categorisation of workers regarding their speed and efficiency. The ones that do not reach the minimum productivity should be relocated.

The lack of feeding materials during a production order is also an issue proved by this project. This is due to the existence of only one warehouse that stores boards of all the types and sizes and sheets of impregnated paper of all colours. For this solution to work, the materials had to be perfectly organised, to be easier to supply the lines with the correct material before the planned start date. This would involve the improvement of their warehouse management system.

As mentioned before, the press is or should be the main bottleneck of the melamine line so one factor that could improve the productivity of the line is the reduction of its cycle times. This is a solution to be experimented as the effects it could have on the final product quality are unsure. This simulation and, consequently, the DT technology could be used to investigate this possibility.

These applications would be more suitable for the test of the developed DT; however, the obtained results are sufficient to conclude on the success of the several stages of the project and, more importantly, on the DT technology.

Chapter 6

Conclusion

This chapter summarises the main conclusions of the dissertation. The achievement of the objectives is reported, and some improvements to methodologies are suggested. Furthermore, future developments that can potentialise this technology are proposed.

6.1 Major conclusions

The main focus of this project was implementing a DT instance integrated with Sonae Arauco's cloud architecture and testing its capabilities and reliability on a real industry use case. This proof of concept is a starting point for using the DT technology within the company's IT solutions.

The study of the BP9 melamine line behaviour was beneficial for identifying problems, mapping the existing assets and defining the use case. During the project's development, it was acknowledged that the proper use case was selected because the problems to look out for were reported, and their root was determined in the result analysis.

The investigation of the DT concept and Azure services was essential, and its advantages were noted during the development. It allowed the selection of the best elements to form the system's architecture and assisted in the creation of twins.

The ontology selected undoubtfully proved not to be the most indicated for the current application. An ontology oriented to the manufacturing industry would be more suitable and assuredly advantageous to the company. It is recommended, for future developments, that the Asset Administration Shell ontology replaces the RealEstateCore ontology as it allows for a better definition of the company's assets and procedures without the need for the modifications done in this project. However, it is imperative that this ontology is finalised.

The comparison with other clouds and DT applications was practically not conducted because the company is satisfied with Microsoft's cloud, which was not the aim of this dissertation. Nevertheless, the experience with Azure was positive since it was carefully designed to be user-friendly and intuitive, removing unnecessary obstacles to the development of the project.

The codding in C# was the most challenging stage of the project as it was where most of the problems occurred. This was a vital development phase, so significant efforts were applied to ensure the project's viability. Analysing the results obtained, these efforts were considered beneficial since they assisted in the proof of concept of the DT.

The utilised output platform, TSI, was tremendously helpful in all stages of the project, being, therefore, indicated to be integrated with DTs. The software was fundamental in several stages of the development and analysis of results. It allowed for the visualisation of outputs and telemetry, which allowed, among others, to identify critical stations and on the attribute selection phase.

Regarding the results obtained and analysing their discussion, the methodology choice to develop the simulation was unfortunate. Nevertheless, having everything into consideration, the error values obtained were acceptable. Furthermore, the simulation has a demonstrated applicability in identifying bottlenecks and the occurrence of issues with an associated time stamp and location within the melamine line. It also accomplished its purpose of providing proof of DT's reliability. The majority of the issues were related to the calculations or the approach of the simulation development, so it is more than reasonable to assume that the DT brought and has even more potential to bring tremendous advantages to Sonae Arauco and the manufacturing industry.

As an overview, several advantages were identified in the implementation of DTs. The company's production lines and factories are described in the same place. This description includes the modelling of objects and the data necessary for their definition. It is helpful for future developments as many services can be integrated, and multiple solutions are established in the same environment. On the other hand, the associated costs were considerably high. The connection with other services implied streaming millions of events through the cloud daily. The company felt the messaging and storage impacts, and the project was focused only on one production line from one factory. The company has several plants with ample dimensions and thousands of assets, so the costs associated with the global implementation of the DT solution will not be negligible.

During its execution, some constraints delayed the project's evolution. At first, the project was supposed to be implemented in a factory in the city of Linares in Spain. However, during the DT creation and before the data ingestion, the lack of binary signals on the local melamine line forced a change of installations. Despite holding back the project, it was a good decision because it allowed for the development of a more complete solution. Moreover, the factory change in the middle of the internship, together with the still felt Covid-19 impacts, removed the possibility of visiting the factory and observing the BP9 line in action. This harmed the project development because it was considerably more difficult to fully comprehend the production line characteristics and behaviour, leading to a less efficient progression.

Taking everything into account, the main objectives of the dissertation were fulfilled, being the DT concept and, more specifically, the ADT is classified as highly rewarding. As much as the associated costs can be substantial with the increase of applications implemented, it can replace other currently utilised services and boost the efficiency of the physical and digital worlds' automation.

6.2 Future work

The DT was modelled and implemented for a particular line of a factory. With further investment and continuity to the project, the DT integration with reality could be performed for the four melamine lines running in parallel in the same physical location and the respective feeding mechanisms. This more complex development would allow for a complete study of production order sequencing, which has the potential to simulate several alternatives until reaching the optimal recipe and preventing costly downtimes.

Regarding the DT functionalities and cloud service integration capabilities, there is a vast range of scenarios; however, Artificial Intelligence and Machine Learning stand out. Their advanced prediction and simulation power, together with the data handling versatility and visualisation interactivity DTs offer, make them ideal for connecting. Integrating these applications on the Azure cloud is viewed as the next logical step for improving the DT application, assisting in producing better manufacturing insights to enhance the company's methods and maximise profits.

To enhance the quality of the developed project, it is suggested that the 3D modelling of the DT environment is conducted to achieve the closest approximation to reality. The developed application has everything necessary to represent reality. However, this next step allows the user to see more clearly where the sensors are, for example, and the movements of the melamine boards in real-time. Finally, to visualise the outputs of the simulation, it would be advantageous to have a display that would ingest the outcomes of the function and allow for a more straightforward interpretation than the TSI offers.

Bibliography

[1] A. Bamberg, L. Urbas, S. Bröcker, M. Bortz, and N. Kockmann, "The digital twin–your ingenious companion for process engineering and smart production," Chemical Engineering & Technology, vol. 44, no. 6, pp. 954–961, 2021.

[2] S. Spellini, R. Chirico, M. Panato, M. Lora, and F. Fummi, "Production recipe validation through formalization and digital twin generation," in 2020 Design, Automation & Test in Europe Conference & Exhibition (DATE), pp. 1698–1703, IEEE, 2020.

[3] T. Mortlock, D. Muthirayan, S.-Y. Yu, P. P. Khargonekar, and M. A. Al Faruque, "Graph learning for cognitive digital twins in manufacturing systems," IEEE Transactions on Emerging Topics in Computing, vol. 10, no. 1, pp. 34–45, 2021.

[4] F. Tao, M. Zhang, and A. Y. C. Nee, Digital twin driven smart manufacturing. Academic Press, 2019.

[5] Q. Qi and F. Tao, "Digital twin and big data towards smart manufacturing and industry 4.0: 360 degree comparison," Ieee Access, vol. 6, pp. 3585–3593, 2018.

[6] M. Grieves, "Origins of the digital twin concept," Florida Institute of Technology, vol. 8, 2016.

[7] M. Grieves, "Digital twin: manufacturing excellence through virtual factory replication," White paper, vol. 1, no. 2014, pp. 1–7, 2014.

[8] E. Glaessgen and D. Stargel, "The digital twin paradigm for future nasa and us air force vehicles," in 53rd AIAA/ASME/ASCE/AHS/ASC structures, structural dynamics and materials conference 20th AIAA/ASME/AHS adaptive structures conference 14th AIAA, p. 1818, 2012.

[9] F. Tao and M. Zhang, "Digital twin shop-floor: a new shop-floor paradigm towards smart manufacturing," Ieee Access, vol. 5, pp. 20418–20427, 2017.

[10] Y. Cai, B. Starly, P. Cohen, and Y.-S. Lee, “Sensor data and information fusion to construct digital-twins virtual machine tools for cyber-physical manufacturing,” Procedia manufacturing, vol. 10, pp. 1031–1042, 2017.

[11] F. Tao, H. Zhang, A. Liu, and A. Y. Nee, “Digital twin in industry: State-of-the-art,” IEEE Transactions on industrial informatics, vol. 15, no. 4, pp. 2405–2415, 2018.

[12] S. Weyer, T. Meyer, M. Ohmer, D. Gorecky, and D. Zühlke, “Future modeling and simulation of cps-based factories: an example from the automotive industry,” Ifac-Papersonline, vol. 49, no. 31, pp. 97–102, 2016.

Chapter A

Twin graphic sections

In this appendix, the twin graphic is divided in 4 parts to allow a better visualisation of its elements and the relationships between them.

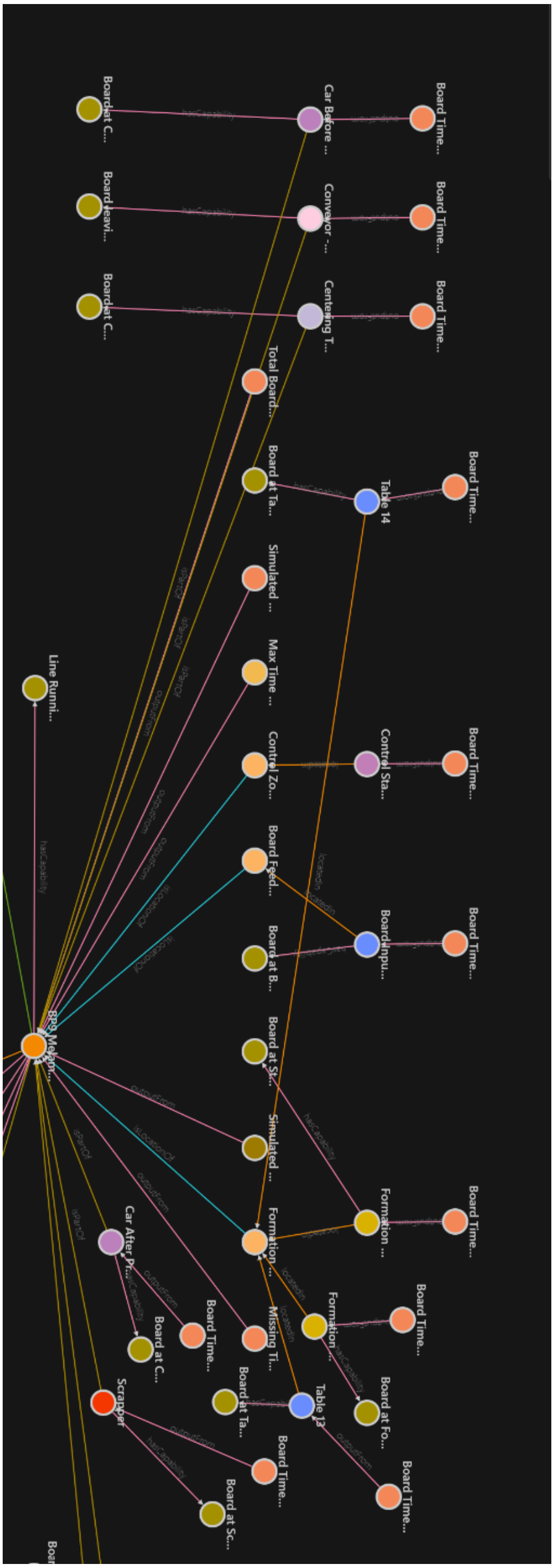

Figure A.1: Twin graphic 1: display of twins in the ADT environment.

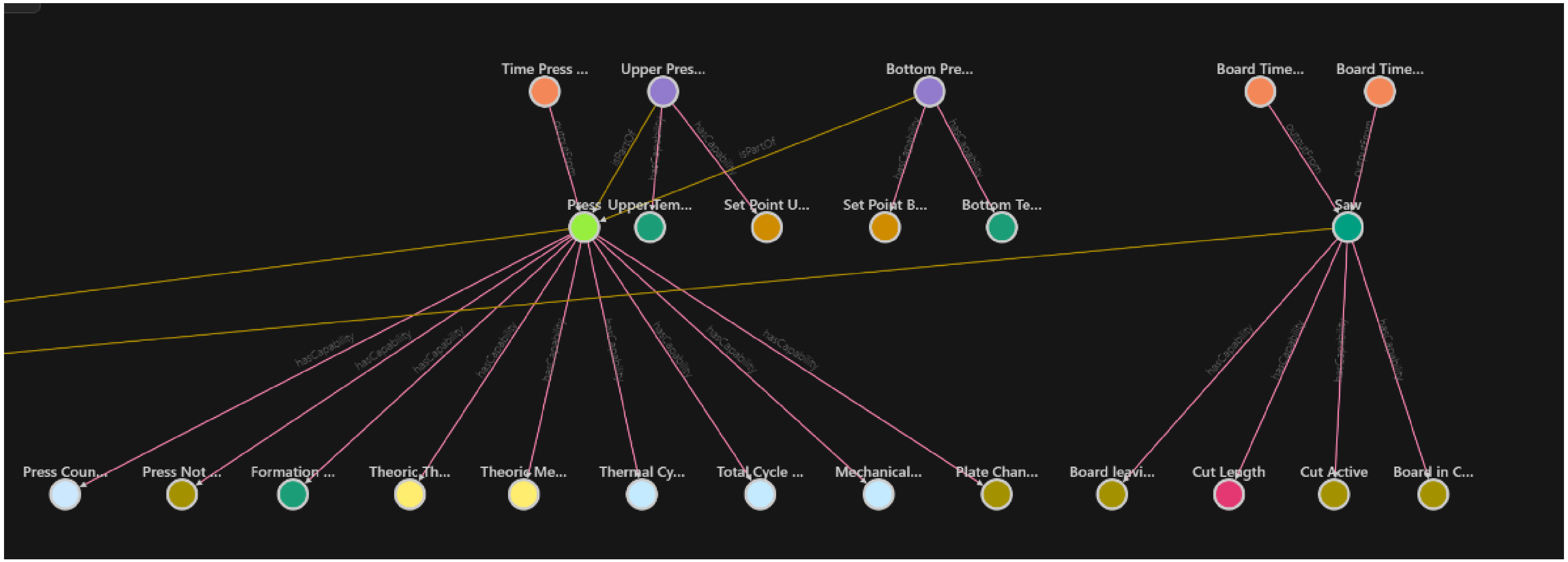

Figure A.2: Twin graphic 2: press.

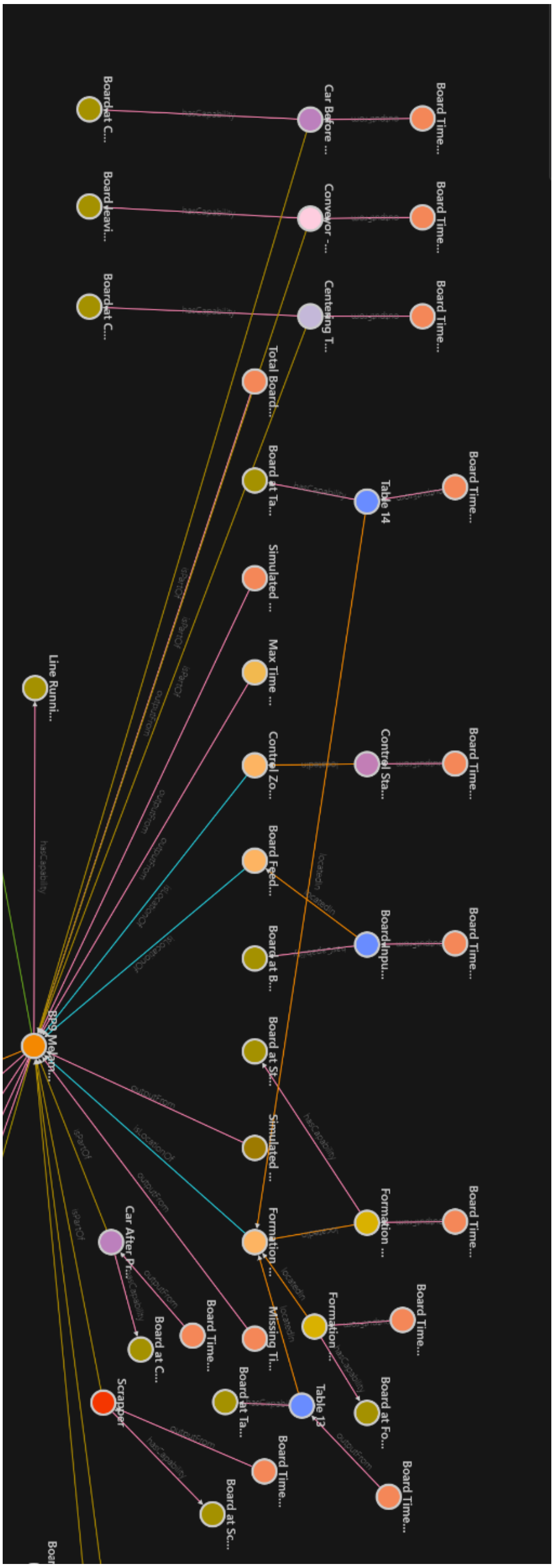

Figure A.3: Twin graphic 3: display of twins in the ADT environment.

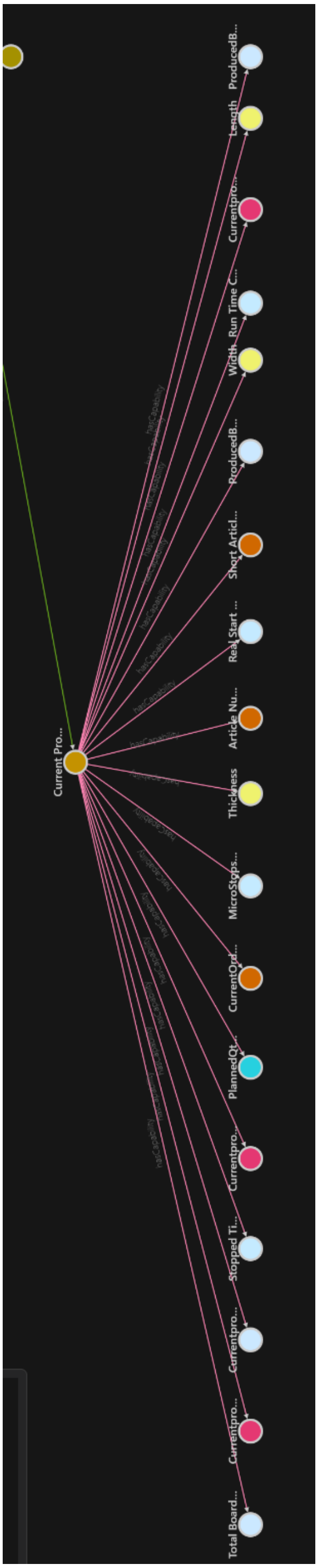

Figure A.4: Twin graphic 4: production order.