BIDIRECTIONAL CONTROL OF THE INTEGRATED PRODUCT-PROCESS DIGITAL TWIN

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By IGIRI UKO ONAJI (170270405)

DEPARTMENT OF AUTOMATIC CONTROL AND SYSTEMS ENGINEERING

The University of Sheffield, UK

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Content

Content i

List of tables viii

List of Figures ix

List of Abbreviations xiii

Acknowledgement xvi

Publications xvii

Abstract xviii

CHAPTER I: INTRODUCTION 1

- 1.1 Background 1
- 1.2 Motivation 1
- 1.3 Discussion of the problem 2
- 1.4 Purpose: Research aim and objectives 4
- 1.5 Contributions 4
- 1.6 Methodology 5
- 1.7 Outline of the thesis 6

CHAPTER II: BACKGROUND AND LITERATURE REVIEW 9

- 2.1 Introduction 9
  - 2.1.1 *Background* 9
  - 2.1.2 *Problem domain* 10
  - *2.1.3 The focus of the literature review* 13
- 2.2 Methodology for literature review 14
- 2.3 Digital twin (DT) concept 16
  - 2.3.1 The concept of the digital twin 17
  - 2.3.2 The evolution of the digital twin concept 19
  - 2.3.3 Perspectives on the digital twin 21

2.3.4 Current industrial understanding and applications......25

2.3.5 The Role of the digital twin in CPPS......26

2.3.6 Cyber-physical integration using other concepts similar to the digital twin......30

2.3.7 Cyber-physical integration using the digital twin concept......31

2.4 Digital twin frameworks for smart manufacturing......32

2.4.1 Related work on digital twin frameworks in manufacturing......32

2.4.2 Integrated digital twin frameworks in manufacturing......34

2.5 Real-time collaborative simulation in digital twin......34

2.6 Cyber-physical control in digital twinning......35

2.7 The Digital twin as a decision-support mechanism across the RAMI4.0 Hierarchy levels..36

2.8 Technical limitations and solutions......37

2.9 Disposition of the thesis/Research gap......43

2.10 Summary......47

CHAPTER III: RESEARCH METHODOLOGY......49

3.1 Methodology......49

3.1.1 Phase 1: Literature review......49

3.1.2 Phase 2: Conceptual model design......67

3.1.3 Phase 3: Objective I: Digital twin architecture for a smart factory......67

3.1.4 Phase 4: Objective II: Development of techniques that support real-time synchronised interactive simulation between the asset-twin......68

3.1.5 Phase 5: Objective III: Bidirectional control......69

3.1.6 Phase 6: Objective IV: Digital twin as a decision-support system across RAMI4.0 Hierarchy levels......70

3.1.7 Phase 7: Objective V: Validate the integrated product-process digital twins as a decision-support system for a CPPS......71

3.2 Digital twin model......71

3.3.1 Digital twin generic description......71

3.3.2 Conceptual model design for the integrated DT 72

3.3 Methodology for including variability in the digital twin: Varying products and processes in the digital twin 74

3.3.1 Fixed process and variable product 77

3.3.2 Fixed product and variable process 77

3.3.3 Variable process and variable product 78

3.4 Cyber-physical control 79

3.5 Digital twin as a decision-support system 81

3.6 Connecting the digital twin to MES/Customer API and Cloud-based services 82

3.7 Case study: Discrete-time CPPS based on the Festo cyber-physical (CP) smart factory 83

3.8 Methods 85

3.8.1 Reference Industry 4.0 architecture 85

3.8.2 Cyber-physical production systems (CPPS) 86

3.8.3 System identification and modelling 86

3.8.4 Product-process dependencies 87

3.8.5 The digital twin for manufacturing 87

3.8.6 The concept of integration 88

3.8.7 Cyber-physical connections and interactions 88

3.8.8 Real-time, two-way and secure connections between physical and virtual spaces 88

CHAPTER IV: INTEGRATED PRODUCT-PROCESS DIGITAL TWIN FRAMEWORK FOR MANUFACTURING 90

4.1 Novelty and contribution to knowledge 90

4.2 Integrated product-process DT 91

4.3 Methodology for implementing the proposed integrated digital twin framework 92

4.3.1 Integrating the product and the process digital twins 92

4.3.2 Product-centric control method 94

4.4 Proposed digital twin framework for manufacturing systems 95

(a) Integrated physical assets 96
(b) Integrated product/process virtual models 96
(c) Intelligent layer 97
(d) Data layer 98
(e) Enterprise layer 99
4.5 Benefits of the proposed framework 99
4.6 Case study 102
4.6.1 Discrete-time CPPS based on the Festo cyber-physical (CP) smart factory 103
4.6.2 Key steps 104
4.6.3 Conceptual model 105
4.6.4 Developed DES supervisory digital twin model of the physical processes 131
4.6.5 Results and discussion 133
4.7 Summary 135
CHAPTER V: REAL-TIME SYNCHRONISED INTERACTIVE SIMULATION 136
5.1 Research contribution 136
5.2 Methodology and case study 137
5.3 Development of the integrated product-process digital twin model 137
5.3.1 Dependency rule 138
5.3.2 Product DT composition 141
5.3.3 Process DT configuration 141
5.3.4 Product DT-process DT interaction 143
5.4 Integrated product-process digital twin for a CPPS 143
5.4.1 Cyber-physical integration 144
5.4.2 Collaborative behaviour between the integrated DT and the physical asset 146
5.4.3 Real-time, two-way and secure connections between the physical asset and the integrated digital twin 148

5.5 Integrated product-process digital twin as a CPPS decision-support system 151
5.5.1 The function of the product DT 151
5.5.2 The function of the process DT 153
5.5.3 Benefits of a Real-time Synchronised Interaction between the Asset-twin 154
5.6 Case study 155
5.6.1 Experimental setup: Festo Cyber-physical smart factory 155
5.6.2 Conceptual model elements 155
5.6.3 Developed integrated DT 157
5.6.4 An integrated product-process digital twin of the Festo CP system 159
5.6.5 Simulation results and discussion 166
5.7 Discussion 170
5.8 Summary 172
CHAPTER VI: DIGITAL TWIN CYBER-PHYSICAL CONTROL STRUCTURE 174
6.1 Research novelty and contribution 174
6.2 System control identification 175
6.2.1 Industrial control structures 175
6.2.2 Physical control structure 176
6.2.3 Applicable control techniques 178
6.3 The proposed cyber-physical control structure for digital twin 179
6.3.1 Background 179
6.3.2 Cyber-physical control structure 179
6.3.3 Components of the cyber-physical control structure 182
6.3.4 Control strategies for the cyber-physical control structure 185
6.3.5 Control modelling strategies for the cyber-physical control structure 186
6.4 Methodology for developing and implementing the cyber-physical control structure 188
6.4.1 Identification of the level of granularities and impact on the level of system control 188

6.4.2 Investigation of the link between the level of granularities and the use of engineering models vs data model-driven models 189

6.4.3 Control implementation between product and process digital twins 189

6.4.4 Control implementation between process DT and physical asset 190

6.4.5 Techniques to achieve virtual control of physical assets and to update the virtual control from physical assets 190

6.4.6 Establish closed control loops at multiple granularities using real-time synchronisation between the processes and the process DT 191

6.5 Case study 192

6.5.1 Festo cyber-physical (CP) smart system control structure 192

6.5.2 Festo CP smart factory DT 192

6.5.3 Festo CP smart factory DT cyber-physical control 193

6.5.4 Key steps 193

6.5.5 Modelling results 195

6.6 Discussion of results 206

6.7 Summary 207

CHAPTER VII: DIGITAL TWIN AS A DECISION-SUPPORT SYSTEM 208

7.1 Research contribution 208

7.2 Digital twin as a decision-support system 209

7.2.1 Simulation and experimentation 209

7.2.2 Real-time data-driven operations 210

7.2.3 Digital twin data: Data generation, storage, model update and data visualisation in the context 211

7.2.4 Benefits of the digital twin as a decision-support system 213

7.3 The proposed framework of the CPPS_DTDSS 216

7.3.1 Background 216

7.3.2 The proposed framework of the CPPS_DTDSS 217

7.3.3 Components of the proposed CPPS_DTDSS infrastructure 218

7.3.4 Interaction loops between the digital twin and associated architecture 220

7.3.5 Benefits of the digital twin as an extended decision-support system across the RAMI4.0 automation architecture hierarchy levels 222

7.4 Case study 224

7.4.1 The DTDSS of the Festo CP smart factory 224

7.4.2 Key Steps 225

7.4.3 Festo CP smart factory CPPS_DTDSS infrastructure 226

7.4.4 Components of the proposed CPPS_DTDSS infrastructure 227

7.4.5 Interaction loops between the digital twin and associated architecture 231

7.5 Discussion 235

7.6 Summary 237

CHAPTER VIII: RESEARCH CONTRIBUTION, CONCLUSION AND FUTURE WORK 238

8.1 Research contributions 238

8.2 Validation 241

8.3 Research Limitations 245

8.4 Recommendations for future work 246

8.5 Conclusion 250

REFERENCES 252

APPENDICES 261

Appendix A: Highlights of Industry 4.0 objectives in the manufacturing 261

Appendix B: Practical work methodology 263

Appendix C: Research methods/techniques 266

Appendix D: Industry 4.0 technologies 286

Appendix E: Proposed framework for determining and developing the digital twin for your business 289

Appendix F: Siemens connected curriculum 298

Appendix G: Validation 299

List of tables

Table 2.1: Identified definitions of the digital twin in literature 19

Table 2.2: Table of companies' views and application purpose 25

Table 3.1: Metrics considered in the selection of digital tools for DT development ……………………67

Table 3.2: Festo stations and the task each performs 84

Table 4.1: Main objects of the Festo digital twin model…………………………………………..132

Table 4.2: The impact of robot *travel-time* on the *total throughput tim*e and *throughput-per-hour* .. 134

Table 8.1: Summary of the outcomes of the validation approach 1 …………………………………242

Table 8.2: Summary of the outcomes of the validation approach 2 244

List of Figures

Figure 2.1: Flow chart of the selection process. Adapted from (Moher et al., 2009) 15

Figure 2.2: (a) Depicts trend of digital twin research interest (b) Digital twin types (c) Research focus between 1994 to 2019 16

Figure 2.3: General digital twin architecture 17

Figure 2.4: (a) Percentage of publications based on digital twin type (b) Trend of the digital twin applicability in process/product lifecycle phases 23

Figure 2.5: Digital twin functionalities 24

Figure 2.6: Analytics in an interactive digital twin Source (Catapult, 2019) 29

Figure 3.1: Chevron chart showing the sequential progression of the methodological steps taken……50

Figure 3.2: Integration of product and process digital twins 68

Figure 3:3: (a) DT components (b) Digital twin general model representation 72

Figure 3.4: DT model structural layout based on RAMI4.0 architecture 72

Figure 3.5: Ontological map connecting the product types to their production processes 75

Figure 3.6: Systematic integration of the product and process digital twins to incorporate variability in process and product DTs 76

Figure 3.7: Illustrating the feedback concept adopted from PLC controllers. 80

Figure 3.8: Festo CP smart factory 84

Figure 3.9: Schematic diagram of the physical production system 84

Figure 3.10: Reference Industry 4.0 architecture (RAMI 4.0) Source (Rojko, 2017) 86

Figure 3.11: Product-process interaction in the production phase 87

Figure 3.12: RAMI4.0 model communication layer using the TCP/IP framework Source (Nazarenko et al., 2020) 89

Figure 4.1: Integration of product and process digital twins…………………..………………………91

Figure 4.2: Collaboration mechanism for integrating the product DT and process DT 92

Figure 4.3: An integrated product-process DT showing the path used by the product twin to influence process configuration using the product-centric control method. 94

Figure 4.4: Digital twin framework of a manufacturing system showing closed-loop interaction 95

Figure 4.5: Analytics in an interactive digital twin From: (Catapult, 2018) 101

Figure 4.6: As-built digital twin architecture 103

Figure 4.7: Flowchart showing the schematics of the system layout and the production flow depicted by the smart carrier path. 106

Figure 4.8: Functional flowchart showing supervisory DT set-up and the digital connection with its physical asset 106

Figure 4.9: Functional flowchart of main activities in stations except for magazine stations 107

Figure 4.10: Functional flowchart of main activities in Magazine stations (Bottom and TopMag stations) 130

Figure 4.11: Overview of the developed Supervisory digital twin of the Festo CP smart factory 131

Figure 4.12: Product digital twin visuals 132

Figure 4.13: Experimental results revealing more details on identified bottlenecks and system behaviour 134

Figure 5.1: The logical interaction between the product attributes and the production system services based on the dependency rule: $\boldsymbol{Az}, \boldsymbol{Qz} \bowtie \boldsymbol{Sz}, \boldsymbol{Wz}\ \forall\ A$ 141

Figure 5.2: The logical interaction between the product DT attributes and the process DT based on the dependency rule 143

Figure 5.3: The CPPS and its integrated DT showing all interactions between elements 144

Figure 5.4: The interaction between the product DT and process DT 145

Figure 5.5: The interaction between the integrated asset-twin. 146

Figure 5.6: The collaboration between the CPPS and its integrated DT during production 147

Figure 5.7: Modelled cyber-physical environment showing an integrated communication network of the virtual access nodes (VAN). 149

Figure 5.8: The interaction and evolution of the integrated asset-twin quantities 151

Figure 5.9: The process DT system reconfiguration Scb by the process DT 152

Figure 5.10: The product DT attributes Ab defined by the process DT services 153

Figure 5. 11: Process chart of the system under investigation (SUI) 156

Figure 5.12: Functional flowchart showing a closed-loop DT set-up and the digital connection between the asset-twin 156

Figure 5.13: Product DT of the Festo CP smart factory 157

Figure 5.14: Festo CP smart factory DT model 159

Figure 5.15: (a) Top case loaded on the carrier at Topcase station (b) Bottomcase mounted on Topcase at Bottom station 160

Figure 5.16: (a) OPC_UA interfaces for each workstation and (b) Real-time interaction. Green values indicate an active change in status 161

Figure 5.17: Functional flowchart showing a real-time structured operational data flow from the physical asset that influences the real-time synchronised behaviour of the DT. 162

Figure 5.18: Real-time synchronised interaction between asset-twin. DT behaviours triggered by actual physical twin activities 164

Figure 5.19: Simulation showing coordination between process and product DTs to build product DT 165

Figure 5.20: Simulation results and analyses using asset configuration 168

Figure 5.21: Simulation results and analyses of the asset in real-time 170

Figure 6.1: Manufacturing control system showing five functional levels (ISA95 automation pyramid). Source (Wikimedia, 2014)........ 175

Figure 6.2: Schematics of a basic model of a controller 176

Figure 6.3: A more detailed model of a controller showing subroutines. 177

Figure 6.4: Cyber-physical control structure showing the interaction between the physical control system and virtual control structure of the digital twin 180

Figure 6.5: Flowchart of the CPPS cyber-physical control structure showing interconnections and communication between the asset-twin. 181

Figure 6.6: Flowchart of the virtual control structure of the DT 184

Figure 6.7: Diagram showing (a) The Forward channel (Asset to DT) and (b) The Reverse channel (DT to asset) between the asset control systems and the DT virtual control system 186

Figure 6.8: Diagram showing the paths between the PLCs of the Festo CP smart factory and its DT virtual control system 197

Figure 6.9: DT control panel showing the Simulation setup, control panel and virtual MES 198

Figure 6.10: Virtual sensors of the various stations reflecting the status of control actions. Green indicates an active state and red indicates an inactive state 199

Figure 6.11: Charts showing the impact of DT control on the energy usage of conveyors. 201

Figure 6.12: Production monitoring with pop-up notifications 202

Figure 6.13: Impact of heating strategy on station performance. (Heat station *process time* and *throughput time* 203

Figure 6.14: DT-panel used in imputing product attributes during production 204

Figure 6.15: HMI panel for experimentation showing the Main menu, setup parameters and Control parameters 205

Figure 7.1: Proposed framework of the CPPS_DTDSS connecting all Hierarchy levels of the RAMI4.0 automation architecture........ 218

Figure 7.2: Schematics showing connectivity and benefits of the collaborative interconnections between the integrated product-process DT and the RAMI4.0 automation architecture Hierarchy levels 223

Figure 7.3: Developed Festo CP system DTDSS connecting all hierarchy levels of the rami4.0 architecture........ 227

Figure 7.4: Functional flowchart showing a closed-loop DT set-up and digital connection across RAMI4.0 automation Hierarchy levels 228

Figure 7.5: Developed Node-RED data stream infrastructure connecting DTDSS components........ 229

Figure 7.6: Festo CP smart factory MES application showing main menu interface 230

Figure 7.7: Siemens Mindsphere cloud service-Main menu showing different applications and service providers 231

Figure 7.8: OPC_UA server-client connection between the asset-twin. DT as an OPC_UA client connected to the asset an OPC_UA server........ 232

Figure 7.9: Communication thread between the DT and the Fest CP smart factory's MES. (OPC_UA Client-Node-RED OPC_UA server node – Node-RED TCP request node)........ 233

Figure 7.10: (a) Communication established between DT and (b) Node-RED customer API GUI (OPC_UA communication) 234

Figure 7.11: Communication between the DT and Siemens Mindsphere cloud services. (OPC_UA, Node-RED and Mindconnect agent)........ 235

List of Abbreviations

API- Applications

AR- Augmented Reality

ASME- American Society of Mechanical Engineers

CAD- Computer-Aided Design Software

CAM- Computer-Aided Manufacturing Software

CAE- Computer-Aided Engineering

CAX- Computer-Aided Technology

CRM- Customer Relation Management

CPS- Cyber-physical Systems

CPPS- Cyber-physical Production System

CPPS_DTDSS- Cyber-physical Production System Digital Twin Decision-support system

CC- Cloud Computing

CNC- Computer Numerical Control

DDAS- Dynamic Data-driven Applications Systems

DES- Discrete Event Simulation

DCS- Distributed Control System

DF- Digital Factory

DL- Deep Learning

DMU- Digital Mock Unit

DNC- Distributed Numerical Control

DT- Digital Twin

ERP- Enterprise Resource Planning System

HTTP- Hyper-Text Transfer Protocol

ICT- Information and Communication Technology

ID- Identification

IDEF0- Integration Definition for Process Modelling

IEC- International Electrotechnical Commission

ISA95- International Society of Automation

ISO- International Organization for Standardization

IT- Information Technology

IoT- Internet of Things

JSON- JavaScript Object Notation

LSTM- Long Short-term Memory

MES- Manufacturing Execution System

MOM- Message Oriented Middleware

NASA- National Aeronautics and Space Administration

NLP- Natural Language Processing

OOP- Object-Oriented Programming

O/I- Output/Input

OPC_UA- Open Platform Communications Unified Architecture

OT- Operational Technology

PLE-Product Line Engineering

RAMI4.0- Reference Architectural Model Industry 4.0

RF- Radio Frequency

RFID- Radio Frequency Identification

RES- Remote Execution Service Reset Resolution

REST- Representational State Transfer

PLC- Programmable Logic Controller

PLM- Product Lifecycle Management

RTLS- Real-time Location System

SCADA- Supervisory Control and Data Acquisition

SMEs- Small and Medium-sized Enterprise

SOAP- Simple Object Access Protocol

SP- Setpoint

SUI- System Under Investigation

SQL- Structured Query Language

SOA- Service Oriented Architecture

TIA-Totally Integrated Automation

VR-Virtual Reality

WWW- World Wide Web

WSN- Wireless Sensor Network

2D- 2 dimension

3D- 3 dimension

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Abstract

The fourth industrial revolution has greatly influenced and redefined the manufacturing industry. Modern manufacturing is driven towards high value-added, technological-based manufacturing. Business-wise, it is to maximise or maintain competitiveness in an emerging digital era. This technological transformation has been triggered by tremendous growth and innovative breakthroughs in the digital world. It has led to the increasing integration of information and communication technologies (ICT) with industrial operational technologies (OT). To support the positioning of the manufacturing industry to effectively play its role in the fourth industrial revolution, this research makes its contribution by exploring and applying the digital twin (DT) concept in the digitisation of manufacturing processes. This is intended to digitise and control manufacturing processes to achieve real-time cyber-physical interaction and integration, involving both product and process digital twins. This is geared towards achieving dynamic production systems as part of the expectations of the fourth industrial revolution.

The methodology adopted in this study involved a systematic literature review, system identification, modelling and simulations. This enabled the definition of entities, functions, quantities, performance metrics and propositions analysed through experimentation. A case study on a Festo CP smart factory was presented as evidence of the feasibility and effectiveness of the propositions made in this research.

The contributions made by this research included:

- A proposed digital twin framework that supports the integration of the product and process digital twins for applications in manufacturing
- Proposed techniques to support real-time synchronised interaction between the asset-twin. These include a dependency rule that logically defines a bidirectional relationship between the product DT and its processes DTs; and a real-time synchronisation mechanism that supports a synchronised real-time interactive environment

- A proposed cyber-physical control structure for a Cyber-physical production system (CPPS) DT and an implementation strategy of the Cyber-physical control structure. This framework integrates the digital twin virtual control structure with the physical asset’s control system over a real-time bidirectional communication link
- A proposed CPPS DT decision support system (CPPS_DTDSS) that positions the integrated product-process DT to access/share resources across the Hierarchy levels of the RAMI4.0 automation architecture. This is an automation reference architecture for Industry 4.0 that includes the product and connected world in its Hierarchy levels. This extends the concept of integration across the Hierarchy levels of the RAMI4.0 architecture

The real-time collaborative interaction between the asset-twin extends the numerous digital capabilities of the DT to the operational phase of the CPPS. This positions the DT as a decision-support mechanism for the CPPS. The CPPS supports its DT simulations, analyses and visualisation with operational data and control. The DT, with a Cyber-physical control structure, can execute real-time control, production management and product customisation.

CHAPTER I: INTRODUCTION

This chapter introduces the research on the digitalisation of manufacturing processes. It highlights the motivation behind this research, discusses the research questions, and presents the research aims and objectives geared towards answering the research questions. Lastly, it presents the outline of the thesis report.

1.1 Background

Modern manufacturing today, has been driven by high-value-ended technologies to high-value low cost-based, manufacturing. Business-wise, it is designed to maximise or maintain competitiveness at a minimum cost. With the increasing advancement in technology and business competition from low labour cost countries, this research is geared toward an increase in equipment utilization, critical production cost reduction and the development of innovative products (Kritzinger et al., 2018, Talkhestani et al., 2018). This would include the development and adoption of advanced innovations to enhance existing manufacturing processes, tools, techniques, products and the design and development of new manufacturing tools (Aivaliotis, Georgoulias, & Alexopoulos, 2019). Socially, this advancement enables the manufacturing industry to meet the dynamic ever-growing expectations of the new socio-economic behaviour of the society introduced by the digital era; for instance, the internet.

1.2 Motivation

A new era of manufacturing called smart/digitised manufacturing has arisen due to the integration of innovations like the interconnections of intelligent components, the internet of things (IoT), sensor data fusion and cloud computing technologies within factory floors (Rosen et al., 2015; Zhang, Ma et al., 2019). These developments have also given birth to the concept of the digital twin (DT). Many industrial researchers present this concept as the pillar for the next generation of digitised manufacturing (Shangguan, Chen and Ding, 2019). This provides the linkage needed to bridge the gap between the physical and virtual space in real-time, interconnect silos of data within a business chain and reinvent the paradigm of demand and supply (Tao & Zhang, 2017; Qi, Tao et al., 2018; Kabaldin et al., 2019).

Today, viewed beyond engineering, the DT concept is considered an instrument for integrating business strategies along the business supply chain (Microsoft, 2017). With this, costly and time-expensive physical models can be replaced with more efficient and effective predictive and diagnostic virtual tools supported with real-time comprehensive data to investigate and manage consequences of both product and process development, operations and servicing decisions on product/process behaviour (Klitou, 2017).

The digitalisation of manufacturing paves way for the application of more sophisticated virtual models and IT technologies thereby allowing the connection of various phases of a product/process lifecycle. The integration of these phases creates room for product/process improvement and optimal resource utility. Being able to mirror the real world through real-time data construct creates a new level of industrial research, production flexibility, enhanced product customisation and increases customer satisfaction owing to energy and resource efficiency, shortened time-to-market and enhanced flexibility.

1.3 Discussion of the problem

Our current world is defined by the first three industrial revolutions, namely: mechanisation, mass production and computerisation. The industrial sector can be said to be in the early stage of its fourth revolution (Liu, Meyendorf and Mrad, 2018). This new era, triggered by the convergence of the digital and the physical worlds creates a cyber-physical environment; an innovational leap that has and is still transforming the manufacturing sector resulting in digital factories (DF) and smart production and products (Biesinger et al., 2019). The drive towards achieving the Industry 4.0 vision for digital factories is faced with challenges like the disconnection of related manufacturing sites, independent models, isolated data and non-self-controlled applications (Catapult, 2019). There is a need to unveil the invaluable potential of the integration of these resources.

From a broad perspective, this research tries to answer the following question: *"How can the integration of both product and process digital twins facilitate the drive towards harnessing the benefits of digitisation in manufacturing processes?"* Current research has treated the product and process digital twins as separate entities. This research is interested in harnessing the digital benefits of the interdependencies between the product and its production processes using the digital twin concept. In an endeavour to answer the aforementioned question, the thesis addresses the following questions:

1. *How can a product and process digital twin be integrated to harness the dependencies between the product and its manufacturing processes?*
2. *What infrastructures are needed to support real-time synchronised interaction between the integrated product-process digital twin and its physical asset?*
3. *How can bidirectional control be achieved between the physical system and the digital twin to enable cyber-physical interaction?*
4. *How can the digital twin concept support decision-making across the RAMI4.0 automation Hierarchy levels?*

1.4 Purpose: Research aim and objectives

In response to the aforementioned research questions, this research aims to digitise and control manufacturing processes by using the digital twin concept to achieve real-time cyber-physical interaction and integration, involving both product and process digital twins. This is aimed toward achieving dynamic production systems as part of the expectations of the fourth industrial revolution.

The research objectives include:

1. Design a digital twin architecture for smart factories that supports the integration of both the product and the process digital twins
2. Develop techniques to integrate the product digital twin, process digital twin and the physical asset to support real-time synchronised interactive simulation
3. Establish a cyber-physical control structure using closed-control loops at multiple granularities that support real-time synchronized bidirectional control between the asset-twin: collaborative control
4. Develop a framework that positions the digital twin concept as a decision-support system across the RAMI4.0 automation Hierarchy level
5. Validate the integrated product-process digital twins as a decision-support system for a cyber-physical production system (CPPS) using a range of dynamic scenarios

1.5 Contributions

This thesis has explored the concept of the digital twin in the digitisation of manufacturing processes to achieve dynamic production systems as part of the expectations of the fourth industrial revolution. Such a production environment would support real-time cyber-physical interaction and integration between both the product and process digital twins and the physical asset. The novelties and main contributions made by this research include:

(a) A proposed digital twin framework that supports the integration of the product and process digital twins for applications in manufacturing
(b) Proposed two techniques to support real-time synchronised interaction between the asset-twin. These included a dependency rule that logically defines a bidirectional relationship between the product DT and its processes DTs; and a real-time synchronisation mechanism that supports a synchronised real-time interactive environment
(c) A proposed cyber-physical control structure for a Cyber-physical production system (CPPS) DT and an implementation strategy of the Cyber-physical control structure. This framework integrates the digital twin virtual control structure with the physical asset's control system over a real-time bidirectional communication link
(d) A proposed CPPS DT decision support system (CPPS_DTDSS) that positions the integrated product-process DT to access/share resources across the Hierarchy levels of the RAMI4.0 automation architecture which is the automation reference architecture for Industry 4.0. This extends the concept of integration across the Hierarchy levels of the RAMI4.0 architecture The RAMI4.0 (Figure 3.8) is the automation reference architecture for Industry 4.0.

1.6 Methodology

The methodology designed for this research divides the research into theoretical and practical works. This methodological approach attempts to support all theoretical propositions with experimental results. Strategically, to measure, monitor and maintain the research progression, the research objectives were broken down into significant milestones which were further clustered into phases that allowed for a sequential build-up to the research aims and objectives within the academic timeframe. The included case study provides applicative evidence and guidelines on the research contributions.

1.7 Outline of the thesis

The research narrative establishes the journey taken to adopt the DT concept as a digitisation tool in manufacturing. First, the benefits of the concept are identified, followed by a methodology designed to achieve cyber-physical integration and harness its benefits within the manufacturing environment. This outline is structured broadly on applicative methodologies using existing concepts, techniques and industrial tools. Building on this foundation, the case study identifies results and propositions for improvement. The remaining chapters are structured as shown below.

Chapter 2 attempted to answer the question "*How does the digital twin concept support the realisation of an integrated, flexible and collaborative manufacturing environment as one of the goals projected by the fourth industrial revolution?"*. This established the basis for the research through literature review. It addressed how the digital twin concept supports integration, flexibility and collaboration within the manufacturing environment. Research trends and gaps were identified, the research objectives and methodology were redefined based on these findings.

Chapter 3 presented in detail the methodological approach adopted for this research. Here the research plan and methods used are defined along with set milestones. The case study was also introduced in this chapter.

Chapter 4 presented a digital twin architecture in detail in response to the question *“How can a product and process digital twin be integrated to harness the dependencies between the product and its manufacturing processes?”.* This included the method of achieving the product-process digital twin integration. Such integration would provide more control over production resources and product quality during production. A case study with key steps on how to implement the proposed framework was presented for validation.

Chapter 5 answered the question “*What infrastructures are needed to support real-time synchronised interaction between the integrated product-process digital twin and its physical asset?”.* This chapter presented the techniques to implement the proposed DT architecture in Chapter 4. This involved the development of the DT model and mechanism for an interactive collaborative simulation. The OPC_UA protocol was implemented as a technique to establish a unified data communication channel between all related system elements. A case study was presented for validation.

Chapter 6 presented answers to the questions: *“How can bidirectional control be achieved between the physical system and the digital twin to enable a two-way interaction”* and “*How can this control infrastructure support production flexibility, product customisation as a decision support mechanism?”.* It presented the proposed cyber-physical control structure using closed-control loops at multiple granularities to support real-time synchronized bidirectional control between an integrated product-process DT and the physical asset. Implemented control techniques and strategies, and the results of such implementations were discussed. A case study was presented for validation and the results presented here showed how the dynamic product DT uses a closed-loop data-driven control to trigger corresponding system configurations for production and support production management. This presents an interesting concept of real-time interactive simulation.

Chapter 7 looked at the concept of the DT as a decision-support system and addressed the question "*How can the digital twin concept support decision-making across the RAMI4.0 automation Hierarchy levels?". In light of this, Industry 4.0 concepts and techniques were applied in the proposed CPPS DT decision support architecture (CPPS_DTDSS). The case study presented here for validation used the Node-RED application as a Message-oriented middleware (MOM) that supports IoT communication and management. It was used to establish communication between the DT, MES/ERP system, customer API and cloud service platform hosting the external database. Also, it was used to create the customer interface to pull customer information for use in the DT platform and provide information to customers.

Chapter 8 is a summary of the research work with some recommendations which propose future research and highlighted some identified limitations. The chapter ends with a conclusion. A recommendation that attempts to address *"How companies can determine the kind of digital twin they need"* (Appendix E), other related research work and supporting information can be found in the Appendix section.

CHAPTER II: BACKGROUND AND LITERATURE REVIEW

The digital twin (DT) concept has a key role in the future of the smart manufacturing industry. This review aims to investigate the development of the digital twin concept, its maturity and its vital role in the fourth industrial revolution. Having identified its potential functionalities for the digitalisation of the manufacturing industry, the digital twin concept, its origin and perspectives from both the academic and industrial sectors are presented. The identified research gaps, trends and technical limitations hampering the implementation of digital twins are also discussed. In particular, this review attempts to address the research question of how the digital twin concept can support the realisation of an integrated, flexible and collaborative manufacturing environment which is one of the goals projected by the fourth industrial revolution.

2.1 Introduction

2.1.1 *Background*

In recent years, the tremendous growth and innovative breakthroughs in the digital world and the increasing integration of information and communication technologies (ICT) with industrial operational technologies (OT) have greatly influenced and redefined the manufacturing industry. This has enabled better energy and resource utilisation, shortened time-to-market for products and enhanced manufacturing flexibility (Rosen et al., 2015; Zhang, Zhou et al., 2019). Innovations like the interconnections of intelligent components within factory floors, Internet of Things (IoT), sensor data fusion and cloud computing (CC) technologies has given birth to a new era of manufacturing most often called smart manufacturing/digitised manufacturing (Tao & Zhang, 2017; Yun, Park, & Kim, 2017).

Several national strategies have been developed to harness the potential of these emerging technologies/innovations within the manufacturing industries. Examples include Industry 4.0 (I4.0) by Germany, Made in China 2025, Strategy 5.0 by Japan, Advanced manufacturing partnerships and Industrial internet strategies in the United States of America (USA) (Zhang, Zhou et al., 2019).

In manufacturing, the convergence of the virtual space with the physical operational space, to enable the interconnection of virtual elements with their operational physical counterparts (cyber-physical integration) has been a significant challenge in achieving the objectives of smart production (Tao & Zhang, 2017; Cheng et al., 2018). The concept of the digital twin (DT) has been discussed for over a decade as an approach to tackle this problem and in recent has gained much more attention worldwide (Cheng et al., 2018; Zhou et al., 2019). It provides the linkage needed to bridge the gap between the physical and virtual space in real-time, interconnect silos of data within a business chain and reinvent the paradigm of demand and supply (Rosen et al., 2015; Schuh & Blum, 2016; Yun, Park & Kim, 2017).

2.1.2 *Problem domain*

(a) Discussion of the problem

Industry 4.0 drives the manufacturing industry into a new era of autonomous and intelligent information exchange, machine control and interoperable production systems. One of the key goals of Industry 4.0 is the connectivity and integration of elements within the production environment (DIN & DKE, 2018). This will allow companies to build a data footprint through sensors and monitoring of machines/equipment. However, there are challenges associated with the existing structure of manufacturing systems: centralised control structures and heterogeneity of data due to the variability of manufacturing vendor products (Tao et al., 2019).

The digital twin concept is presented as a prospective solution to this challenge. This brings us to the research question: *"How does the digital twin concept support the realisation of an integrated, flexible and collaborative manufacturing environment as one of the goals projected by the fourth industrial revolution?"*. By enabling the integration of both physical and virtual spaces, a DT of a manufacturing system can provide the integrated platform necessary to harness the potential of generated data. This would see more data-based corrective actions taken in real-time to optimise production lines and increase productivity.

(b) Past work on review

Negri et al. (2017) reviewed the roles of the digital twin in the cyber-physical system (CPS)-based production systems. This paper also presented the history of the concept, the definitions of the digital twin in scientific literature, its role within Industry 4.0 and some recommendations for future research. Kritzinger et al. (2018) presented a systematic literature review that focused on the use of digital twins in manufacturing. In the context of production science, they gave a holistic overview highlighting the manufacturing areas in which digital twin has been applied, the concepts, enabling technologies and level of integration in recorded use cases. Having criticised the synonymous use of the terms digital model (DM), digital shadow (DS) and digital twin (DT), they presented these three terms as subcategories of the digital twin based on the level of physical-virtual data integration. Enders and Hoßbach (2019) presented a systematic review providing a comprehensive cross-industry overview of the digital twin applications. Zhang, Ma, et al. (2019) published a systematic review that focused on the current state-of-the-art of digital twinning within the context of product-service systems.

It was observed that little work had been done in the context of the product-service systems area. Only two studies out of the 59 papers focused on product-service systems. In an attempt to build an understanding of the development and applications of the digital twin in industry, Tao et al. (2019) presented a review on the digital twin in industry. The focus was on the key component of digital twins, current developments, major digital twin applications, current challenges and lastly, recommendations on possible directions for future work. Aivaliotis, Georgoulias and Alexopoulos (2019) reviewed the use of the digital twin in the field of maintenance and health prediction. They investigated already existing implementations and proposed ways to improve them. Lu et al. (2020) reviewed digital twin-driven smart manufacturing. In the context of Industry 4.0, the development of digital twin technologies, impact, reference model, application scenarios and research issues of digital twin towards smart manufacturing were discussed. Jones et al. (2020) presented a systematic literature review with a thematic analysis of 92 digital twin publications from the last 10 years. In characterising the digital twin concept, 13 characteristics were presented namely physical entity/twin; virtual entity/twin; physical environment; virtual environment; state; realisation; metrology; twinning; twinning rate; physical-to-virtual connection/twinning; virtual-to-physical connection/twinning; physical processes; and virtual processes.

From the reviews mentioned above, it was observed that there has been an increasing interest in the digital twin concept. However, a variation in the definition, description, classification and application of the concept was observed. Despite the disparity in the perception of the digital twin concept by various interest groups, the last four years have witnessed many use cases in manufacturing (Figure 2.2) (Tao, Zhang & Nee, 2019). This work created a holistic picture of the research progress made so far within this field and identified the following focus areas for future research:

1. Common grounds for varying ideologies to add clarity to their applicability

2. Tracking the evolution of the concept up to the current understanding and applications within the manufacturing sector
3. Integrating both product and process digital twins to utilize their dependencies in a cyber-physical production system (CPPS)
4. Forging a research roadmap towards achieving the full dividends of the concept within the manufacturing industry

2.1.3 The focus of the literature review

Past reviews have pointed out challenges and research foci within this field suggesting that there is a need to track the developments made in tackling these challenges and find possible applications of these solutions within the manufacturing field. This research made its contribution by carrying out a thorough literature review to investigate the potentiality of the digital twin concept as an integrated platform to promote flexibility and integration in manufacturing. A flexibility that allows systems to easily adapt to changes in product type, quality, quantity and the integration of the automation information system to support data-driven control methods. In this regard, a holistic picture of the research progress made so far within this field is fundamental. This should include tracking the evolution and application of the digital twin concept from inception to date, and identification of research gaps, trends and technological triggers. Finally, identified limitations in the application of the DT concept are should be met with proposed solutions.

In this regard, the rest of the chapter is structured as follows: Section 2.2 presents the methodology for the literature review. Section 2.3 presents the discussion on the digital twin concept and its application. Digital twin frameworks for smart manufacturing were presented in Section 2.4 and real-time collaborative and interactive simulation in digital twinning was discussed in Section 2.5. Section 2.6 presents the discussion on cyber-physical control in digital twins and Section 2.7 presents a discussion on the digital twin as a decision-support system across the RAMI4.0 automation Hierarchy levels. Section 2.8 presents identified technical limitations and proposed solutions and Section 2.9 presents the disposition of this research. The chapter concludes with a summary of the systematic literature review.

2.2 Methodology for literature review

This chapter presents the methodology used in the systematic literature review and the main quantitative findings. Figure 2.1 shows the methodology used to gather the digital twin-related literature. This method involved a literature search of the Scopus and ScienceDirect databases and quantitative and qualitative analyses of the selected papers. The keywords “digital twin” and “manufacturing” with the keyword Boolean “AND” were used for the search. The identification and collation of the critical studies were done using the steps explained in Figure 2.1: A total of 168 publications were considered for meta-analysis and unpublished data were not considered.

A meta-analysis was done to increase the power and precision of this research outcome and more importantly using statistical measures, a survey of the landscape enabled the proposition of a map out for future research directions (Stapic et al., 2012). This research may be biased since the choice of which journal article should be included or not was subjective to the researchers’ judgement. The definition of quality is dependent on the researcher and as such the quality of the articles used in the study may vary with the person. Figure 2.2a presents the number of publications considered in the highlighted years.

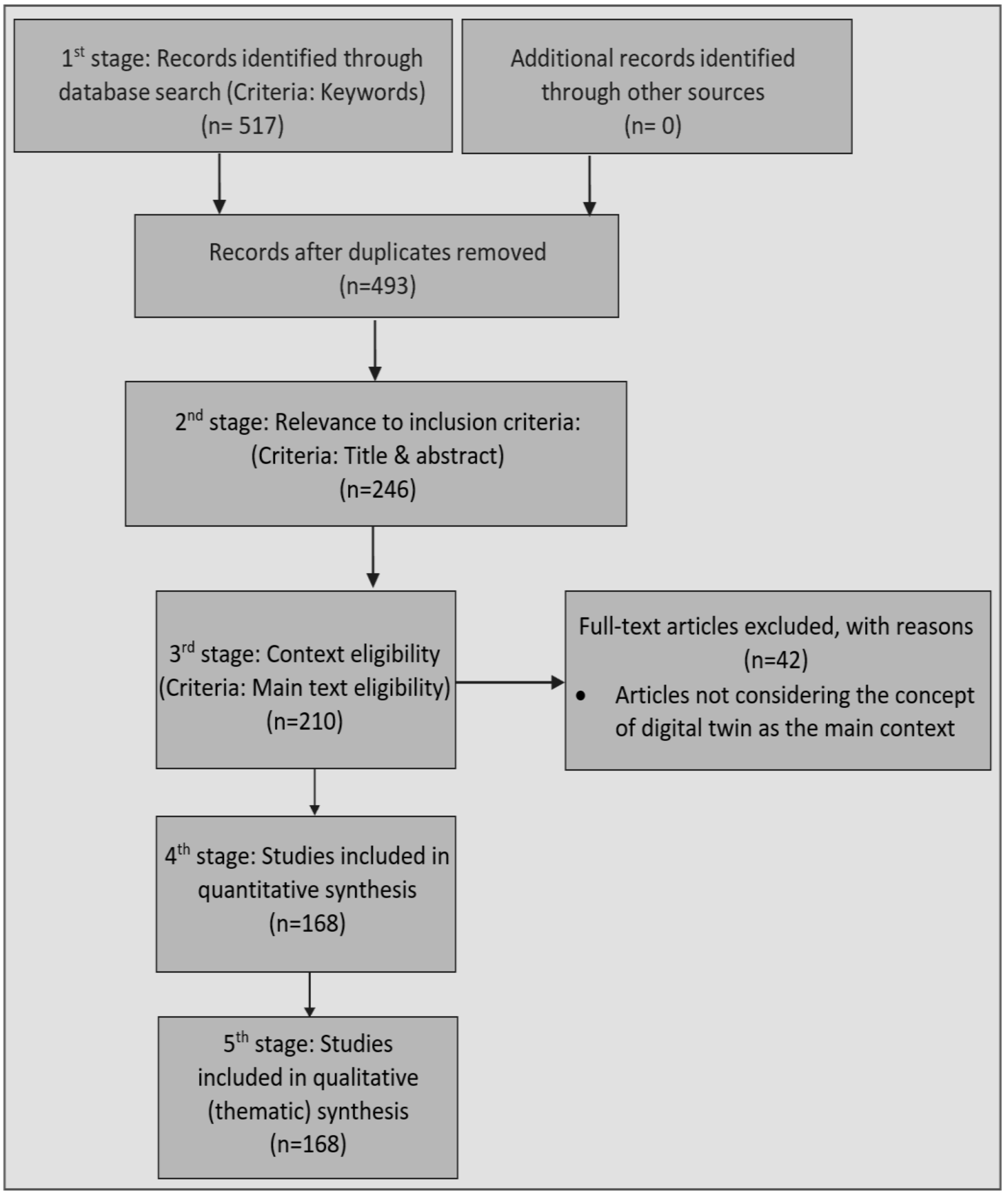
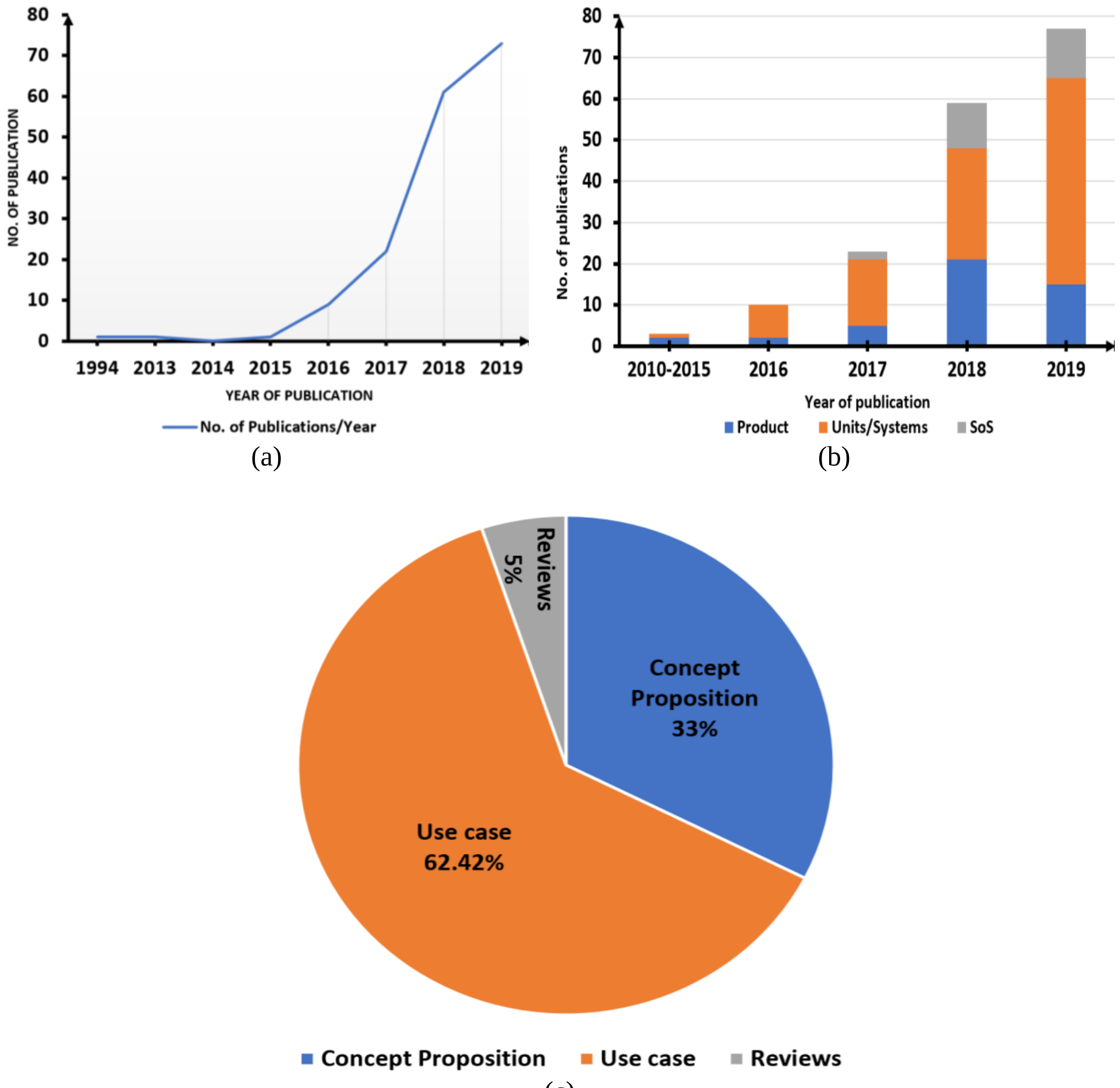


Figure 2.1: Flow chart of the selection process. Adapted from (Moher et al., 2009)

Figure 2.2(a) demonstrates the growing research interest in the area of the digital twin, especially from the year 2017. Figure 2.2(b & c) shows an increased application of the concept at systems and system-of-systems (SoS) levels. These findings reveal a growing acceptance of the concept as an essential driving force/element for the fourth manufacturing generation.



(a) (b)

(c)

Figure 2.2: (a) Depicts trend of digital twin research interest (b) Digital twin types (c) Research focus between 1994 to 2019

2.3 Digital twin (DT) concept

This section presents the key findings on the DT concept from the literature review conducted. This includes the evolution, perspectives and current understanding of the digital twin concept. It also presents the role of the DT in CPPS and briefly discussed technologies used to achieve cyber-physical integration.

2.3.1 *The concept of the digital twin*

The digital twin (Figure 2.3) is a virtual replica of its physical asset built mainly of structural and behavioural models mainly for basic control, monitoring and evaluation of its performance (Cai et al., 2017; Martinez et al., 2018).

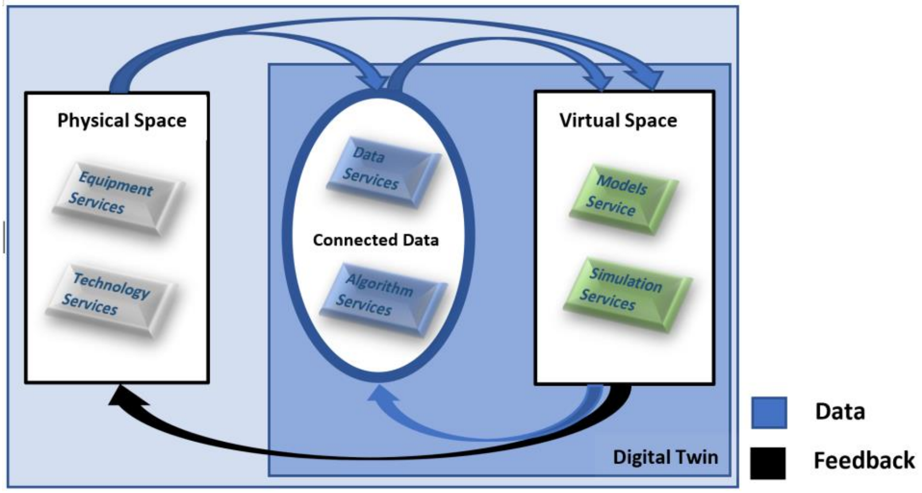


Figure 2.3: General digital twin architecture

(a) Characteristics of the digital twin

A digital twin, as shown in Figures 2.3 & 4.4, has the following characteristics which differentiate it from simulation models (Modoni, Sacco & Terkaj, 2016; Cheng et al., 2018; Martinez et al., 2018):

1. Real-time reflection: highly synchronised with the physical space, the virtual space is a real-time reflection of the physical space with a multi-level of fidelity.
2. Interaction and convergence: This characteristic is further divided as follows:
    a) Interaction and convergence in physical space: It is a complete integration of system phases, elements, services and interaction. Data generated in various phases of physical space is connected and accessible.

   b) Interaction and convergence between historical data and real-time data: Having both multi-physics models and data-driven approaches, a comprehensive digital twin contains both domain knowledge and timely operational information of the system.
   c) Interaction and convergence between the physical and virtual spaces: The digital twin is an integrated platform providing a smooth bidirectional connection between the two spaces.
3. Self-evolution: The digital twin can update its data in real-time automatically, mirroring its physical asset. Parallel connectivity allows comparison between the two spaces enabling continuous improvement of the virtual models.

(b) Technological triggers for the development of the DT concept

The past decades have seen much advancement in computer technology. This has resulted in the development and fusion of more sophisticated virtual models of physical products/systems (Weber et al., 2017). These models are not only used for design verification and validation in systems engineering but increasingly are been used as a model-based definition of the required product/system characteristics. Furthermore, the developments in ICT, microchips and sensor technologies like the *RFID* technology paves way for smart products and now smart factories (Schleich et al., 2017, Stark, Fresemann and Lindow, 2019). These have expanded data generation beyond geometrical measurements and scanning with easy, quick and reliable capabilities to track and communicate operational information. They can feed the virtual models with real-time data relating to their operational statuses such as their environmental conditions, system performance and load (Schroeder et al., 2016).

One will not fail to acknowledge the influence of new sciences like data mining, pattern recognition, deep learning, reverse engineering and modern data analysis techniques in unveiling more potentials in this generated data sets and other dependencies between product, process, operational characteristics and business strategic decisions (Weber et al., 2017; Leng et al., 2019). This has projected operational data as the linkage between the virtual world and the physical world. The aforementioned capabilities in system engineering have increased the possibilities of data gathering and exchange between both the virtual and physical worlds. Moreover, this forms the basis for the current understanding of the “digital twin vision” (Liu, Zhang et al., 2018; Liu, Meyendorf & Mrad, 2018).

2.3.2 The evolution of the digital twin concept

Since the public presentation of the digital twin concept, authors have argued on the vision of the digital twin resulting in different definitions and applications (Table 2.1). In recent years, more authors are inclined to the notion that the vision refers to a comprehensive virtual representation with connectivity to the physical and functional description of the product/system all through the lifecycle phases (Yun, Park & Kim, 2017; Cheng et al., 2018; Kritzinger et al., 2018). Table 2.1 presents some identified definitions of the digital twin. It reflects a gradual transformation of the concept and its applicability.

Table 2.1: Identified definitions of the digital twin in literature

No	Ref	Year	Definition of digital twin
1	(Shafto et al., 2012)	2010-2015	“A Digital twin is an integrated multi-physics, multiscale, probabilistic simulation of an as-built vehicle or system that uses the best available physical models, sensor updates, fleet history, etc., to mirror the life of its corresponding flying twin.”
2	(Schroeder et al., 2016)	2016	“The Digital twin being a virtual representation of the real product. It has product’s information since the beginning of the life until the disposal of the product.”
3	(Grieves & Vickers, 2016)	2016	‘‘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.’’

4	(Brenner & Hummel, 2017)	2017	“A digital copy of a real factory, machine, worker, etc., that is created and can be independently expanded, automatically updated as well as being globally available in real-time.”
5	(Stark, Kind, & Neumeyer, 2017)	2017	‘‘A Digital twin is the digital representation of a unique asset (product, machine, service, product service system or another intangible asset), that compromises its properties, condition and behaviour using models, information and data.’’
6	(Weber et al., 2017)	2017	“A digital representation of all the states and functions of a physical asset.”
7	(Blum & Schuh, 2017)	2017	“A virtual representation of a product on the shop-floor.”
8	(Bohlin et al., 2017)	2017	“A comprehensive physical and functional description of a component, product or system, which includes more or less all information which could be useful in the current and subsequent lifecycle phases.”
9	(Negri et al., 2017)	2017	“The virtual and computerized counterpart of a physical system that can be used to simulate it for various purposes, exploiting a real-time synchronisation of the sensed data coming from the field.”
10	(Tao et al., 2018)	2018	“A real mapping of all components in the product life cycle using physical data, virtual data and interaction data between them.”
11	(Scaglioni & Ferretti, 2018)	2018	“A near-real-time digital image of a physical object or process that helps optimize business performance.”
12	(Talkhestani, et al., 2018)	2018	“A current, digital model of a product or production system that contains a comprehensive physical and functional description of a component or system throughout the lifecycle.”
13	(Haag & Anderl, 2018)	2018	“A comprehensive digital representation of an individual product. It includes the properties, condition and behaviour of the real-life object through models and data.”
14	(Liu, Meyendorf, & Mrad, 2018)	2018	“An integrated multi-physics, multiscale, probabilistic simulation of an as-built system enabled by digital threads, that uses the best available models, sensor information, and input data to mirror and predict activities/performance over the life of its corresponding physical twin.”
15	(Zhuang, Liu, & Xiong, 2018)	2018	“A virtual, dynamic model in the virtual world that is fully consistent with its corresponding physical entity in the real world and can simulate its physical counterpart’s characteristics, behaviour, life, and performance in a timely fashion.”
16	(Sierla et al., 2018)	2018	“Digital twin: a near-real-time digital image of a physical object or process that helps optimize business performance.”
17	(Kunath & Winkler, 2018)	2018	“ The Digital twin of a physical object as the sum of all logically related data, i.e. engineering data and operational data, represented by a semantic data model.”
18	(Tharma, Winter, & Eigner, 2018)	2018	“Digital twin of a real distributed product is a virtual reflection, which can describe the exhaustive physical and functional properties of the product along the whole life cycle and can deliver and receive product information.”
19	(Eisentrager et al., 2018)	2018	“A digital twin is a digital model of a real object containing lifecycle records and dynamic status data, which are synchronized in real-time. The model will be used to gain knowledge that can be transferred to the real object.”
20	(Negri et al., 2019)	2019	“An integrated simulation of a complex product/system that, through physical models and sensor updates, ontol twin.”
21	(Biesinger et al., 2019)	2019	“A digital twin is defined as a realistic model on a current state of the process and behaviour of real objects with its structure and elements that are connected to it.”
22	(Kabaldin et al., 2019)	2019	“ A set of mathematical models characterizing in real-time the different states of the equipment, the technological processes, and the business processes in production conditions.”

The definitions of the digital twin given by NASA and Grieves reflect a broader view of its existing applications (Shafto et al., 2012; Grieves & Vickers, 2016). This research sees the digital twin for manufacturing as *a set of integrated virtual information construct of a potential or actual physical system detailed with all necessary minuscule and macro-level multi-physics, multi-scale geometric and simulative probabilistic specifics, suitable for its creation*. Virtual models of suitable granularity with defined functionalities are developed and integrated into a networked system (Cheng et al., 2018). The physical system interlinked with this integrated virtual entity updates it with operational data, thus becoming an exact digital representation of its physical asset (Haag & Anderl, 2018). The development of the digital twin for a new physical asset should begin at the design/engineering stage and evolve through the assets' lifecycle (Rosen et al., 2015; Martinez et al., 2018; Qi et al., 2018). For already existing systems, the digital twin can become an additional component modelled to reflect the existing functionalities of the system (Enders & Hoßbach 2019).

2.3.3 Perspectives on the digital twin

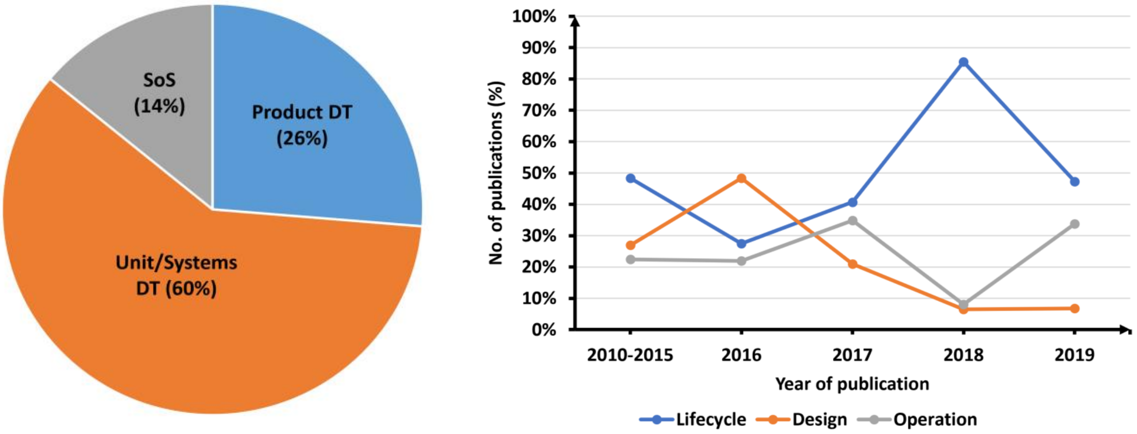
The digital twin concept in an earlier time was applied to product design (Zhang, Xu et al., 2019). In recent times it is perceived to encompass the entire business value chain resulting in digital twins of products, production processes, system performance and services (Leng et al., 2019). Despite non-unification in definition and description (Table 2.1), there is a similarity in the key components of the digital twin: real-time interaction and the replication of physical asset functionalities in the virtual space.

For this research, the digital twin concept can be applied within the manufacturing industry primarily at three levels, namely: product, unit/systems and system of a system (SoS)/shop-floor levels. These virtually represent the integration of process, raw material, tools/equipment, finished products and services, including all static and dynamic compositions of the production system (Qi et al., 2018; Qi, Tao et al., 2018). Virtual models used for a digital twin can include the following physical models (geometric, performance, simulation), relational rules and behaviour models that reflect the state, characteristics, behaviours and performance of its physical entities (Cheng et al., 2018). They can be used for simulations during virtual commissioning, monitoring, diagnostics, prediction and control of the state and behaviour of its twin to support decision-making in the development and operation phases of the product, as well as reflect information continuity throughout the product lifecycle (Schleich et al., 2017; Haag & Anderl, 2018). Figure 2.2 shows increased usage of the concept within the manufacturing sector.

Digital twin of a product: The digital twin of a product is simply its digital construct mapping the individual product in the virtual space. Its level of functionality and comprehensiveness is dependent on the physical twin and intended use (Tao et al., 2018; Haag & Anderl, 2018).

Digital twin at a unit/system level: A digital twin at a unit level of the CPS systems is at its smallest possible granularity. Such small units include components and equipment (e.g. computer numerical control (CNC) machines, robots), materials (transport facilities like automated guided vehicles (AGV) and other value-added raw materials), and smart environments (Kritzinger et al., 2018). The digital twin at a system level is an integrated data-oriented virtual replica of all necessary process elements. This includes all unit-level digital twins of manufacturing equipment, material flow, operating systems, human resources, and other value stream elements (Blum & Schuh, 2017; Qi, Tao et al., (2018). At the system level of a shopfloor, models considered include production capability models for production capability and characterisation, process models to link process-related parameters to product design attributes and mirror the interaction between a product and the model of its corresponding production process model (Cheng et al., 2018).

Digital twin at an SoS level: The digital twin smart service platforms can be used to achieve collaboration between system-level CPSs and digital twins. This could be a collaboration within a factory site where production lines can interact or different factory sites. Such an integrated platform enables the integration of the various lifecycle processes of a product, data and resources. This is an enabling environment for cross-systems and cross-platform interconnection and interoperability and optimisation of servitisation (Qi, Tao et al., 2018).



(a) (b)

Figure 2.4: (a) Percentage of publications based on digital twin type (b) Trend of the digital twin applicability in process/product lifecycle phases

Figure 2.4(a) shows more use of the digital twin to support the unit/systems level. Figure 2.4(b) demonstrates the publication trend in the last ten years. A large number of publications in 2018 highlight the use of the DT concept in a physical asset's lifecycle, enabling an enriched digital twin database built right from the design stage to be available all through its lifecycle (Jones et al., 2020). Publications in 2019 show an increased discussion of the digital twin in the operational phase with a focus on simulation and optimisation using real-time operational data.

There is a congruence amongst authors that digital innovations like sensor data fusion, IoT, edge and cloud computing technologies, deep learning and machine learning in Artificial intelligence, big data analytics, faster algorithms, increased computational power and the availability of more operational data are triggers for the modification of the expectations of the concept (Lu & Xu, 2018; Scaglioni & Ferretti, 2018; Zhang, Zhou et al., 2019).

Analysis of the articles identified six key functionalities inherent in the digital twin applications namely, prognostic and diagnostic analyses, simulation (online and offline), control, monitoring/supervision and optimisation (Figure 2.5) (Martinez et al., 2018; Zhuang, Liu, & Xiong, 2018; Zhang, Zhou et al. 2019; Zhang, Xu et al., 2019). As seen in Figure 2.5, in recent years, there has been more acceptance of the potentiality of the digital twin concept to provide all six functionalities. Figure 2.5 demonstrates a steady rise in both simulation and optimisation as a result of the availability of more factual data (operational data) for simulation and a better understanding of the physical asset through mirrored/factual virtual representation/analysis.

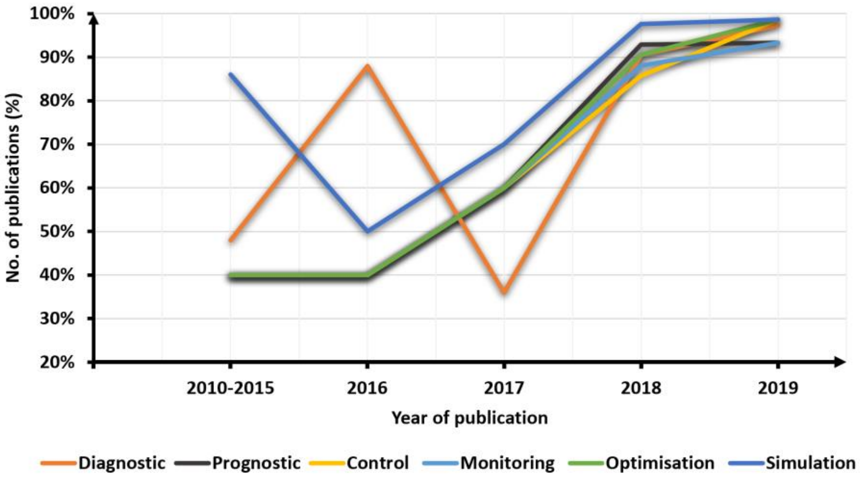


Figure 2.5: Digital twin functionalities

2.3.4 Current industrial understanding and applications

The disparity in the understanding of the digital twin vision in the industry is seen in its application, as shown in Table 2.2. It is being used along with various phases of the product lifecycle, interconnect business partners and customers. Microsoft Corporation views the digital twin concept as a business transformation strategy (Microsoft, 2017).

Table 2.2: Table of companies' views and application purpose

Ref	Companies	View	Purpose
(Schleich et al., 2017)	Parametric Technology Corporation (PTC)	Real-time connectivity between the virtual and physical world	Provide efficient after-sales services using digital twin data.
(Cheng et al., 2018)	General Electric (GE)	Modelling of the current state of its physical twin	To improve the efficiency of performance and health forecast of products throughout their lifecycle
(Microsoft, 2017).	Microsoft Corp.	A business transformation strategy	Integrate the business supply chain
(Schleich et al., 2017)	Dassault Systèmes		Improve product design performance
(Schleich et al., 2017)	TESLA Inc.		To achieve synchronous data flow between vehicles, factories and other companies.
(Cheng et al., 2018)	NASA	Interconnection of both physical assets and an equivalent virtual replica of the physical system	Used for fault prediction and validation of related systems
(Cheng et al., 2018)	U.S. Department of Defence	An integrated simulation virtual replica of the physical asset	Used for health maintenance of aerospace crafts
(Schleich et al., 2017)	Siemens	Virtual models of a physical production system	Establish a connection between virtual and physical space to capture the digital process of products from the design stage to manufacturing to improve efficiency and quality
(Shubenkova et al., 2018)	Predix Asset Performance Management (Predix APM)		Service based platform for industrial-grade analytics for operation optimization and performance management
(Shubenkova et al., 2018)	DXC Technology		A software platform used for hybrid car manufacturing

2.3.5 The Role of the digital twin in CPPS

Integrating production systems with ICT technologies and employing artificial intelligence in manufacturing systems transforms traditional production systems into what is now known as cyber-physical production systems (Negri et al., 2019). The CPPS paradigm with more ICT enhancements, scalable modular structures and distributed control introduces autonomous integrated, adaptable production systems that shortens engineering time in production processes and the cost of mass customisation. (Qi et al., 2018).

(a) Decision-support system

The idea of a supportive decision-making system becomes realisable with the digital twin concept. Built on real-time operational data, the CPPS is capable of making its own decisions about its future or supporting external decision-making systems (Zhang, Zhou et al., 2019). Being able to mirror the physical environment within the digital model allows for better evaluation of both internal and external changes. Notably, with this comes the possibility of analysing the interactive dynamism between these internal and external factors resulting in a timely response to such changes. This is of great influence on product and process management and optimisation (Stark, Fresemann & Lindow, 2019).

Data models mostly used in engineering and simulation tools are not compatible resulting in data silos within production systems (Schuh & Blum, 2016). Secondly, there is the issue of insufficient details to meet all parameter needs. Thirdly, the proprietary format limits the amalgamation of relevant engineering data and models for each object. The digital twin concept provides the needed integrated platform enriched with a semantic description enabling relevant data of the same format available throughout its lifecycle (Schroeder et al., 2016; Schleich et al., 2017). This concept will replace existing time-consuming processes like reverse engineering where reflecting changes in the virtual model and existing data would involve a series of manual operations like the creation of new geometric models, conversion of data formats to suit manufacturing and simulation tools, setting up of new parameters and properties of the simulation model (Weyer et al., 2016; Vachalek et al., 2017).

(b) Data acquisition, data flow and communication management

Recent transformation in economic development and adjustment in industrial structure has led to continuous integration of information, communication industry and manufacturing (Vachalek et al., 2017). This has greatly improved the level of industrial production with timely data collection, dynamism in planning and operations, and automatic monitoring and supervision of system status (Zhang, Zhang et al., 2017). However, scientific literature has identified the lack of interaction and interoperability between disconnected related industrial sites, independent digital models, non-self-controlled applications and isolated data silos created within the physical workspace and virtual information space (Zhang, Zhang, & Yan, 2018).

The digital twin can be used to tackle this interconnectivity challenge (Cheng et al., 2018). Data flow is very important to actualising a realistic digital twin. Data could include machine/equipment data stream, health status, work instructions, production status, component location, and sensor data stream (Jones et al., 2020). Uhlemann et al., (2017) pointed out the importance of digital data acquisition in implementing the digital twin concept in a CPPS. Carrying out real-time evaluation and analysis for highly complex production systems would require nothing short of a real-time generated database (Tao, Sui et al., 2018). In this regard, more research should be carried out on automated data acquisition and selection.

Fully automated digital multi-modal data acquisition, evaluation and quantification of underlying process data still falls short of the expectations of Industry 4.0. The reasons for this are not farfetched from the fact that the majority of the planning operations, transmission and storage of information are manually managed and the prevailing difficulty in benchmarking results due to a lack of sound theoretical evaluation criteria (Uhlemann et al., 2017). This has resulted in low-efficiency values and real-time performance (Zhang, Zhang et al., 2017). Even though these manually achieved planning results are analysed with the aid of simulation, complexities still flout manual controllability posing a challenge to the evaluation and quantification of these planning procedures (Uhlemann et al., 2017).

(c) Analytics

In non-production industries, data analytics (Figure 2.6) has been a significant tool used for evaluating past incidences and the prediction of the future state. For example, Yarra Trams from Melbourne (Australia) achieved a 99% increase in service quality based on the obtained data and foresight gained when they analysed data acquired from 9100 trams and other data sources (Schuh & Blum, 2016). This gave them insight and knowledge about disturbances, performance and passenger volume in their network. Data collection and usage are also essential within the manufacturing environment. More implementation of data analytics methods in manufacturing would see to increased efficiency of value-added processes because it presents a higher potential for improving system efficiency (Schuh & Blum, 2016; Vachalek, et al., 2017). Operational data extracted from manufacturing processes have facilitated the enhancement of manufacturing efficiency leading to a more lean and competitive establishment (Tao, Sui et al., 2018).

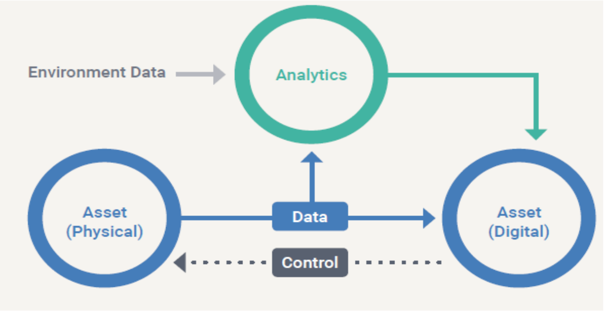


Figure 2.6: Analytics in an interactive digital twin Source (Catapult, 2019)

(d) Simulation Perspective

Traditionally, simulation is done at the design phase using estimated or historical data as input. The reliability of functionalities provided by the virtual system is highly dependent on how much the physical system can be emulated. This constraint can be attributed to system complexity and uncertainties. With the digital twin concept, this known constraint to building realistic digital models of its specific physical twin can be handled using real operational and sensory data to update the digital twin (Zhang, Liu et al., 2017). This integration will improve the digital model accuracy and capabilities by leveraging simulation at the operation execution stage. This creates new real-time operational potentials like autonomous decision inference, predictive simulation, automated control, self-optimisation, supervision, and monitoring because the digital twin based on such data would always provide real-time status of its physical twin in various applications (Kritzinger et al., 2018; Zhang, Ma, et al., 2019; Lu et al., 2020). This also comes with off-line review, diagnostic and prescriptive analysis. For example, machine part wear or system failure can be predicted using pattern recognition systems and third-degree regression models based on data received from simulation detections (Zhang, Zuo & Tao, 2018).

2.3.6 Cyber-physical integration using other concepts similar to the digital twin

In the last decade, other digital solutions for an integrated manufacturing environment have been reported in the literature, for example, the Cyber-physical system (CPS), Digital mock-up unit (DMU), Symbiotic simulation and the Product avatar. They all attempt to connect the physical space with the virtual world. The CPS with sensing, computation, control and communication capabilities attempts to achieve physical asset integration (Ward et al., 2021). The DMU, a system engineering 3D modelling process developed based on CAX (CAD/CAE/CAM) technology uses computer simulations as a replica of the actual mock-up (Zhang & Li, 2013; Rios et al., 2015). They can imitate the geometrical, physical and behavioural characteristics of the actual product mock-up thus providing real responses to exterior prompting as would the actual mock-up. Like the DT, real-time interactions with the product enable immersion in sensory perception (Rios et al., 2016; Tao, Zhang et al., 2019).

The symbiotic simulation system, birthed under discrete event simulation (DES) draws inspiration from symbiosis in biology. It emphasises a mutually beneficial close relationship between a physical system and its simulation system (Mitchell & Yilmaz, 2008). Like the DT, the simulation system has access to real-time sensor operational data from the physical system. With this, highly accurate simulations of the physical system are carried out and in turn, the physical system benefits from the decisions made based on the outcome of the simulations of several scenarios representing different operational decisions (Mitchell & Yilmaz, 2008). The product avatar concept with no explicitly significant difference from the DT concept focuses on user-oriented product formation. Like the DT, it also considers sensor data and the physical product is digitally represented using several models (Rios et al., 2015). In addition to integration, the digital twin offers the advantages of inclusiveness of communication, interaction and collaboration between the virtual and physical space (Tao, Zhang et al., 2019).

It serves as a representation of both the digital and physical properties of the current and future state of the product, equipment or process (Schroeder et al., 2016).

2.3.7 Cyber-physical integration using the digital twin concept

Cheng et al. (2018) present the aims of a smart factory for the fourth manufacturing generation and analysed them in four contexts namely (i) physical integration and data collection, (ii) digital/virtual models and simulations, (iii) data and information technology systems integration and lastly, (iv) databased production operations and management methods. Viewing the capabilities of the digital twin from these perspectives constructs a more vivid picture of how it supports integration, flexibility and collaboration within the smart manufacturing environment.

Physical asset integration and data collection: The creation of ubiquitous interconnections between physically separated elements/subsystems of a production system based on a collaborative and context-awareness initiative will support data collection, interaction and interoperation within an integrated environment. Such an integrated operational environment is obtainable using the CPPS concept.

Digital/virtual models and simulation: The creation of multi-dimensional models by the integration of faithful-mirrored virtual models of both the product/processes systematically constructed using all necessary data (both engineering and operational data) within a closed-loop bidirectional network with the physical assets will contain geometric and physical properties models of elements, response models of behaviours and logical models of relationships. This will enable reliable and synchronous real-time systems/models co-simulation, correction, modification and control.

Data and information system integration: The virtual models provide the mechanism (relational rule model) for a methodical integration and unambiguous fusion of cyberspace (all elements/flows/businesses-covered) data with data perceived from the physical world. This mechanism will support the dynamic generation and iterative co-evolution of models and big manufacturing data.

Data-based production operations and management methods: Physical-cyber consistency and synchronisation present an avenue for more effective utilisation of generated data for value creation through collaboration. Operational optimisation in factories can be improved through the integration of data-driven services and interdependencies of applications allowing on-demand matching and utilisation of services.

2.4 Digital twin frameworks for smart manufacturing

This section first reviews the proposed digital twin frameworks from the literature and then projects the author's perspective on DT frameworks for smart manufacturing.

2.4.1 Related work on digital twin frameworks in manufacturing

Grieves' standard architecture for a DT model consists of a physical asset, virtual replica and connection which is sufficient to establish a cyber-physical interaction (Shafto et al., 2012; Grieves & Vickers, 2016). This architecture in some use-case has been extended up to a 6-dimensional framework by the inclusion of DT data and services (Tao et al., 2018; Zhang, Zhou et al., 2019: Zhang, Xu et al., 2019). These enable the fusion and evolution of both physical and virtually generated data and the addition of analytical functionalities to the digital twin.

Tao et al. (2018) presented a digital twin-driven product design (DTPD) framework. This serves as a guide on the creation of a product digital twin and the utilisation of its generated knowledge in the product design process. Zhang, Zhou et al. (2019) proposed a data and knowledge-driven digital twin framework for a manufacturing cell (DMTC). It supports an autonomous manufacturing cell using data for the perception of manufacturing problems and knowledge for solving identified problems and has five-dimensional space namely the physical, digital, data, knowledge and social space. This framework is expected to support self-thinking, self-decision-making, self-execution and self-improving. Cheng et al. (2018) also present the aims of a smart factory for the fourth manufacturing generation. In this case, the digital twin concept is used to achieve physical connection and data collection, virtual models and simulations, data and information technology systems integration and lastly, databased production operations and management methods. These expectations are also embraced by other authors like Ellgass et al. (2018), Qi, Tao et al. (2018) and Zhang, Zhou et al. (2019).

Stark et al. (2019) applied information factories in the development and operation of a digital factory twin. They proposed an 8-dimensional digital twin model. Four of these dimensions namely integration breath, connection mode, update frequency and product lifecycle characterise its environment and the other four dimensions: CPS intelligence, simulation capabilities, digital twin model richness and human interaction describe its behaviour (capability richness expressed in levels). Lu et al. (2020) presented a digital twin reference model with three components namely an information model, a communication mechanism and a data processing module. The information model has two subtypes: a model for a product digital twin and another for a production digital twin.

2.4.2 Integrated digital twin frameworks in manufacturing

The fourth industrial revolution is data-driven with more smart products and systems within the business domain. This necessitates more cyber involvement in industrial operations and business activities as a whole, thus promoting the integration of its resources (Choi et al., 2017). The existence of CPPS supports the integration of physical assets. This integrated entity creates a digital bridge between smart resources and smart products in making (Coronado et al., 2018).

Modelling the CPPS should also have a digital representation of the dynamic interaction between the product and its production processes. This logical interaction can enhance the management of the production processes, and support production flexibility, product customisation and quality of the product. An integrated product-process digital twin platform is needed to explore this product-process dynamic interaction to unveil potential benefits. A CPPS integrated product-process digital twin with logically connected data/control/resources is a suitable digital platform where the interaction of the product and process models is used to enhance the control/management of the physical asset performance and product quality.

2.5 Real-time collaborative simulation in digital twin

One of the expectations of the DT concept in manufacturing is the real-time closed-loop connectivity between the asset-twin (Tao, Zhang & Nee, 2019; Jones et al., 2020). This involves a real-time synchronisation between the asset-twin such that the bidirectional interaction supports operational/virtual data analytics for diagnostic, control and optimisation (Onaji et al., 2022). A bidirectional interaction within the cyber-physical space positions the DT as (i) a substantial monitoring and supervisory platform, (ii) an extension of the control structure enabling virtual data-driven control of the physical asset (iii) a suitable structure for implementing real-time simulation during production (iv) and an effective decision-support system using experimental results made available for design/production management and high-level business decisions (Catapult 2019, Tao, Zhang et al., 2019; Onaji et al., 2022).

Data integration in digital twinning has been greatly emphasized (Jones et al., 2020). This allows operational data to be used to update the DT which in turn creates a virtual representation of the production operation alongside performing analytical experiments. Models are mostly operated offline creating some gap between the data generation, analyses and feedback to the physical system (Blum & Schuh, 2017; Enders & Hoßbach, 2019, Jones et al., 2020). Generated data can be used to support the production process more effectively if simulation experiments are done in real time and results are used to improve/optimise the management of the production processes and product quality.

2.6 Cyber-physical control in digital twinning

The DT concept is a cyber-physical integrating and asset-twin collaborative platform in manufacturing (Tao et al., 2019; Jones et al., 2020). Research literature presents implementations of the DT concepts with successes in data integration and updating of the virtual space with operational data (Liu, Meyendorf, & Mrad, 2018). However, the digital twin either as a product, machine or production DT has been used to support production (Lu, Liu et al., 2020). The real-time bidirectional interaction between the asset-twin should also support a DT data-driven control of the physical asset. As a platform for experimental simulations, analytics and information extraction, virtual results are used to improve industrial operations within the physical space (Shubenkova et al., 2018). The utility of these virtual results in real-time control/management of the asset is constrained by issues in the interconnectivity and heterogeneity of the virtual and physical space and the lack of virtual control strategies (Negri, Fumagalli & Macchi, 2017, Onaji et al., 2022).

An integrated product-process DT in a closed-loop with its CPPS provides new capabilities for the digital twin to harness the possible benefits from the dynamic interaction between the product and its production processes. A DT decision-support platform with control capabilities can use its virtual resources to manage the production resources, services, system performance and the production of the product in both offline and/or online/real-time modes (Qi, Tao et al., 2018). For an integrated DT, a cyber-physical control structure is needed to harness this modelled dynamic interaction which stands out as a real-time benefit to the physical asset. Such a control infrastructure would support the virtual control of the asset from the DT, reconfiguration of the processes based on product specifications and vice versa. This structure should provide the needed mechanism to support/enable real-time implementation of decisions made based on the DT analytical results/collaborations between the asset-twin and operators.

2.7 The Digital twin as a decision-support mechanism across the RAMI4.0 Hierarchy levels

The DT of a CPPS has been discussed as a cyber-physical platform that achieves remarkable data and control integration, real-time interactive simulation and experimental analytics for data-driven control and product customisation. It is built to integrate the three lower levels (Sensors and Signal, PLC/DCS/CNC and SCADA) of the ISA 95 industrial automation pyramid (Figure 6.1), or the first five levels (product, field devices, control devices, station and work units) of the RAMI4.0 automation architecture for Industry 4.0 (Figure 3.8). Its digital twin data is a construct of the operational activities of the physical asset and the digital processes of the digital twin across these levels.

From a business/managerial perspective, it would be strategically beneficial to extend the functionalities of the DT of a CPPS across the levels of the MES, ERP and connected world of the RAMI4.0 Hierarchy levels. These levels can furnish the digital twin with production management data and higher-level analytical resources. This extends and positions the digital twin as a decision-support system across the Hierarchy automation level to facilitate informed business strategic decisions. The generated information and capability of the DT can be made available to the MES level to support production, quality, inventory, maintenance or scheduling purposes. At the ERP level and in the connected world, the customer and supply chain data can be made available for DT analyses. Also, DT-generated information can be made available for business decisions made for and by the customers and the supply chain. For instance, the customer can be updated on the status of its order relative to the calculated current efficiency of the production system. In line with this, a framework that connects the DT of a CPPS to the levels of the MES, ERP and Connected world is needed. In this research, the connected world is limited to the customer and supply chain.

2.8 Technical limitations and solutions

The research identified some technical limitations hampering the implementation of the current vision of the digital twin in achieving closed-loop synchronisation between the digital and physical space/cyber-physical fusion (Qi et al., 2018; Tao et al., 2019). These technical limitations and proposed solutions are described in detail below:

1. *Lack of quantifiable metrics of uncertainty in digital twin models, and unresolved uncertainties in the prediction of complex systems (Schuh & Blum, 2016; Jones et al., 2020):* Uncertainties are unique to systems due to the variability in the conditions that creates them. No two products from the same production line are identical in performance. The use of data-driven models is presented here as a solution to this challenge. The availability of microchips, digital tags and sensor technologies like the

RFID technology has expanded data generation beyond geometrical measurements (Zhou et al., 2019). This has made scanning easier and quicker with reliable tracking capabilities to communicate operational information (Brenner & Hummel, 2017). Integrated product-process models can then be fed with real-time data relating to their operational statuses such as environmental conditions, system performance and product quality (Zhang, Ma, et al., 2019). Such real-time instance data can help in identifying the pattern of change in the behaviour/characteristics of the system/product. The use of machine learning algorithms can be used to engineer unique patterns/metrics that can be used to maintain the health of the system.

2. *Virtual confidence:* This poses a challenge due to the multi-complexity of manufacturing systems resulting in engineering estimation and presumptions. Data from the factory floor is compared with data from the virtual model to investigate the behaviour of a machine in operation against expected behaviour. The use of real-time data instances in the virtual platform increases virtual confidence (Grieves & Vickers 2016).

   Engineering models are known to be a very effective representation of well-known processes. Data-driven models are stochastic and tend to represent the variability of a system. This would be an effective means of representing the product-process interaction and the progressive development of the product. The management of virtual models and connectivity to the physical twin would be improved if they are built to the lowest possible level of granularity with unique identification, functionalities and control. The combination of both model approaches would increase the functionality of the integrated digital twin.

   More research should be done to establish the benefits of using various virtual model approaches either separately or combined in the digital twin. It is interesting to know what levels of engineering and data models combination can be achieved. Trade-off analysis in use cases would highlight the advantages/limitations this combination presents.

3. *Variance in the framework of the digital tools used to achieve virtual confidence, i.e. linking models with data from the factory floor (machine or sensor data):* One major challenge with the digital tool used to achieve virtual confidence lies in the variance of the functional/data semantics/communication frameworks (Tao, Zhang & Nee, 2019). Interaction/access to heterogeneous digital platforms/data sources is limited because they are dependent on the integration endpoints and the capabilities of the database they are built to work on. This has limited the integration of tools from different vendors needed in implementing cyber-physical integration that supports real-time communication for smart production (Blum & Schuh, 2017; Zhang, Tao & Zhang, 2017; Cheng et al., 2018). A potential solution is for middleware vendors to encourage software collaborations by adopting widely accepted communication protocols. An example includes the collaboration between MTConnect and OPC_UA communities to provide an MTConnect-OPC_UA specification that improves the interoperability and consistency between both standards. This capacity is transferable to all manufacturing technologies, equipment, devices or software implementing these standards. The integrated process-product digital twin as an aggregate model requires more collaboration between machines/equipment and virtual entities. Communication constraints associated with using heterogeneous digital platforms in building the models can be handled by either using the same digital platform or using platforms with unified data/communication semantics that supports real-time communication like the OPC_UA/MTConnect.

   Another potential solution is the standardisation of information model semantics. The systematic approach toward the development of semantics for information models would encourage a continuous effort towards the conformance and usage of the same standards (Xu et al., 2019). This would allow modelling platforms to effectively represent both the product and process composition. For example, the ISO 10303 standard provides a neutral data structure enabling CAD systems to exchange product data. ISO 14649 and ISO 10303-238 standards use modern associative language enabling a direct connection between CAD design data for machining and downstream fabrication processes (Lu, Xu, & Wang, 2020).

Software vendors in collaboration with researchers should expand the capabilities of their products. Newer versions of existing digital twinning software with collaborative capabilities that supports the combined representation of process flow and product behaviour are needed. The idea of a closed-loop integrated digital twin that recreates the product-process interaction using enhanced 3D visualisation and data would be an added advantage for more investigative results in diagnostic analysis.

4. *Lack of an explicitly defined ontology:* A closed-loop supply chain network would need an explicitly defined ontology. Providing an overt formal specification of the network conceptualisation and standards enables seamless business integration between trading partners (Lu et al., 2020). Ontologies have an essential role to play to ensure adequate flow of information, reuse of data between project phases, easy information accessibility, integration of process and product models with ERP systems, data communication through the network and reading data stored in electronic tags and databases (Cai et al., 2017; Negri et al., 2019). Blum and Schuh (2017) discussed several ontologies for IT systems that use RFID technology to achieve the smart linkage between the virtual and physical world.
5. *Challenges in the inclusion of human functionality in the virtual space:* Cyber-physical integration in manufacturing also involves the inclusion of human functionality resulting

in more human-machine interactions. The old control methods involve more human control which limits the autonomy of the system and restricts human-machine collaborations. Another challenge here involves the difficulty in transferring human operations into machine procedures to be handled by the machine to increase precision and performance.

Digital twinning promotes human-machine collaborations where precision is managed by the machine and certain decisions are handled by the operator. More effective and fast communication links are needed to ensure such interactions are seamless and aligned to the system operation. Also, designed algorithms should adopt object-oriented structures in ways that allow human inputs as part of their operational blocks. State-of-the-art technologies for human-machine interfaces include augmented and virtual reality, natural voice processing and gesture control. The concept of immersion stands to be an effective approach for virtual human-machine interaction.

Voice interaction is the most effective and quickest means of expression for human beings (Nagabushanam, George, & Radha, 2020). Nagabushanam et al. (2020), highlight advancements in Natural language processing (NLP) using neural networked-based methods. This has been applied in deep learning (DL) and long short-term memory (LSTM) algorithms with a certain level of accuracy and efficiency. In recent times, advancement in remote sensing technologies has contributed to better gesture recognition. Technologies like ambient light, cameras and image processing, sound and wearable devices, Radiofrequency (RF) and mmWave radar are been used to capture operator activities. With faster communication, sensing and processing capabilities, the development of gesture training and control is a promising development for the digital twin system.

6. *Lack of professional skills sets:* The fourth industrial revolution comes with a wave of new technologies demanding new skill sets to manage them. To create more ways for the actualisation of the digital twin concept, the manufacturing industry continuously needs to liaise with academia to make fast advancements toward these emerging technologies, contextual and social resources (Ward et al., 2021). The industry provides the funding, expertise, application knowledge and related field data. Academia provides the technological know-how like advanced methodologies from mathematics, control and computer engineering and takes responsibility for grooming the new generation workforce equipped with interdisciplinary skills. These will result in a progressive transformation of their industrial/research environment, and work method. A collaboration between these two sectors creates a versatile learning environment with a bidirectional channel for knowledge sharing and transfer resulting in the combination of theoretical knowledge with industrial practices.
7. *Challenges in managing big data, defining semantic data models, data management systems and scalable databases for data storage on a single platform, the integration of existing simulation packages and semantic interoperability of data from heterogeneous sources:* Data models mostly used in engineering and simulation tools are not compatible, resulting in data silos within production systems (Macchi et al, 2018). There is the issue of insufficient details to meet all parameter needs. Also, the proprietary format limits the amalgamation of relevant engineering data and models for each object. The heterogeneity of gathered data from both physical and virtual spheres poses to be a challenge. The proposed DT framework supports an extensible framework for data acquisition (data gathering, storage, organisation and distribution) and analyses for all parts of the system. Lu and Xu, (2018) presented semantic web technology, an evolution of the World Wide Web (WWW) technology as a distributed and scalable standardised

interface for the surrounding systems. This creates a graph of connected facts by linking up documents to pieces of information. The actualisation of uniform data interfaces and out-of-step data computing technologies is also a potential solution to these challenges.

2.9 Disposition of the thesis/Research gap

The clarification of the DT concept has been a major focus in literature. There is increasing evidence in the literature on the use of the digital twin in manufacturing (Jones et al., 2020). Despite this and recorded applications, there still exists variance in the definition, description, classification and application of the concept (Onaji et al. 2022). Within the manufacturing industry, there exist, digital twins of the product, process, systems, production and performances. These variations in types each tap into unique benefits based on application (Cheng et al., 2018, Onaji et al., 2022).

CPPS supports the integration of physical assets and creates a digital bridge between smart resources and smart products in making (Coronado et al., 2018). An integrated digital platform for the CPPS would integrate existing DT potentials and also unveil more benefits within the cyber-physical sphere. The combination of the product and process DTs on a single platform would enhance the utilisation of their dependencies to promote flexibility and product customisation. Processes are configured about the products to be manufactured. The quality of the finished product is also influenced by the effective management of the processes/resources used. An automated configuration of production setups based on the virtual product specifications could be a benefit of an integrated DT twin on a CPPS. Production process/machine configurations can be mapped to defined virtual product specifications such that these specifications trigger the desired setup strategies when demanded.

There have been several DT framework propositions in manufacturing. However, none of the proposed DT frameworks in the literature addresses the integration of the product and process DTs (Subsection 2.4.1). None have considered the modelling of the interaction between the product and its production processes (Grieves & Vickers, 2016, Tao et al., 2018; Zhang, Zhou et al., 2019: Zhang, Xu et al., 2019). As a result, they do not present the integration of the product and process digital twins from this perspective. The novelty obtainable here is an architecture for a CPPS integrated product-process DT with logically connected data/control/resources as a suitable digital platform where the interaction of the product and process models is used to enhance the control/management of the physical asset performance and product quality. The question arises "*How can a product and process digital twin be integrated to harness the dependencies between the product and its manufacturing process?"*

An integrated product-process DT architectural framework is needed to inform and instruct the manufacturing industry/research community on its application. This would also include the techniques/concepts for implementation and applicative methodical evidence to support the industry and direct digitisation research in manufacturing. Lu et al. (2020)'s model talked about the product and the process information models. There is a need to extend these ideas to the integrated product-process DT concept. This would involve mapping all logically related product-process data and operational mechanisms. This creates a digital platform to harness the interdependence between the product and its production processes. This dynamic interdependence/interaction has not been harnessed in DTs to improve production management in real-time. This is an identified gap in digital twin research. The novelty here would be a proposition of techniques needed to model and implement this product-process interaction in digital twinning.

The dynamic interaction between the product and its production processes can be modelled as a logical interaction to establish a collaboration mechanism between the product DT, process DT and physical assets. This dynamic interaction between the asset-twin in real-time can be used to define the DT behaviour. This mechanism during production would create new DT collaborative functionalities that would improve the performance of the DT as a decision-support system. The question arises "*What infrastructures are needed to support real-time synchronised interaction between the integrated product DT, process DT and physical assets?*"

To extend the benefits of the DT concept to the operational phase of manufacturing, real-time synchronised interactive simulation is needed. This is a simulation scenario where the online DT simulation can be driven by triggers/data from the physical asset and in return, the DT can support/manage/control the physical asset based on experimental/analytical data. The logical modelling and implementation of the product DT-process DT connection and the asset-twin connection are necessary to support a real-time data-driven synchronised simulation, production flexibility and product customisation are advocated.

The DT vision intends to improve and implement smart manufacturing with not just simulations but real-time control (Cheng et al., 2018; Onaji et al., 2022). This calls for the interdependence of the asset-twin. There still lacks a structured approach for the implementation of control and reliability requirements in digital twins for manufacturing processes. The integration at the control level is a digital twin expectation that needs attention. The lack of applicative strategies and demonstrative case studies on the virtual control aspect of the digital twin is an identified gap and contributing to this area is a novelty for this research. There exist real-time data extraction but there is a lack of real-time analyses for optimisation or the improvement of production performance. The literature review lacks data on implemented control integration and virtual control of the physical system. The question arises

“How can bidirectional control be achieved between the physical system and the digital twin to enable a two-way interaction?”

One major challenge of the current industrial infrastructure is the disconnection between the various Hierarchy levels of the automation pyramid. This is because they are built with components (hardware/software) predefined to suit specific purposes and most often are from different vendors. As a result, one tends to find issues with communication due to variations in data semantics and system architectures. There is a need for an infrastructure that connects these Hierarchy levels of the automation pyramid. This includes mechanisms/methodologies to access and distribute information/resources across the Hierarchy levels. It should determine the accessibility and control level of all associated parties and infrastructure to evolve and preserve data. The DT as a proponent of integration and collaboration can be used to eliminate the information silos. This interconnectivity across the system makes information readily accessible to all interest groups. The question arises *“How can the digital twin concept support decision-making across the RAMI4.0 automation Hierarchy level?”.*

The idea of using the product twin and the process twin in an integrated environment is new and would present the opportunity to investigate the potential inherent in the interaction between the product and its production process. The use of an integrated product-process DT structured around the product-process interaction as a decision-support system for production is still lacking and needs more research and results from evidence-based applications to advance this field. There is still a lack of literature on the mechanism to make useful information/decisions available to all associated parties within the business chain.

2.10 Summary

This chapter presents a literature analysis on the digital twin concept to address the question: *"How does the digital twin concept support the realisation of an integrated, flexible and collaborative manufacturing environment as one of the goals projected by the fourth industrial revolution?".* A review of the literature was conducted to investigate the development of the DT concept, maturity and its vital role within the manufacturing industry. There is a growing acceptance of the DT concept as an essential driving force/element for the fourth manufacturing generation. It is perceived as a proponent of technological development with the potential to transform the current manufacturing landscape into a smart cyber-physical environment (Jones et al., 2020). The DT concept since its first definition by Professor Grieves as the digital construct of the physical asset (Shafto et al., 2012), has evolved in definition and applicability. However, there still exist variances in the definition, description, classification and application of the DT concept (Onaji et al., 2022). The review findings also highlighted that there was no common framework for a digital twin model creation but it has found applicability in the various stages of the product/process. The integration of ICT technologies and AI into production systems has paved the way for a lot of possibilities with the digital twin in manufacturing. Six key functionalities inherent in the digital twin applications were identified: prognostic and diagnostic analyses, simulation (online and offline), control, monitoring/supervision and optimisation. Lastly, technical limitations were identified and proposed solutions for the implementation of the DT concept in manufacturing were discussed.

The digital twin concept is still evolving. It was initially applied to product design. In recent times it is perceived to encompass the entire business value chain resulting in digital twins of products, production process, system performance and services. The current vision of the DT concept in manufacturing supports the realisation of an integrated, flexible and collaborative manufacturing environment. Supported by a closed-loop bidirectional communication network, it promotes asset-twin co-evolution through real-time interaction, control and convergence in three key areas: within the physical space, between the physical and virtual spaces and between historical and real-time data.

CHAPTER III: RESEARCH METHODOLOGY

This chapter presents the methodology adopted for this research. The methodological path and descriptions follow a logical progression that enabled the researcher to use established knowledge and techniques to achieve the aforementioned objectives in the first chapter. The research plan involved both a theoretical and a practical approach. The rest of the chapter presents the methods used, concepts and techniques applied in the course of the research.

3.1 Methodology

This section outlines the methodological path adopted in achieving this research's aim and objectives. It ensured the milestones are met and the research remains focused on laid down objectives. Strategically, to measure, monitor and maintain the research progression, the research objectives were broken down into achievable milestones to allow for a systematic build-up of the research aim and objectives within the academic timeframe. First, a literature review was done to establish the basis for the research and the conceptual model design approach was adopted to define the modelling and simulation objectives across the research. The remaining phases involved the set objectives arranged in a logical manner that defines their dependencies. Figure 3.1 presents a progressional chart of the research.

3.1.1 Phase 1: Literature review

The first task was to investigate the progress and current trend in the Industry 4.0 initiative. This provided information on what is desired, and attainable and what are the current interests of key players in industrial manufacturing and the research community. This formed the basis for research aims and objectives formed and a methodology mapped around the research aims and objective. The digital twin concept was identified as a trending phenomenon that can be

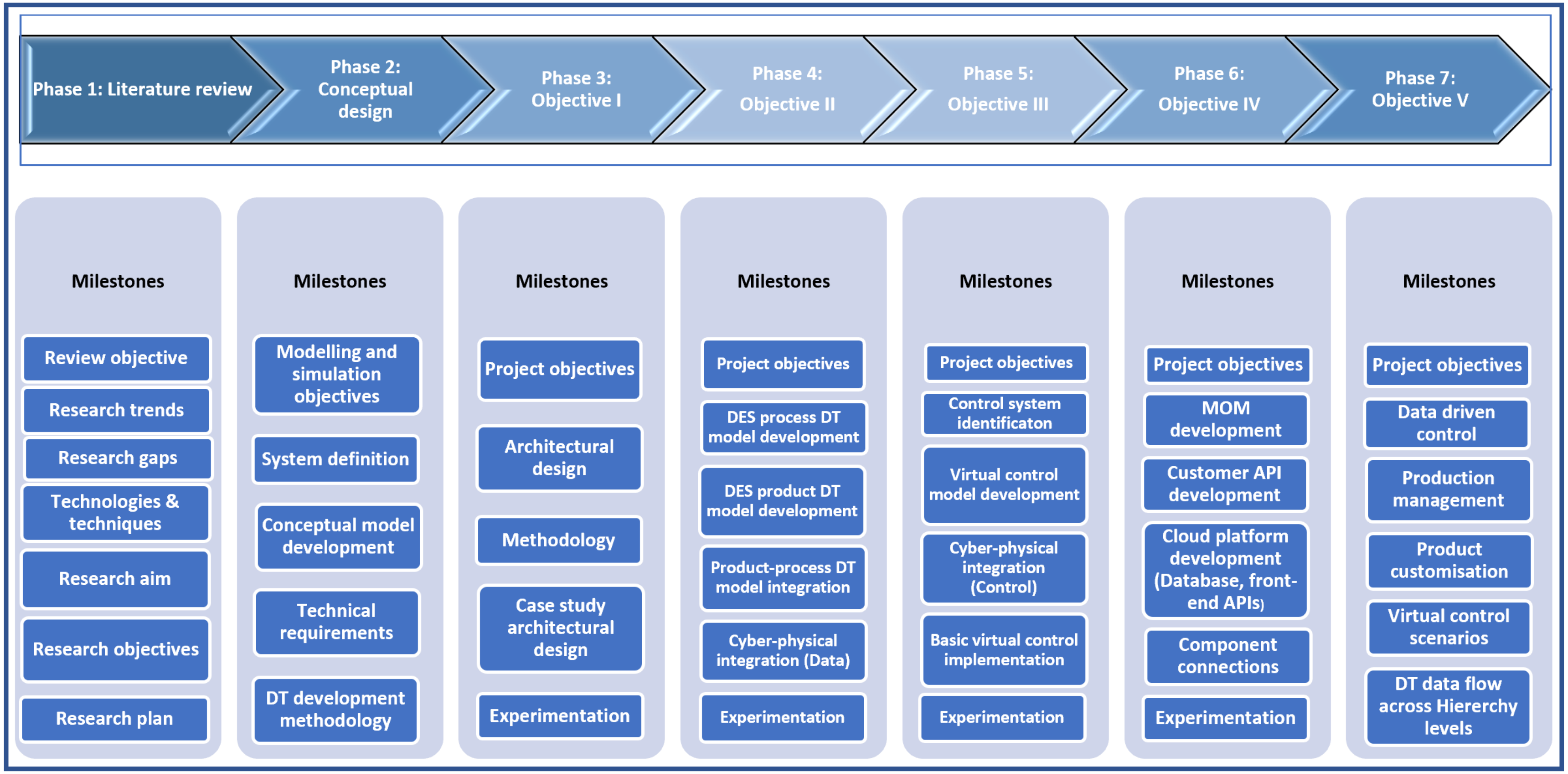


Figure 3.1: Chevron chart showing the sequential progression of the methodological steps taken

used to pursue the Industry 4.0 initiative. Further research was done on the DT concept and was adopted as an applicative technique to be used to achieve the aim of this research.

3.1.2 Phase 2: Conceptual model design

The first milestone here was the identification and description of the modelling and simulation objectives aligned to the research objectives. Also, developing a conceptual model detailing the structural DT layout, theoretical expectations and practical involvement of using the digital twin concept in manufacturing. This involved an evaluation of the feasibility and implementation of the concept or postulations. The selection of the digital tools needed to build the DT depends on the established DT design objectives. This describes the DT functional composition and maps these DT functionalities to a pool of digital tools. Table 3.1 presents the metrics considered in the selection criteria for the digital tools used in building the DTs for this research.

Table 3.1: Metrics considered in the selection of digital tools for DT development

Selection metrics	**Evaluation criteria**
Functionality	The purpose/service provided and its value to the DT project
Interconnectivity	The communication interfaces for connectivity with other digital tools.
Compatibility	The suitability of the tool for the DT project and its purpose. Compatibility in terms of data semantics and communication protocols
Affordability/availability	The financial implication and the accessibility (remote, cloud-based, licensed/open-sourced/free) of the tool to the DT developers and DT users
User interaction	The level of convenience in user engagement during development and use

3.1.3 Phase 3: Objective I: Digital twin architecture for a smart factory

A systematic literature review was carried out to identify existing DT architectures from published papers. Based on this, process mapping and system ontology was used to propose an architecture that takes advantage of the interdependences between the product and its production processes to integrate both the product and process DT. This was then applied to a case study: the Festo CP smart factory.

3.1.4 Phase 4: Objective II: Development of techniques that support real-time synchronised interactive simulation between the asset-twin

This stage handled the development and implementation of techniques that utilise the cyber-physical integration to achieve real-time synchronised interactive simulation between the asset-twin. Integration at this stage was limited to data integration. This is illustrated in Figure 3.2 and involved:

a. Development of techniques for linking virtual products models with virtual process models using a combination of engineering models and data-driven models (Figure 3.2 index b)
b. Development of techniques for physical-virtual space integration to support the real-time update of the DT model with operational data, (Figure 3.2 index a)

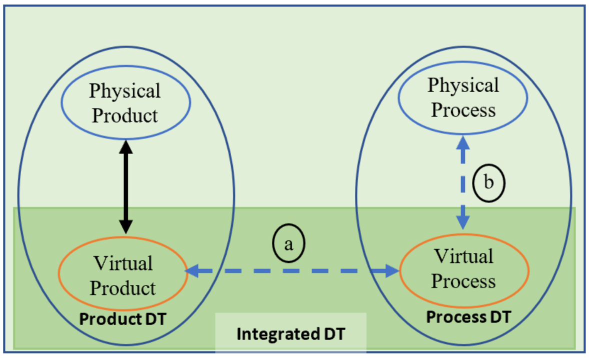


Figure 3.2: Integration of product and process digital twins

The case study was used to validate the propositions developed at this stage. A methodology on how to develop integrated DTs with real-time synchronised simulation capabilities is designed. These data were used to provide the information needed to trigger partial or full control in the next level of the digital twin.

3.1.5 Phase 5: Objective III: Bidirectional control

(a) Cyber-physical control structure using closed-loop control at multiple granularities

This stage improved the capability of the digital twin to include a bidirectional control. The DT being able to run in real-time and also integrate operational data would have the capacity to control the real system and vice versa. This stage involved the:

- Identification of control subroutines/granularities of the physical system and replicating them on the digital twin
- Development of the virtual control panel
- Implementation of a digital linkage between the physical system control and the digital twin control system
- Development/implementation of control strategies like the push-pull control technique and product-centric control and data-driven control strategies to manage the physical twin from the virtual platform
- Validate the bidirectional control strategies using a range of dynamic scenarios

(b) Use of FESTO kit to identify the levels of granularities and impact on system control:

The level of granularity of control is dependent on the set objectives of the digital twin design and the physical system functionality. Investigations on the Festo CP smart factory control capabilities and system functionalities were carried out to define the level of control granularities that can be achieved. This would include determining what parameters of the process and product can be sensed, monitored and controlled. Interest was built on the selection of the appropriate control level of granularity to ensure the accessibility of historical data without compromising the support for real-time data processing. Analysis was then carried out to determine how this influences the quality of decision-making. The case study DT at this stage is upgraded with functionalities that enable real-time data-driven control. It can manage the operation of the physical asset using operational information. It is positioned to support product customisation and implement production management strategies that reduce waste due to quality assurance and downtime.

3.1.6 Phase 6: Objective IV: Digital twin as a decision-support system across RAMI4.0 Hierarchy levels

The DT with a bidirectional communication link is presented as a data/resource integration mechanism. Horizontal integration can be achieved across the product/process lifecycle. Interestingly, using the digital twin to achieve vertical integration across the RAMI4.0 architecture Hierarchy levels would enable accessibility and distribution of data/resources spread across the RAMI4.0 hierarchy levels. The MES, ERP and the connected world of the RAMI4.0 Hierarchy levels were connected to the DT of the product and processes resulting in the accessibility to more data, MES, ERP and cloud-based resources like front-end APIs, specialised analytical tools and databases. The digital twin can be seen providing information for informed decisions across the RAMI4.0 hierarchy levels. For instance, the marketer knows how the production system is performing and can give the customer a more accurate delivery time. The operator knows which products are in dire need and creates a lean strategy for production based on a pull-push demand.

3.1.7 Phase 7: Objective V: Validate the integrated product-process digital twins as a decision-support system for a CPPS

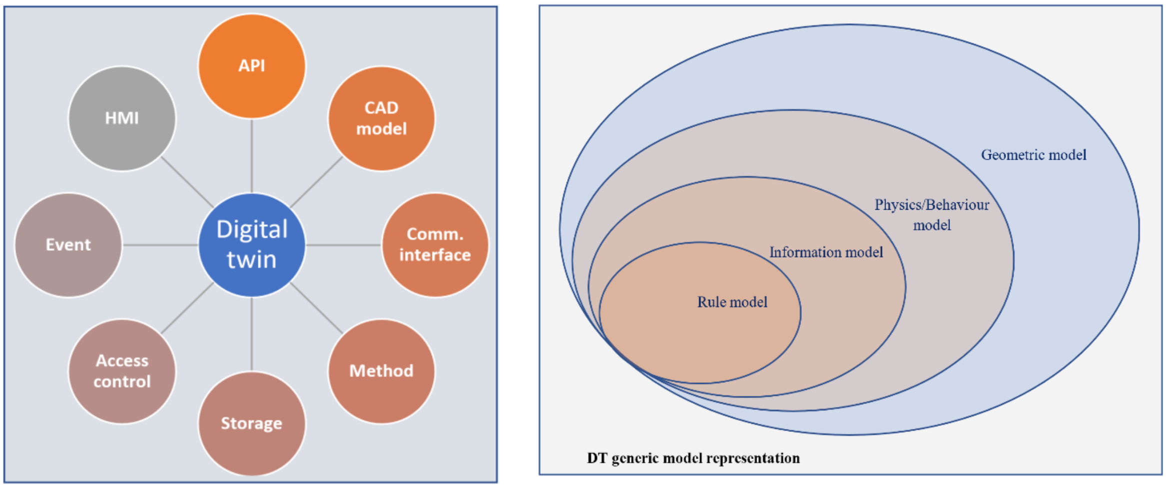
This phase is used to run predefined control simulations. The following scenarios were used for validation:

i. Updating virtual assets from physical assets (Figure 3.2, index a)
ii. Linking the virtual products with virtual processes (Figure 3.2, index b)
iii. Controlling physical assets from virtual assets (Figure 6.4)
iv. DT accessibility across the RAMI4.0 hierarchy levels (MES/ERP and Connected world) (Figure 7.1)

3.2 Digital twin model

3.3.1 Digital twin generic description

The generic composition of a DT model would consist of the method, storage, access control, event, HMI, API, communication interface and CAD model (Figure 3.3a). These support the design functions of the DT (Steinmetz et al., 2018) and can be encapsulated in different model compositions as shown in Figure 3.3b. The product and process DT architecture can have the same component composition and can be represented using the same digital object but they differ in functionalities. This is because their physical assets twins are unique in description, function and relation.



(a) (b)

Figure 3:3: (a) DT components (b) Digital twin general model representation

3.3.2 *Conceptual model design for the integrated DT*

A conceptual model design was the first step taken for the development of the DT 3D model. The abstract structure of the DT (Figure 3.4) was designed based on the RAMI4.0 automation architecture. This represented both the structural interdependencies of the CPPS components and obtainable behavioural features. Basic process behaviour/functionalities that can be modelled and visualised were identified. This layout is built from the bottom upwards.

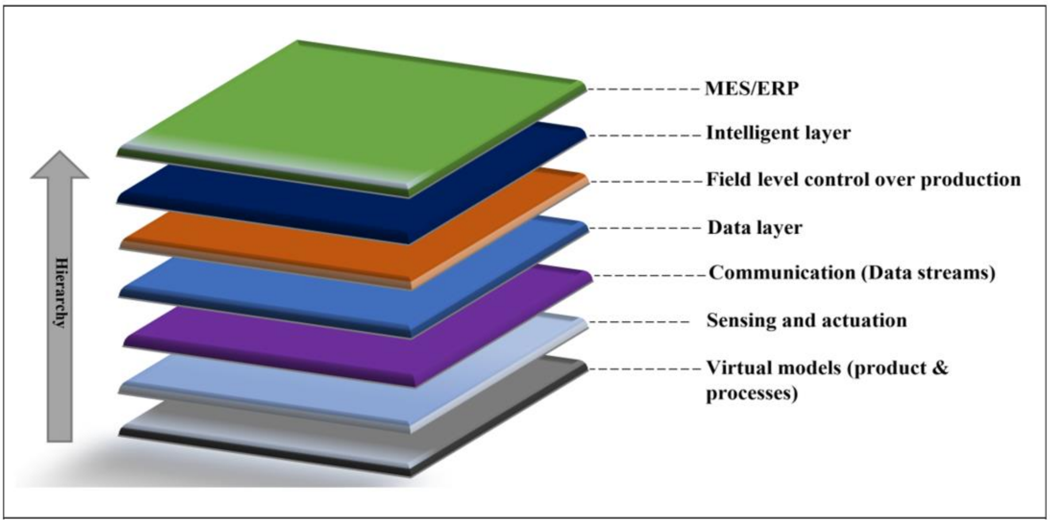


Figure 3.4: DT model structural layout based on RAMI4.0 architecture

(a) *Virtual model layer:* This layer forms the framework of the virtual platform. Models considered here include (a) Product models for product structure and shape characterisation. (b) Resource geometric models detailing the shape, size and trajectory of relevant elements for simulating interference, time and cost of production processes. (c) Resource physical models detailing variation in physical factors/parameters of resource geometric models and equipment compensation. (d) Production capability models for production capability and characterisation. (e) Process models link process-related parameters to product design attributes and mirror the interaction between a product and models of its corresponding production processes (Cheng et al., 2018).

(b) *Sensing and actuation layer:* This allows for the inclusion of virtual sensors and actuators. Most of which are existing in the physical system.

(c) *Communication layer:* The communication layer provides the necessary digital link across the cyber-physical space. This supports data streams and interconnectivity amongst associated resources.

(d) *Data layer:* This comprises a database(s) and all necessary data management structures. Storage elements like tables, lists, variables and databases.

(e) *Field level control over the production layer:* This is the virtual replica of the control structure of the modelled system. It comprises control dashboard elements like pushbuttons and switches within the different domains: system, process and component levels. Control granularities are defined and implemented.

(f) *Intelligent layer:* This layer contains algorithms used to generate information from generated data, manage the digital twin response and present them as needed in the applications.

(g) *MES layer:* A virtual MES interface is created to model production orders. This is used to assign production details to products. This also can be linked to the MES/ERP level to receive customer orders and optimise production schedules.

(h) *Application layer:* This is an extended layer not shown in Figure 3.4 It could be launched on the same systems or distributed across the distributed network (Cloud for example) provided they have access to the digital twin data. Nonetheless, these are unique applications that can be used for predefined services, analytics or data processing. These could include front-end applications for special services, analysis or visualisation within the MES/ERP or the connected world.

3.3 Methodology for including variability in the digital twin: Varying products and processes in the digital twin

In real-life scenarios, most modern manufacturing infrastructures/systems accommodate different products of the same portfolio/family. Product line engineering (PLE) to improve productivity in terms of time, effort, resources, cost and quality, creates product portfolios by taking advantage of identifiable products' similarities while managing their variations (Krueger and Clements, 2013). This enables the reuse of existing production setups/resources with little alteration/recalibration, product components/raw materials and application of variability in product attributes. Automobile or electronics component production lines and food packaging industries have a domain of products manufactured/packaged simply by reconfiguring the production lines and varying the raw materials. The DT for manufacturing should also accommodate such variabilities to reflect the real manufacturing environment and the existence of uncertainties due to diversity. In line with this, this research defined certain terminologies to clarify its intentions and research direction in terms of variability.

- Fixed product: One type of product with fixed characteristics.
- Variable products: This is considered in two contexts, first, different products of the same family domain that can use the same production facilities and secondly, the same product type with variation in attributes- geometric (size, colour, texture, shape), raw material, finishing/polishing, processing time etc.

Fixed processes: A production line with fixed modular/station/modular sequence and processes that do not change in configuration

- Variable processes: A flexible production line that allows one to remove/add processes, modify the configuration of existing processes and restructure the processes sequence

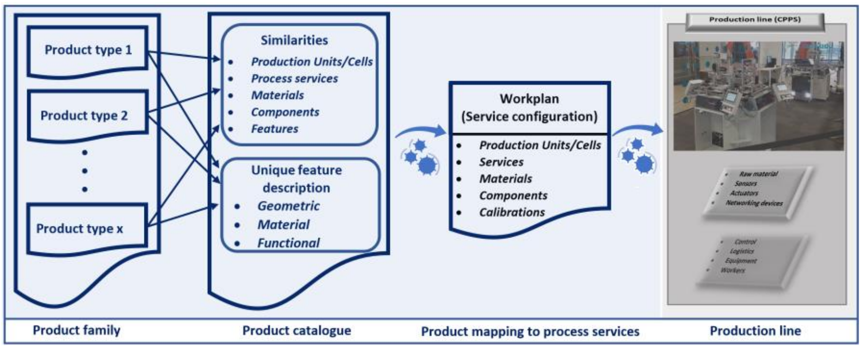


Figure 3.5: Ontological map connecting the product types to their production processes

As shown in Figure 3.5, each product type would be digitally defined as a product catalogue. This would contain the product description detailing its unique variation/features, class(s) of similarities (features and production services) and a work plan that identifies and defines the sequence and configuration of its associated production materials/services. The work plan transforms this information into executable production instructions. For example, a product family of motherboards for laptops. The variation here can be the processors/RAM configurations, type of power ports, the number/type of USB ports, and cooling fans. The work plan designed in the MES is used to make production orders for the selected products.

The strategy in Figure 3.6 adopted to include these variabilities in products and processes of the DT involves three steps. The first two steps had one component fixed and the other varied. The third step had the varied product and process digital twins integrated. This was done this way for proper structuring and management of the model development. Each objective/milestone was verified and validated before progressing to the next. Another advantage here is that it makes it easier to debug the codes to ensure the desired model behaviour is achieved.

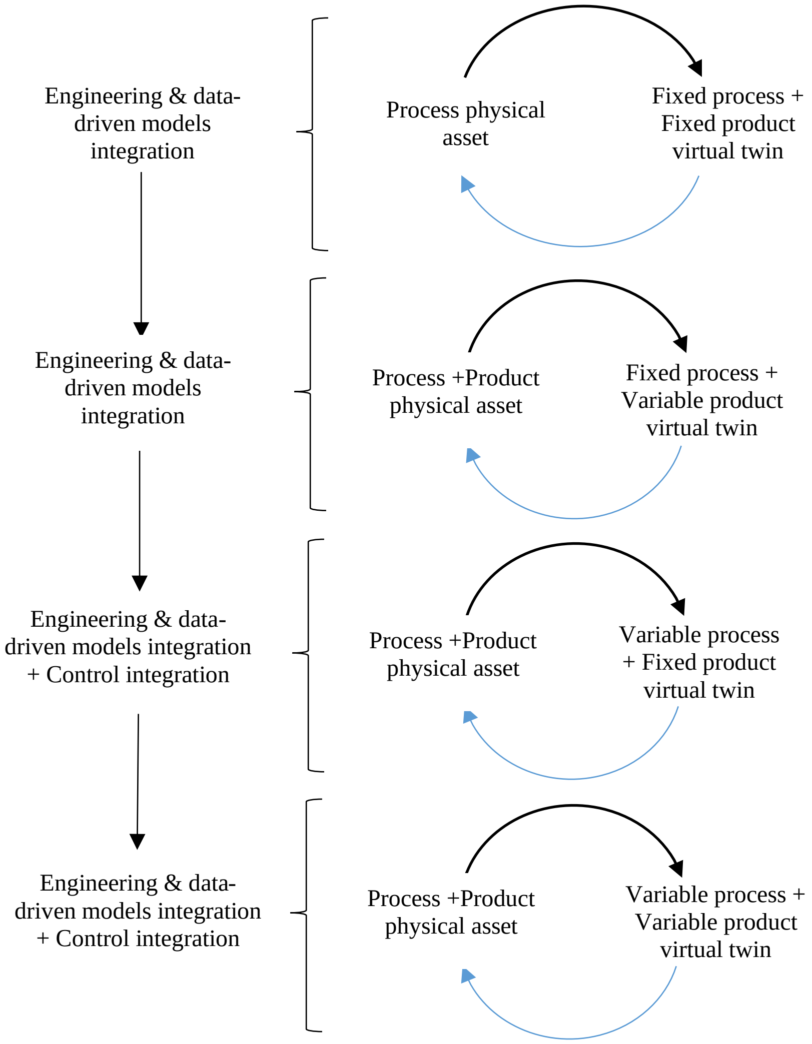


Figure 3.6: Systematic integration of the product and process digital twins to incorporate variability in process and product DTs

3.3.1 Fixed process and variable product

The process configuration is fixed and thus needs no modification at this stage. Variability is intended on the product DT. The DT should be able to assemble predefined product descriptions. Variation is observable in the part composition, property variation and process composition.

(a) Objective

i. Define products to be modelled
ii. Integrate defined products with the existing digital twin model

(b) Virtual model modifications

i. Created data tables with the products description
ii. Modelled predefined parts
iii. Define part attributes
iv. Modified control algorithms for product selection and production

3.3.2 Fixed product and variable process

The product description is fixed and thus needs no modification at this stage. Variability is intended for the process DT. The DT is should be able to accommodate predefined station configurations and system layout. Variation is observable in the processing time and the process configuration to be used for the selected product.

(a) Objective

i. Define process variability

ii. Define feasible station reconfigurations
iii. Add process variability to the DT model

(b) Virtual model modifications

i. Remove stations to allow for configuration
ii. Create Make provision for system layout reconfiguration
iii. Add algorithms to implement process layout reconfigurations
iv. Modifications
v. Results

3.3.3 Variable process and variable product

This implies the DT can accommodate variations in the products and also reconfiguration in the process DT.

(a) Objective

i. Integrate both variable product and process twins

(b) Virtual model modifications

i. Map products to predefined process configurations
    - Define process configurations based on real system capabilities
    - Update product description table with designated process configuration
ii. Modify model algorithms to enable manual station reconfigurations and automatic reconfiguration based on the product selected
iii. Results

3.4 Cyber-physical control

(a) Cyber-physical control structure using closed-loop control at multiple granularities

The capability of the digital twin includes bidirectional control. The DT being able to run in real-time and also integrate operational data would have the capacity to control the real system and vice versa. Interest was built on the selection of the appropriate control level of granularity to ensure the accessibility of historical data without compromising the support for real-time data processing. Analysis was then carried out to determine how this influences the quality of decision-making.

(b) Control strategy

The virtual control design considers the real system control structure. These include the hierarchical control layers and the use of interlocks. To build the virtual control strategy, the concept of feedback in PLC configuration was adopted. When control signals are transmitted, the control response is fed back to the control signal source. This is used to inform the control process of the control outcome. Its implementation can be found in chapter 6. The control triggers and response signals of the physical controllers were identified as connection nodes between the physical controllers and their virtual replicas. This can be seen in Figure 3.7.

The level of granularity of control is dependent on the set design objectives of the digital twin and the nature of the functionalities physical system functionality. The *FESTO* CP smart factory is designed using a decentralised control approach where each process module has an independent Siemens *PLC (S7 300)* control unit. Investigation of the *FESTO* CP smart factory control capabilities and system functionalities would define the level of control granularities that can be achieved. This would include determining what parameters of the process and the product can be sensed, monitored and controlled.

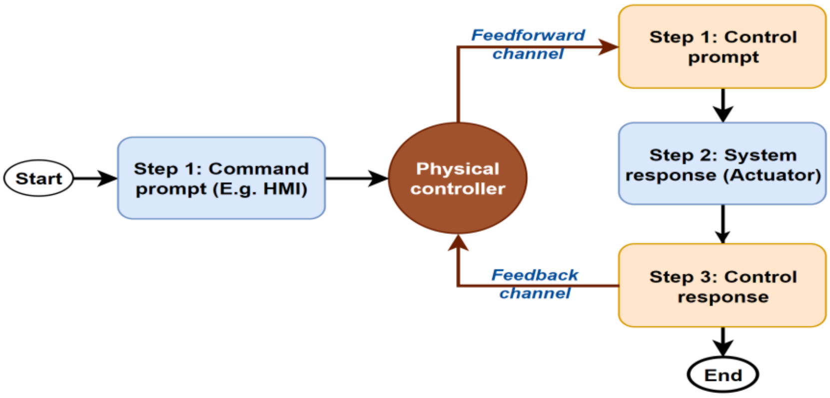


Figure 3.7: Illustrating the feedback concept adopted from PLC controllers.

(c) Trade-off analysis between the level of granularities and the use of engineering models vs data-driven models:

Engineering models are known to be a very effective representation of well-known processes. Data models are stochastic and tend to represent the variability of a system. The trade-off analysis between the level of granularities needed and the use of both engineering and data-driven models was investigated. This determined which approach best achieves this objective i.e. the level of engineering and data model combination.

The configuration of the virtual models and simulation depends on the nature of the physical processes and products. Application types for virtual modelling and simulation are considered under the categories of production layout, production processes and system entities within them (Cheng et al., 2018, Enders & Hoßbach, 2019). For production layout applications, the focus is on optimisation of the layout and appropriate model configuration. For production processes, the focus is on the verification of production processes, the test of production plans, the balance of production lines and the relationship between them. For system entities, the focus would be on the optimisation of structure and performance, electromechanical dynamics, multi-dimensional display of appearance and functionalities

3.5 Digital twin as a decision-support system

The digital twin with a bidirectional communication link is presented as a data/resource integration mechanism. Horizontal integration can be achieved across the product/process lifecycle. Interestingly, using the digital twin to achieve vertical integration across the RAMI4.0 architecture Hierarchy levels would enable accessibility and distribution of data/resources spread across the RAMI4.0 hierarchy levels.

A holistic picture of the business is created as the digital twin data becomes a composition of all product-associated data (production, management, customer and supply chain inclusive). This same DT data is made accessible across the RAMI4.0 architecture Hierarchy levels for decision making. Also, cloud-based analytical tools/databases of more specific functionalities are made available to the digital twin-CPPS infrastructure. The digital twin having access to all these data and analytical tools can process relevant information that is made available to the appropriate authorities for informative business/management/strategic decisions.

In the case study, the Enterprise and connected world levels were connected to the digital twin built at the lower four hierarchy levels. This enabled the accessibility to more data, MES and cloud-based resources like front-end applications, specialised analytical tools and databases. Aware of the cyber-security threats information is processed and distributed as authorised across the internet.

3.6 Connecting the digital twin to MES/Customer API and Cloud-based services

One of the objectives of this project is to integrate all levels of the automation information pyramid. Eliminating the information silos by integration and interconnectivity across the system makes information readily accessible to all interest groups. One challenge of current industrial infrastructure is the disconnection between the various layers. This is physical and virtual because they are built with components (hardware/software) predefined to suit specific purposes and from different vendors. As such, one tends to find issues with communication due to variations in data semantics and system architectures. Also, the various phases that make up the lifecycle of products are isolated. The DT stands to be a suitable platform to gather, integrate and maintain lifecycle data of products/processes. With a dynamic data layer, all related data are mapped and stored. Also, with a data evolving mechanism, DT data can evolve to retain historical, current and if possible futuristic information.

Interestingly, the advancement in IoT technology has increased the possibility of establishing communication between infrastructures of dissimilar architecture and data semantics. Protocols like OPC_UA allow communication and data sharing within a heterogeneous network. Also, with the concept of collaboration, communication semantics continue to be standardised allowing communication between systems that initially cannot work together because of the variance in their architecture. The concept of edge computing paves way for communication via the internet, establishing interconnectivity within the heterogeneous network, unifying data semantics, and reducing computing work on remote systems using cloud facilities. This project used the Node-RED application as a channel to communicate and interconnect components through the internet.

The MES is located on a different computer. To connect the MES/ERP layer of the Festo CP smart factory to the digital twin located in a separate computer, the OPC_UA protocol in conjunction with the Node-RED application was used. This made it possible for the digital twin to send production orders to the MES and receive MES data. The DT and the Node-RED applications communicate using the OPC_UA protocol and the Node-RED application communicates with the MES using the TCP communication node.

To also have access to customer data, the OPC_UA protocol in conjunction with the Node-RED application was used. The Node-red was used to create API for customer interaction. Generated data is sent to the Siemens Mindsphere cloud service using a mind connect node. The DT uses these data streams to collect stored customer orders.

3.7 Case study: Discrete-time CPPS based on the Festo cyber-physical (CP) smart factory

The Festo cyber-physical smart factory: Figure 3.8 is the integrated physical asset. It is an Industry 4.0 compact CPPS used for teaching and the development of smart industrial automation-based skills. Its resources have been interconnected and monitored over a TCP/IP/Ethernet/OPC_UA network infrastructure using sensors and RFID technologies. It adopted a distributed control with each module having its Programmable logic controller (PLC). The system is managed using the manufacturing execution system (MES) linked to a database (ACSE, 2018). It is composed of two production islands and a logistics network of conveyors, carriers for conveying the flow entity and an autonomous vehicle (Robotino). The workstations are built with six stations and two transfer bridges (Table 3.1). Further details about the Festo CP smart factory can be found in (ACSE, 2018).

Figure 3.8: Festo CP smart factory

Table 3.2 gives a list of the Festo stations and the task each performs and Figure 3.9 presents the schematics of the system layout.

Table 3.2: Festo stations and the task each performs

Station	**Task**
Top case (Station 1)	Place the Topcover of the phone on the carrier
Measuring (Station 4)	Inspects the workpiece on the carrier
Bottom case (Station 5)	Loads the carrier with the Bottom cover of the phone
Press (Station 6)	Couples the top and bottom cover by pressing them together
Heat-tunnel (Station 7)	Heat workpiece to a predefined temperature
Output station (Station 8)	Removes finished products from the production line
Bridges (Station 2&3)	Transfer terminal the workstations
Robotino	Transfer product between workstations

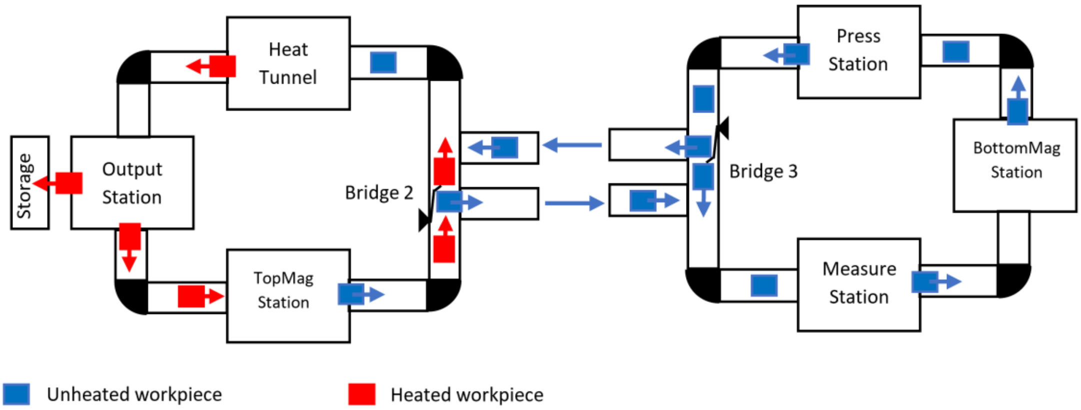


Figure 3.9: Schematic diagram of the physical production system

The Festo CPPS uses a distributed numerical control (DNC) network system with a manufacturing data collection sub-system of RFID, embedded PLC acquisition modules and other non-NC equipment like sensors for perception and data fusion. This system also handles the transmission of acquired data from the underlying equipment to the MES and supports instruction release and control from the MES to the equipment.

3.8 Methods

This section highlights the key concepts, techniques and methods used in achieving the research objectives. More details can be found in Appendix C.

3.8.1 Reference Industry 4.0 architecture

The RAMI4.0 (Figure 3.10) is the automation reference architecture for Industry 4.0. This model in pursuit of a uniform structure and standards makes it possible for gradual migration from Industry 3.0 to Industry 4.0 (DIN & DKE, 2018). This has been chosen for this research as the reference model upon which all architecture for this research has been built. The reason is that it is wildly adapted and has thoroughly been worked with as a standard road map by the industrial and academic community (Zezulka et al., 2016; Rojko, 2017).). It minimises the number of different standards required despite the integration of information, automation and operational technologies in manufacturing. It considers existing operational standards, thus providing unification in standards and structure for the next generation of industrial infrastructures intended to use Industry 4.0 technology and techniques. More on this framework can be found in Appendix C.

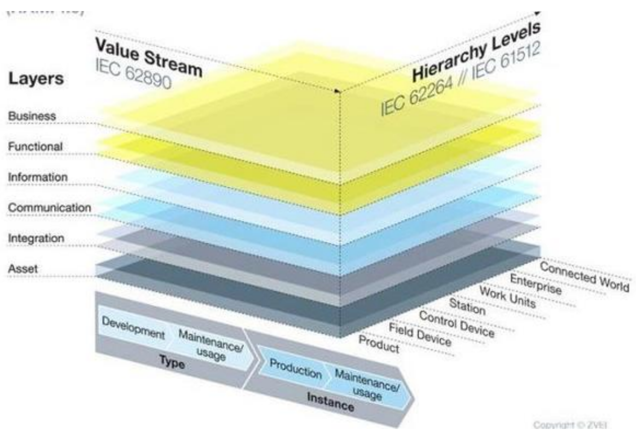


Figure 3.10: Reference Industry 4.0 architecture (RAMI 4.0) Source (Rojko, 2017)

3.8.2 Cyber-physical production systems (CPPS)

The physical asset referred to in this research is the CPPS. Industry 4.0 proposed smart production lines are built using cyber-physical systems (CPS). These are operational machine networks integrated with ICT components and sensors. These autonomous systems are meant to make their own decisions based on machine learning algorithms, real-time operational data and environmental conditions data, data analytics and successful past behaviours (Rojko, 2017; Ward et al., 2021).

3.8.3 System identification and modelling

System identification is the first step taken in defining the physical system to be modelled. This identifies the structural and functional composition of the production system and associated products. This also covers the identification of the digital accessibility of the system. The DES modelling theory is used to define the graphical and algebraic specifications used to represent the composition, structure and operation of the CPPS and its product(s).

3.8.4 Product-process dependencies

There exist dependencies between the product and the processes from which they have been created. The product defines the production processes and process configurations. These dependencies were used to establish a logical relationship between the product-process DT and its physical asset. In the production phase, the product is logically dependent $(\bowtie)$ on its production processes (Figure 3.11). During production, this logical dynamic interaction (x) in the physical space is in one direction (Eqn. 3.1).

$$Processes \overset{\bowtie}{\to} Product \qquad \text{(Eqn. 3.1)}$$

This dynamic interaction builds the finished product thus defining its actual attributes and quality.

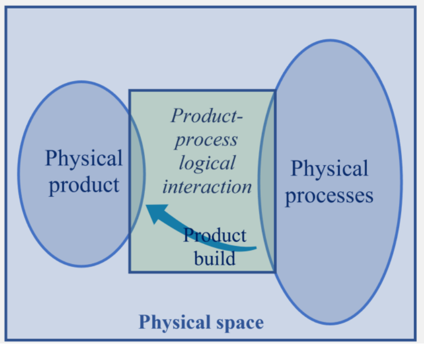


Figure 3.11: Product-process interaction in the production phase

3.8.5 The digital twin for manufacturing

The digital twin concept is viewed beyond engineering. It is considered an instrument for integrating business strategies along the business supply chain (Microsoft 2017). At its basic level, the digital twin (as shown in Figure 2.3) is a virtual replica of its physical asset built mainly on structural and behavioural models mainly for basic control, monitoring and evaluation of its performance (Onaji et al., 2022). Key to the concept is the integration of the physical and virtual space all through the lifecycle of the subject-product/process. This research uses this concept to achieve data/control integration and interaction across the RAMI4.0 Hierarchy levels.

3.8.6 The concept of integration

Integration in this research is considered a concept that allows for the interconnectivity, interaction and interdependency of related/associated components/functionalities to form a unified platform. This could include physical components like subsystems, data, control structures or even layers within an architecture. Integration in production systems was considered under the following categories: physical asset integration, virtual space integration (product and process digital twin), and cyber-physical integration. This concept forms the core idea/interest of this research.

3.8.7 Cyber-physical connections and interactions

To achieve cyber-physical integration using data and control, there has to be an established bidirectional communication link between all associated elements of the cyber-physical system. This enables the desired interaction and accessibility of resources. These communications exist between the physical product and its virtual twin, the units of the CPPS, the physical processes and their digital twins. Connection is needed between the product asset-twin, the process asset-twin and the product and process DTs.

3.8.8 Real-time, two-way and secure connections between physical and virtual spaces

Most industrial communication networks are built using the ProfiNet/TCP/IP Ethernet protocols. This provides better-improved communication, and cyber-security and utilises unique IP addressing for each active device (controller, computers and communication devices) in the network (Nazarenko et al., 2020). Figure 3.12 shows a zoomed-in view of the RAMI4.0 model communication layer showing the TCP/IP framework.

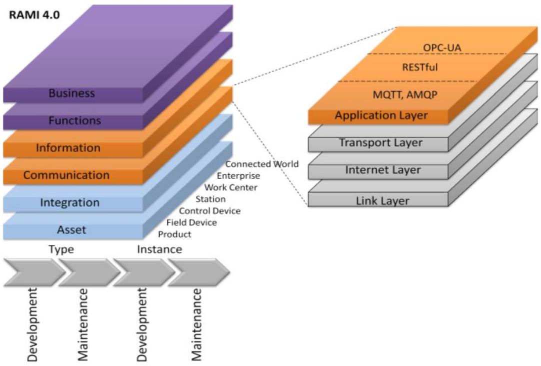


Figure 3.12: RAMI4.0 model communication layer using the TCP/IP framework Source (Nazarenko et al., 2020)

The Open platform communications universal architecture (OPC_UA) specified in IEC 62541 was built on the basic web TCP/IP/HTTP/SOAP technologies. It provides standardised and secured access to industrial systems, machines and other related devices enabling manufacturer-independent control and data exchange (Pethig et al., 2017). It stands out to be an industrial communication protocol suitable for Industry 4.0. This was used to provide a uniform standardised interface between the asset-twining for secured access to control and data exchange.

CHAPTER IV: INTEGRATED PRODUCT-PROCESS DIGITAL TWIN FRAMEWORK FOR MANUFACTURING

This chapter address the research question: "How can the product and process digital twins be integrated to harness the dependencies between the product and its manufacturing process". A conceptual framework that supports the integration of the product and process digital twins for applications in manufacturing is proposed. It also discusses techniques for implementing the various layers and the benefits they present. The application and benefits of the proposed framework are presented in the case studies.

4.1 Novelty and contribution to knowledge

The novelty presented in this chapter is the proposition of an integrated product-process digital twin framework. This DT framework integrates both the product and process DTs to further support flexibility, control and production management in manufacturing. A flexibility that allows systems during production to easily adapt to changes in product type, quality, quantity and the integration of the automation information system to support data-driven control methods. This was implemented in the case study introduced in Section 3.7 and forms the basis for the DT developed and used in this research.

In this regard, this chapter presents and discusses the proposed integrated product-process DT. The methodology for the proposed framework is discussed in Section 4.3, the actual framework is described in Section 4.4 and the benefits of the proposed framework for manufacturing systems are discussed in Section 4.5. Section 4.6 presents a case study and the chapter concludes with a summary.

4.2 Integrated product-process DT

Three key components present in all proposed digital twin frameworks are the physical assets, the digital twin and the cyber-physical integration created by the connection of the physical asset and its virtual replica (Jiang et al., 2021). For this research, the physical asset is the cyber-physical production system (CPPS) (Ward et al., 2021). The process DT is a digital representation of the structure and behaviour of the physical asset with the capacity to represent and influence the current state of its physical twin through synchronous interaction. The product DT is the digital construct of the physical product.

The product DT can be integrated with the process digital twin to harness possible benefits from the dynamic logical interaction between the product and its production processes. In the production phase, this logical interaction between the product and its production processes can be modelled and extended into the digital twin model as shown in Figure 4.1 This becomes the collaborative mechanism between product, process DT and physical asset. The physical asset provides the data on the product production which is used to update the process and product twins.

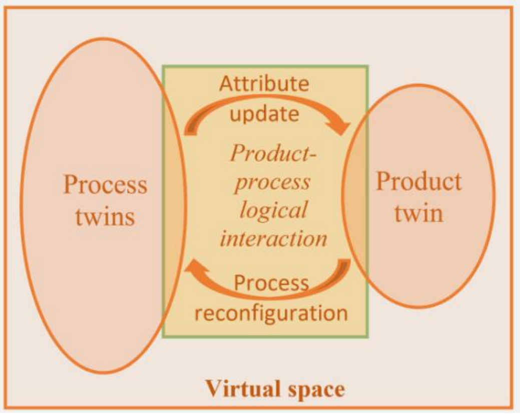


Figure 4.1: Integration of product and process digital twins

Integration is done by mapping all logically related product-process data and operational mechanisms. The product(s) and their production processes are interdependent. These dependencies could be harnessed to improve product quality and production efficiency, reduce waste and shorten time-to-market.

4.3 Methodology for implementing the proposed integrated digital twin framework

This subsection discusses the integration of the product and process digital twins and also, the approach used in utilising the dynamic interaction between the product and its production processes in supporting flexibility and product customisation.

4.3.1 Integrating the product and the process digital twins

The dynamic interaction between the product and its production processes is modelled as a collaboration mechanism between the product DT and its process DT in Figure 4.2. This logical interaction is a product attribute-process services mapping that can be bidirectional where the process DT provides data (value addition) for building the product DT and the product DT provides process configurations relative to the predefined product specifications.

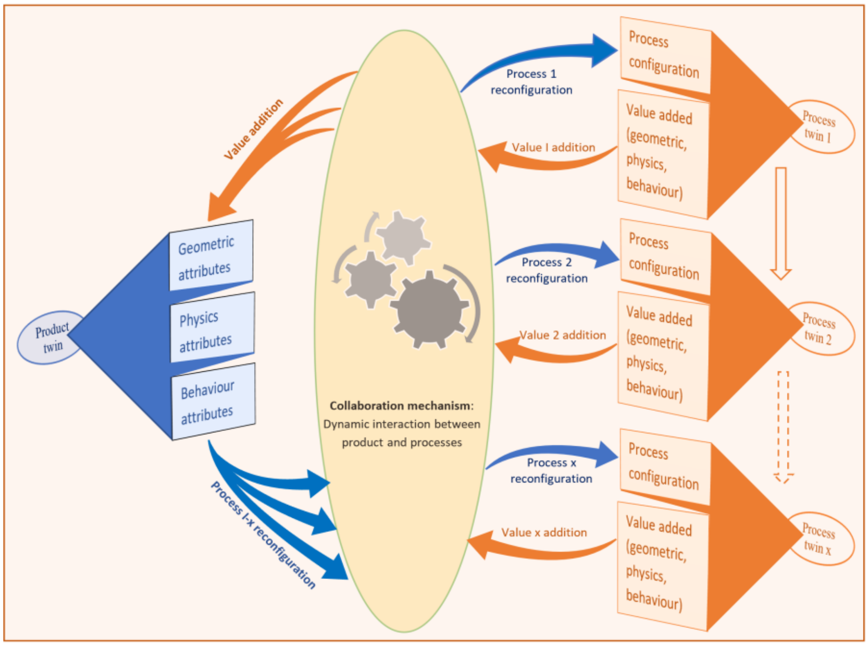


Figure 4.2: Collaboration mechanism for integrating the product DT and process DT

This collaboration mechanism (Figure 4.2) can be implemented using a relational rule model. The integration of the product and process is achieved using the steps below:

- Stage 1: Carry out a logical mapping of the product attributes to the respective process services that generate them. This is done by identifying the value-added services that build the product and its attributes.
- Stage 2: Develop the process and product models. This can be done on the same or separate digital platform(s). Using the same digital platform eliminates the challenges/constraints with communication links between heterogeneous platforms.
- Stage 3: Develop a relational rule model that logically implements the interaction between the process digital twin services and the product digital twin attributes. This establishes the logical connection between the product digital twin and the process digital twin. It maps the product attributes to the respective service configurations and manages the logical integration of the product and process data to create an integrated product-process digital twin information model.

The product DT based on product specifications can influence the configuration of the production system through the process DT. On the other hand, the production system through the process DT can provide the product data needed to mirror the physical product. With model standardization, heterogeneity in generated data can be eliminated between the digital twins. This would enable the integration of product and production data/resources and collaboration would improve each other's performance and in general the physical asset. For instance, using the product digital twin, the product quality can be monitored during production hence reducing the production cost related to quality assurance activities.

4.3.2 Product-centric control method

Product-centric control is an emerging agile method that is intended to simplify material handling, control, product customisation and information usage within the supply chain. It uses unique identification for all associated resources which are linked to control instructions. While the product is in production, it directly requests material handling and processes from service providers within the supply chain (Lyly-Yrjänäinen et al., 2016; Sierla et al., 2018). To promote product customisation and production flexibility using the proposed digital twin framework (Section 4.3), the product-centric control method is adopted to enable the product twin to influence its production (Eisentrager et al., 2018; Sierla et al., 2018). Product specifications defined in the virtual space can be linked to process configurations such that processes/machines can be configured to handle customer variation. This could involve the arrangement of raw materials, the sequence of processes and the resources in general (Sierla et al., 2018). Useful time is saved as setup time, due to some manpower reorganisation/reconfiguration of the production layout is reduced.

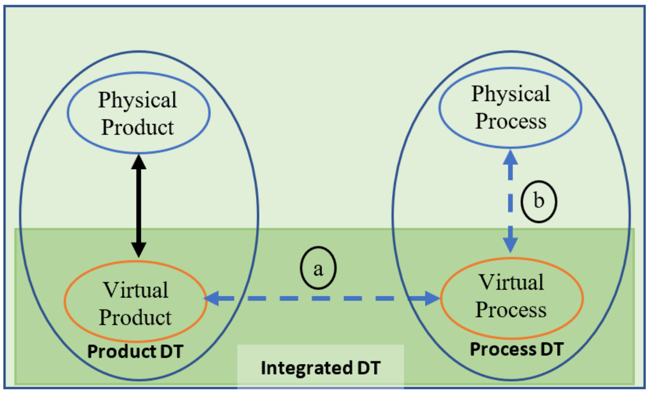


Figure 4.3: An integrated product-process DT showing the path used by the product twin to influence process configuration using the product-centric control method.

Figure 4.3 shows the path (a-b) used by the virtual product to trigger the configuration of the physical system. When the product is selected, its specifications determine the configuration of the virtual process model, which in turn triggers the configuration of the physical system.

4.4 Proposed digital twin framework for manufacturing systems

This section presents the proposed digital twin framework that supports the integration of both product and process digital twins. The framework proposed (Figure 4.4) in this section comprises six components: (a) Integrated physical assets, (b) Integrated product/process virtual models, (c) Intelligent layer, (d) Data layer and (e) Enterprise layer. Like the other frameworks highlighted above, this framework supports the identified six key functionalities inherent in the digital twin applications listed in Section 2.3. This framework attempts to address the following key issues: (1) The integration of all interconnected physical elements, (2) Ultra-high synchronisation of the virtual space with the physical space that supports real-time interactive simulation and (3) Data fusion covering all elements, flows, business services and data-driven and application-oriented services integration (Yun, Park, & Kim, 2017; Kritzinger et al., 2018).

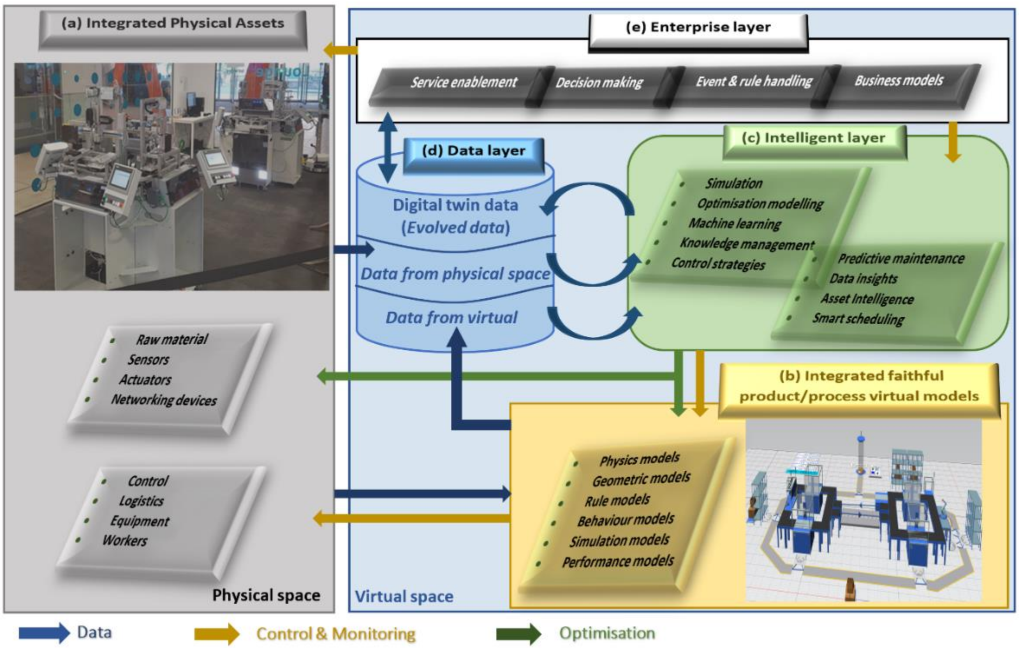


Figure 4.4: Digital twin framework of a manufacturing system showing closed-loop interaction

(a) Integrated physical assets

This refers to a composition of all related manufacturing entities of the system interconnected, monitored and managed using advanced automation equipment like microcontrollers, programmable logic controllers (PLCs), human-machine interface (HMI) for human inclusion as an asset, computer-aided controls and technical processes; information technologies like sensors, radio frequency identification (RFID), network infrastructures like servers, intelligent routers, switches, TCP/IP/Ethernet/OPC_UA/MTConnect protocols and software (Qi, Zhao et al., 2018). This enables the automation of repetitive processes that move and exchange information across the system, enabling process execution, control, data perception and transmission (Zhang, Zhou et al., 2019). Assets here could include passive resources like work-in-progress (WIP), active resources like equipment-CNC machines, robots, workforce, transports, smart environments, smart manufacturing devices, sensors and communication gateways (Zhang, Xu et al., 2019).

(b) Integrated product/process virtual models

This involves the creation of multi-dimensional models by the integration of faithful-mirrored virtual models. These models, systematically constructed using all necessary data (both engineering and operational data), should contain models of geometric and physical properties, models of elements, response models of behaviours and logical models of relationships (Tao & Zhang, 2017). In a closed-loop network with their physical twin, these models will enable reliable and synchronous systems/models co-simulation, correction, modification and control.

The level of model granularity is defined by the intended functionality and level of fidelity. The choice of modelling technique(s) and integration of models is evaluated based on modelling needs, communication infrastructure and interest behaviour of the physical asset. Well-defined properties of the physical system can be modelled using engineering principles while dynamic behaviours can be modelled using stochastic models which are maintained using operational data. This approach would facilitate the evolution of the virtual models to reflect the current state of the physical twin, and support diagnostic, prognostic and prescriptive analysis. More recent simulation software has been developed to support digital twinning with the inclusion of OPC_UA interfaces with standardised data exchange, better streaming/storage/processing of data and communication. Data management is been improved with modalities like redundant digital thread or data engineering engines to handle missing/breaks in data transmission. For example, Siemens Tecnomatix equipped with 3D visualisation and OPC_UA connectivity can be used for real-time supervision, control and visualisation of the physical twin.

(c) Intelligent layer

The physical connection and collection of data allow for the creation of ubiquitous interconnections between physically separated elements/subsystems of a production system and virtually separated models/algorithms. This layer serves as the brain of the digital twin. It is composed of machine learning/AI algorithms and rules configured to integrate all layers of the digital twin using a constructive collaborative and context-awareness initiative. This design-specific initiative supports data analytics (collection), resource interaction and interoperation within an integrated environment (Rosen et al., 2015). Programs suitable for specific functionalities are incorporated to perform at a certain level of autonomy. Even when distributed control and computerisation are used to improve system speed and reliability, these algorithms/models enable every member to become aware of the existence of each other and their operability.

This layer equipped with artificial intelligence and machine learning algorithms is accessible to both enterprise, engineering and operational data to generate information needed to support production and enterprise decisions (Macchi et al., 2018). Thus this presents the digital twin as a supportive decision-making system with dynamic knowledge built through a continuous accumulation of its interaction.

(d) Data layer

Data and information system integration is achieved at this layer, enabling a systematic integration and unambiguous fusion of cyberspace data (all elements/flows/businesses-covered) with data perceived from the physical world. This layer will support the dynamic generation and iterative co-evolution of models and big manufacturing data (Zhang, Zhou et al., 2019). By the interaction of the physical space with the virtual space, virtual information/models can be updated and operated using real-time data. The integration of physical and virtual data can be achieved through the co-evolution of models/data using algorithms to generate information instances of the current status of the physical asset or results of simulation analysis (Tao, Zhang & Nee, 2019). This can then be used to update/reconfigure virtual models or control/influence the operation of the physical system. Being able to generate and access standardised data makes accumulated information accessible to all connected entities. Special database middleware providers like Oracle and Microsoft provide platforms for data processing, security and storage.

(e) Enterprise layer

Based on the reference model (RAMI4.0) of I4.0, the enterprise layer falls under the hierarchy levels. This layer, using service systems such as Enterprise resource planning (ERP) and Customer relation management (CRM) implements data-based production and management methods like service enablement, business models and business decision making, event and rule handling (Cruz Salazar et al., 2019). Cyber-physical consistency and synchronisation present an avenue for more effective utilisation of generated data for value creation.

Operational optimisation in factories can be improved through the integration of data-driven services and interdependencies of applications allowing on-demand matching and utilisation of services (Negri et al., 2018). The internet of things (IoT) which allows the connection of people and things using internet services/networks and edge/cloud computing are potential technologies that can extend the vertical integration of this layer across the business chain (Brenner & Hummel 2017). It provides service and interface layers needed to seamlessly include contributions made by customers and suppliers to the activities/decisions made within the system (Qi, Zhao et al., 2018).

4.5 Benefits of the proposed framework

The proposed digital twin framework offers the following benefits:

(a) *Integration:* This framework has a generic structure applicable to any manufacturing system, is expandable, enables fast and easy integration of new resources (physical and virtual) and lastly, is robust to uncertainties peculiar to the manufacturing system. Considering the industrial automation pyramid from ISA 95, this digital twin framework attempts to integrate (vertically and horizontally) all layers by adopting standardised communication like the TCP/IP/Ethernet standard, uniform data formats like the JSON format and predefined protocols like the OPC_UA and MTConnect protocol (Cruz Salazar et al., 2019). This supports the real-time bidirectional connectivity of IoT within the production system, operational data generation, storage and use, bidirectional control and online/offline simulation. All six layers of the framework are applicable to both product and process DTs, thus it supports the integration of both product and process DTs, which in extension promotes product customisation, process flexibility and a supportive decision-making system.

(b) *Interconnectivity:* The DT framework can be used to tackle interconnectivity challenges arising due to the lack of interaction and interoperability between disconnected related industrial sites, independent digital models, non-self-controlled applications and isolated data silos created within the physical workspace and virtual information space (Blum & Schuh, 2017; Cheng et al., 2018). The use of standard data formats and communication specifications like the OPC_UA and MTConnect protocols promotes uniformity in data. Also, the use of IoT, Cloud computing, Machine learning algorithms and Internet technologies like the 5G network to generate, process and distribute relevant information enables communication and collaborations along the supply chain (Negri et al., 2017).

(c) *Production flexibility and product customisation:* In an integrated product-process digital twin platform, the virtual product influences its production as product specifications defined in the virtual space influence the configuration of equipment/production layout. When product customisation is automated, it reduces human intervention and reduces setup time during the reconfiguration of the production setup to include customer demand variations in either the same product or when changing products (Sierla et al., 2018). It expedites a new era of production where last-minute changes to production flexibly respond to disruptions and failures caused by suppliers.

(d) *Analytics:* Data analytics has been a monumental tool used for evaluating past incidences and the prediction of the future state (Schuh & Blum, 2016). As shown in Figure

4.5, the proposed digital twin framework enables the inclusion of both operational and environmental data for analytics (Rosen et al. 2015; Catapult, 2018). These additional data reflect the real state of the manufacturing infrastructure. The inclusion of such information in analyses reduces the impact of presumption or engineering estimations. This would facilitate the enhancement of manufacturing efficiency leading to a more lean and competitive establishment (Onaji et al., 2019; Schuh & Blum, 2016).

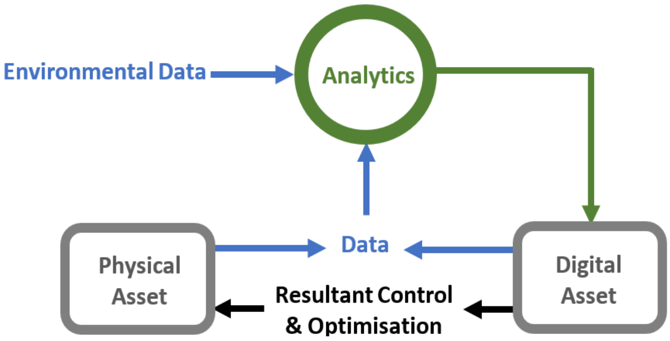


Figure 4.5: Analytics in an interactive digital twin From: (Catapult, 2018)

(e) *Supportive decision-making system:* Built on real-time operational data, the CPPS is capable of making its own decisions about its future or supporting external decision-making systems (Zhang, Zhou et al., 2019; Zhou et al., 2019). Mirroring the physical environment within the digital space enables analyses of the interactive dynamism between the product, process and environmental factors resulting in a timely response to such changes. Based on analytical outcomes, the digital models connected to the control system can trigger necessary control commands. This is of significant influence on product and process management and optimisation (Weyer, et al., 2016; Jones et al., 2020). The digital twin integrated platform enriched with a standardised semantic description can retain relevant data throughout its lifecycle (Schuh & Blum, 2016; Cheng et al., 2018).

(f) *The inclusion of human factors in digital twinning*: Section 2.8 highlighted the inclusion of human functionalities and human-machine interactions as a challenge to cyber-physical integration in manufacturing. Human interference is considered in this DT framework because manufacturing in the near future would still involve more human control and participation in production. To support the autonomy of the systems and promote human-machine collaborations within the cyber-physical space, the transfer/modelling of human operations into machine procedures to be handled by virtual models/CPPS is projected as a potential solution. Here, precision is managed by the CPPS and certain decisions are handled by the operator. Adopting object-oriented structures for modelling algorithms would allow for the inclusion of human inputs as operational blocks of the algorithms. With faster communication, sensing and processing capabilities, state-of-the-art technologies for a human-machine interface like augmented and virtual reality, natural voice processing and gesture control/recognition can be used to capture and interact with operator activities.

4.6 Case study

This subsection presents a case study of a CPPS supervisory digital twin developed based on the proposed digital twin framework in Section 4.4. Here the preliminary work is applicative evidence and contribution to reinforcing the diversified use of the proposed digital twin framework/ideas to encourage more investment and further adoption in existing industrial infrastructures. This case study is based on the Festo cyber-physical smart factory described in Section 3.6. The digital twin development at this phase is taken into consideration a fixed product and fixed process infrastructure. More details of this approach can be seen in Section 3.4.

4.6.1 Discrete-time CPPS based on the Festo cyber-physical (CP) smart factory

The Festo cyber-physical smart factory digital twin architecture: Figure 4.6 presents the digital twin architecture for the Festo cyber-physical smart factory. This shows the digital connection between the physical asset, digital twin, data space, MES/ERP and the connected world (Cloud access to customer, supply chain and other digital tools). The intelligent layer is embedded in the digital twin platform. This framework has taken into consideration the digital accessibility of the physical asset (TCP/IP/OPC_UA/HTTP protocols) and available tools (Node-RED & Siemens Mindsphere cloud services) for communication across the RAMI4.0 automation architecture hierarchy level.

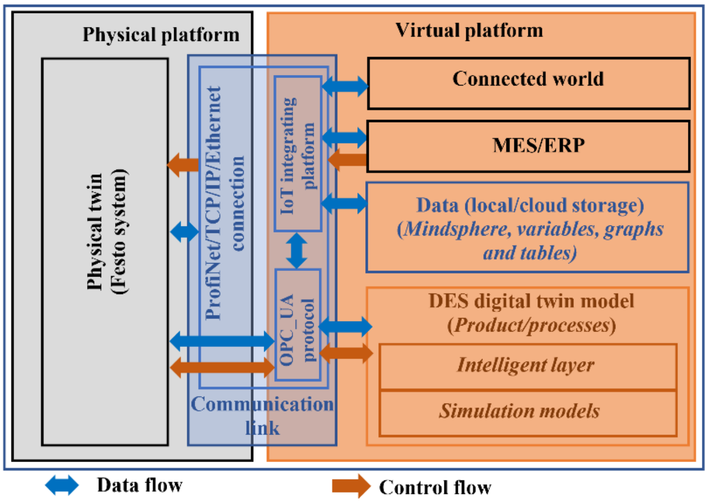


Figure 4.6: As-built digital twin architecture

The project objective at this stage of the research was to build a supervisory digital twin (Figure 4.8) that supports process monitoring and experimental analysis. This model is fed with live streams of data from the sensory devices on the physical asset, which can be used to investigate bottlenecks in the processes and their impact on the final product.

4.6.2 Key steps

The methodology used in developing the digital twin of the Festo CP smart factory involved the following steps: conceptual model design, virtual model development, control panel development, data layer development, intelligent layer development and lastly, verification and validation process. This approach allows the gradual build-in of the complexity of the existing physical system.

(a) *Conceptual model design:* This involved the definition of the project objective, system definition and the construction of a conceptual model. It includes the identification of the processes and product attributes to be digitised, physical data, process behaviour/functionalities to be modelled/visualised and lastly, investigating the accessibility of the existing system architecture to identify how it can be digitally assessed.

(b) *Virtual models development:* This includes the process and product simulation models whose granularities were defined by the functionalities and modular structure identified in the first step. It involved building the 3D models, implementing the relational rule model that established the interaction between the product attributes and process twins services, control codes and simulation flow. The Tecnomatix plant simulation software (a platform for agent-based/ discrete event simulations(DES)) was used to construct the DES DT model of the processes (Figure 4.11). It is a platform with a very fast simulation speed that also provides real-time bidirectional communication links using the OPC_UA protocol on the TCP/IP/Ethernet network. It also provides great 3D visualisation and statistical analysis tools that can be used for analytics to achieve logistic process improvement, material flow optimisation and efficient resource usage (Onaji et al., 2019). This stage also took care of the creation of the OPC_UA interfaces used to establish the bidirectional communication between the physical system and virtual platform.

(c) *Control panel development:* This stage involves the addition of control elements like pushbuttons linked to control instructions/algorithms of the virtual model, input, output/display elements for data. These graphic user interfaces (GUI) elements control the virtual simulation and online connection to the physical system.

(d) *The data layer development:* It includes involves the inclusion of data storage elements like tables, global and local variables and interfaces for visualising information. Both operational and virtual data were stored for analytical use.

(e) *Intelligent layer development:* Algorithms here generate virtual data and process data to provide required information during controlled experiments. This extracted information can be used to manage or improve the operation of the physical system.

(f) *Model verification and validation:* These steps are carried out intermittently all through the development stages. All logic and modelled operations are debugged and tested to ensure they are error-free and built following the project design.

4.6.3 Conceptual model

The first step to developing the digital twin conceptual model was the system identification process, which outlined the system layout and production flow (Figure 4.7).

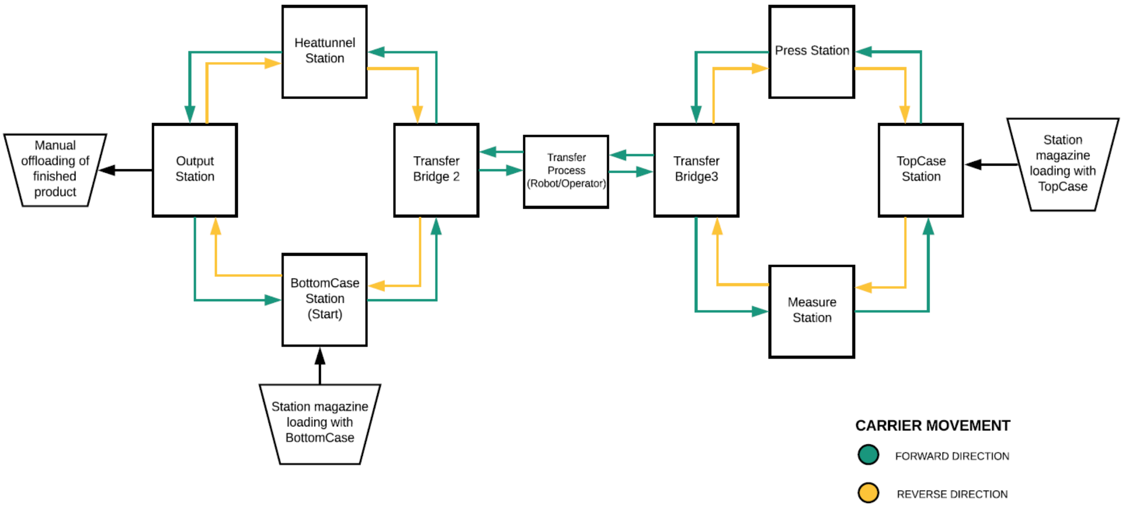


Figure 4.7: Flowchart showing the schematics of the system layout and the production flow depicted by the smart carrier path.

The IDEF0 standard for process/function flowchart representation was used to represent a high-level functional flowchart of the proposed Supervisory Festo CP smart factory digital twin (Figure 4.8). This shows the asset-twin setup and cyber-physical connection using the OPC_UA protocol.

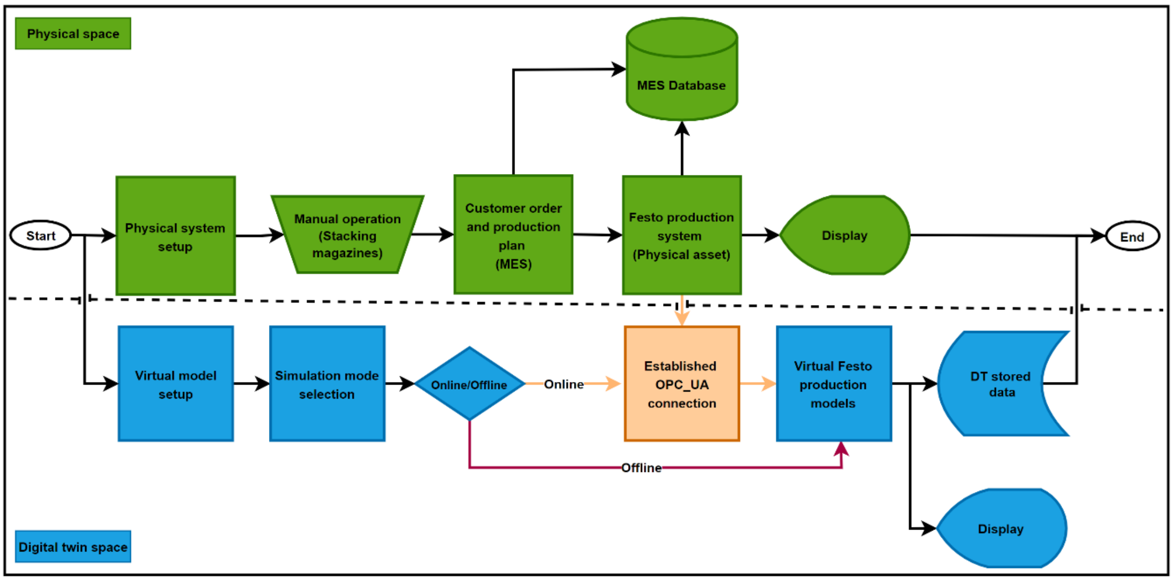


Figure 4.8: Functional flowchart showing supervisory DT set-up and the digital connection with its physical asset

Other outcomes of this phase included the identification of the work processes and the process flow at each station as shown in Figures 4.9 and 4.10. These pieces of information were used to define the setup procedure, the production flow, the process activities that can be modelled for the supervisory digital twin and establish the connection between the asset-twin.

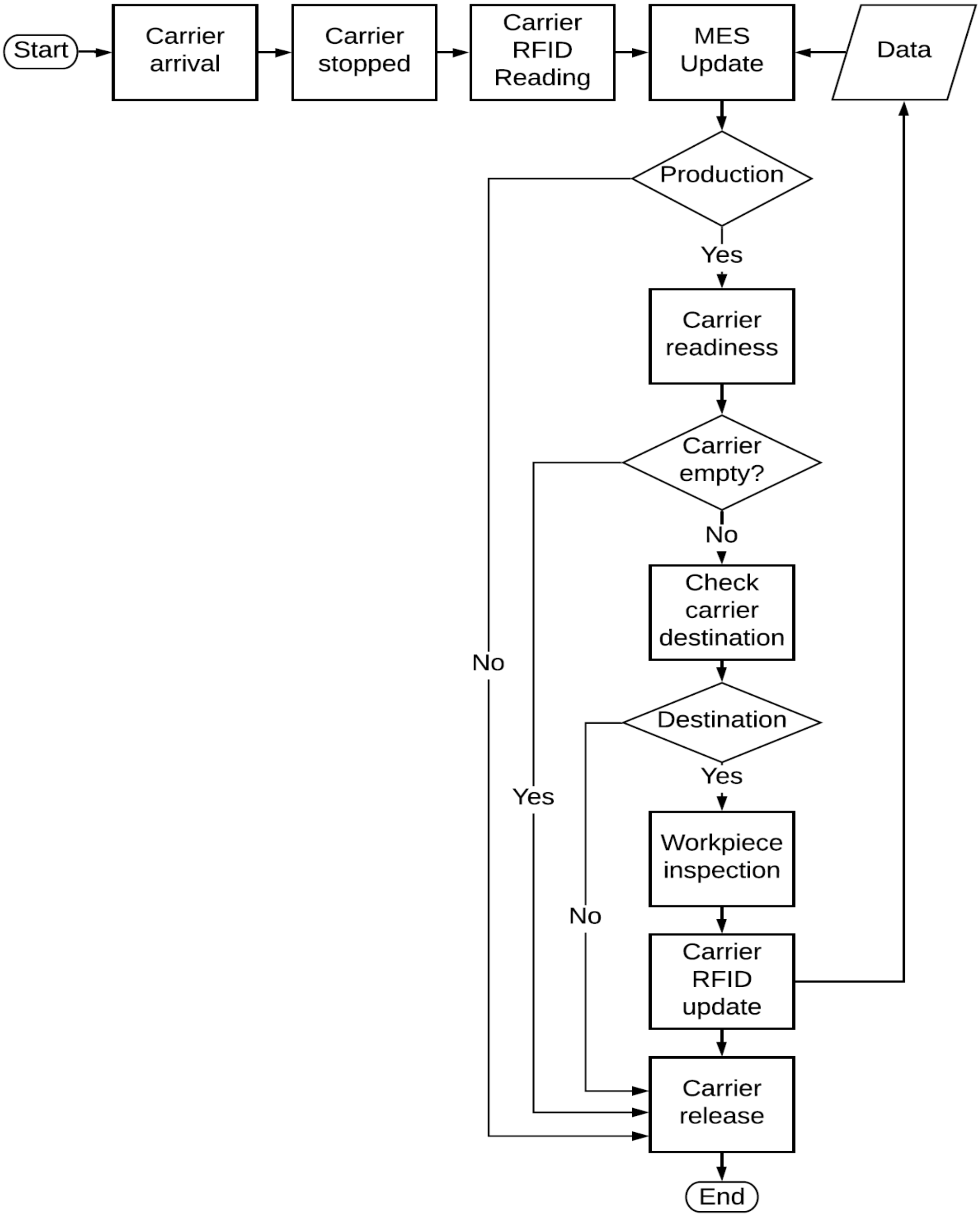


Figure 4.9: Functional flowchart of main activities in stations except for magazine stations

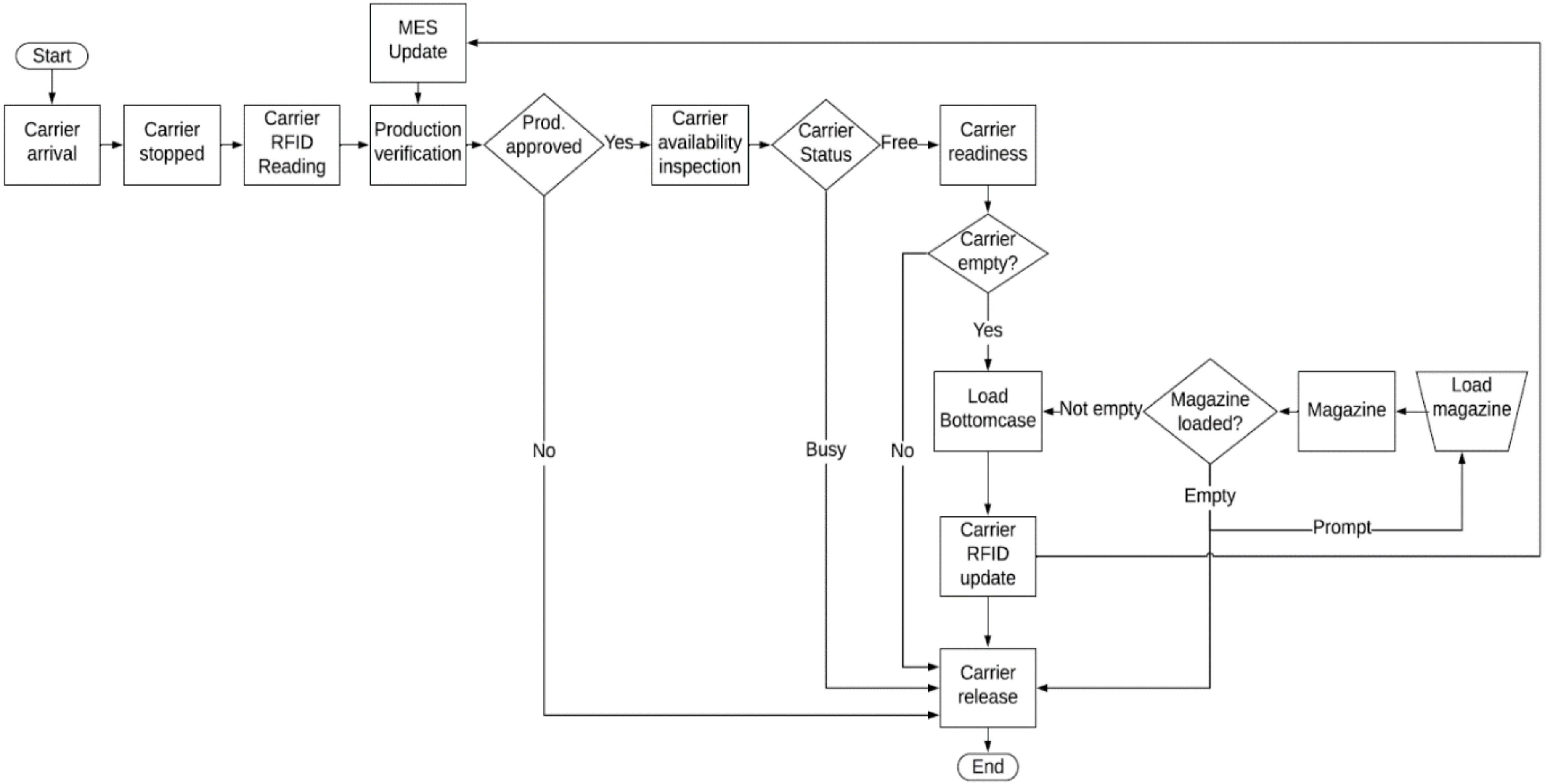
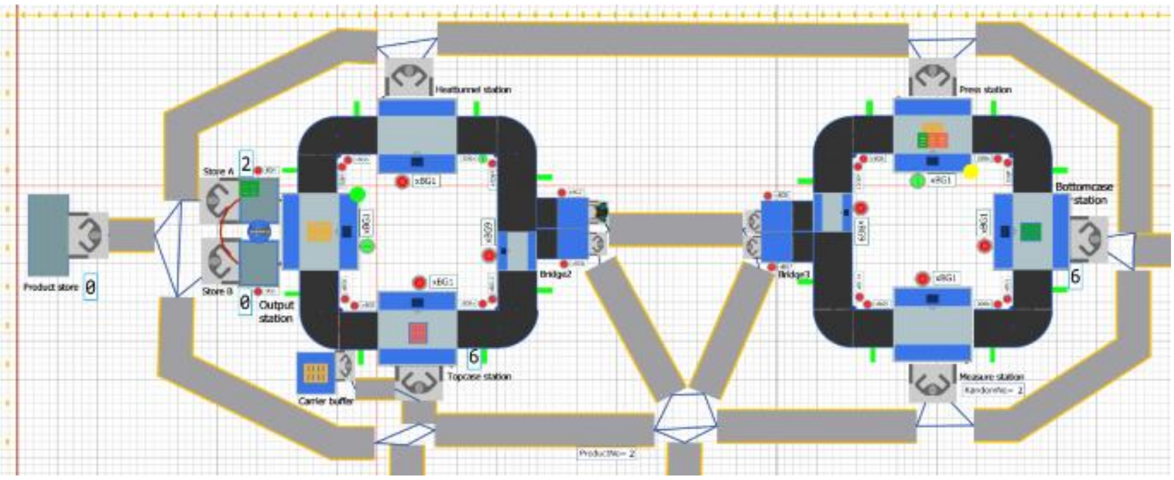


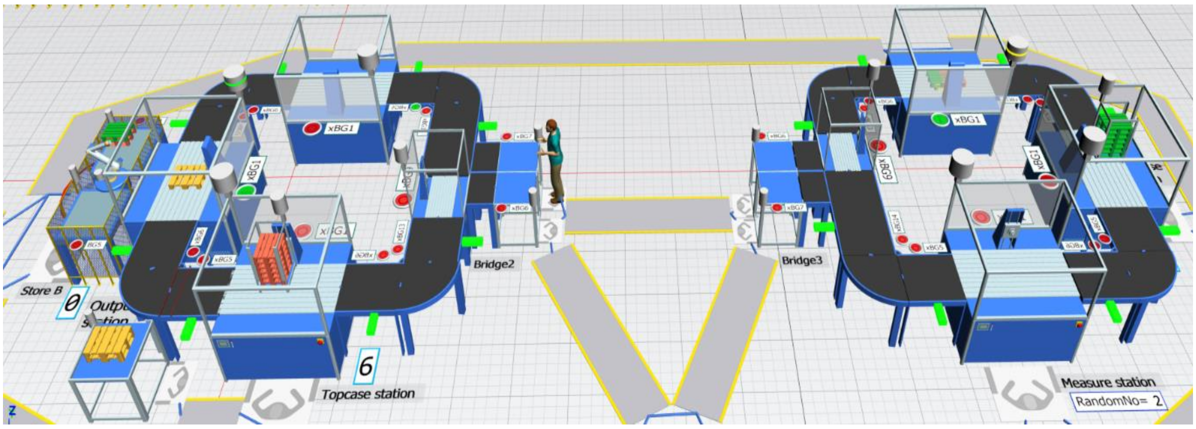
Figure 4.10: Functional flowchart of main activities in Magazine stations (Bottom and TopMag stations)

4.6.4 Developed DES supervisory digital twin model of the physical processes

(a) *Developed DES process digital twin model:* The developed DES digital twin model of the Festo CP smart factory (Figure 4.11), inherits predefined behaviours and interactions of the system with its control algorithms developed to manage the material flow. This was achieved using the predefined material flow objects (Table 4.1) of the simulation software. Figure 4.11(a & b) shows the DES digital twin of the Festo CP smart factory showing process flow.



(a) Top-view of the DES digital twin model of the Festo CP smart factory showing process flow



(b) 3D view of the process DT model

Figure 4.11: Overview of the developed Supervisory digital twin of the Festo CP smart factory

Table 4.1: Main objects of the Festo digital twin model

S/no	Material flow objects	Number	Justification
1	Stations	8	Process execution
2	Footpath	4	Robotino path
3	Conveyors	16	Transport-conveyors
4	Operator	1	Robotino
5	Workspace	2	Robotino docking stations
6	Checkbox	12	Position sensors at stations and bridges
7	Source	1	Part creation and intro into the system
8	Store	1	Product from the system is stored for removal

(b) *Developed DES product digital twin model:* The product is a simple composition of a top and bottom case for a phone. At this stage of the research, the product is a Fixed product. The process flow analysis provided details on the services and their weight on the attributes of the product. This information is conveyed along the production line using RFID technology mounted on the carriers. The RFID chip on the carrier enables a progressive transmission of the product data as the physical product is processed. This enables a real-time synchronised update of the product's digital twin. Figure 4.12 presents the product's DT visuals: a geometric model and extracts of its information model.

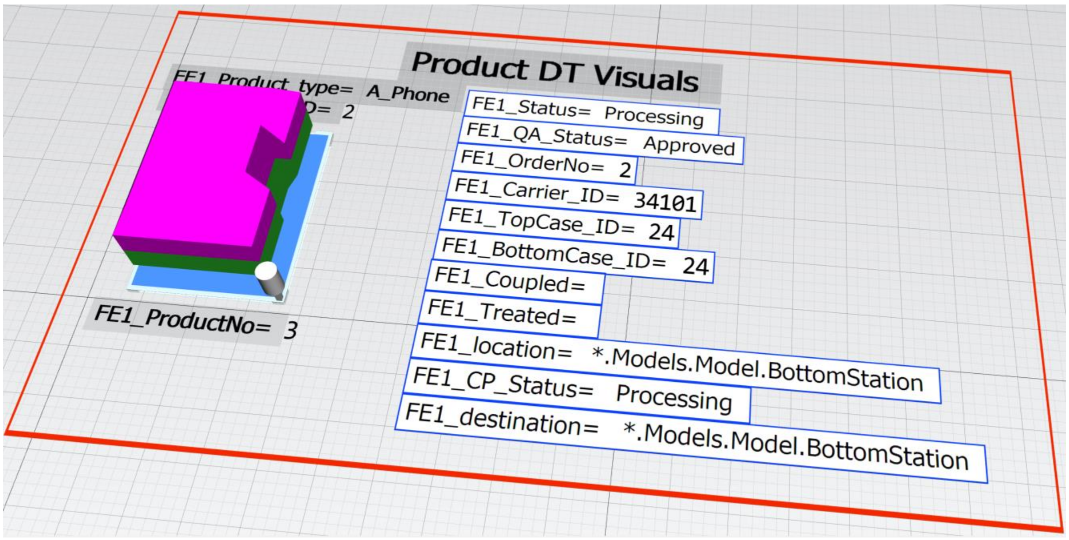
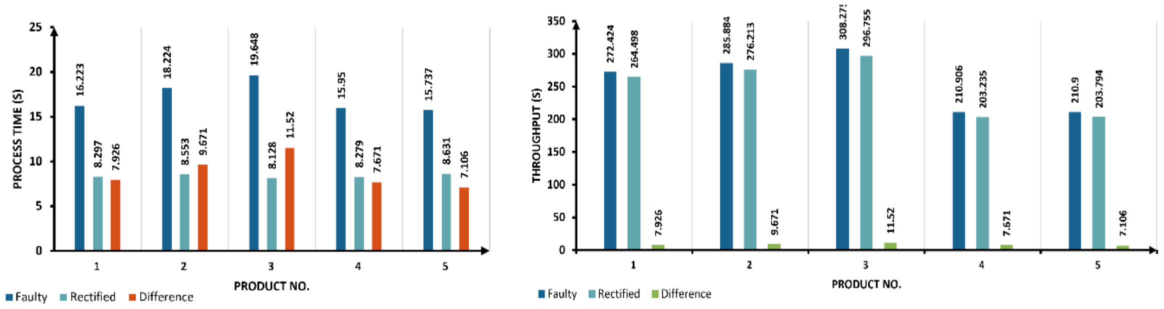


Figure 4.12: Product digital twin visuals

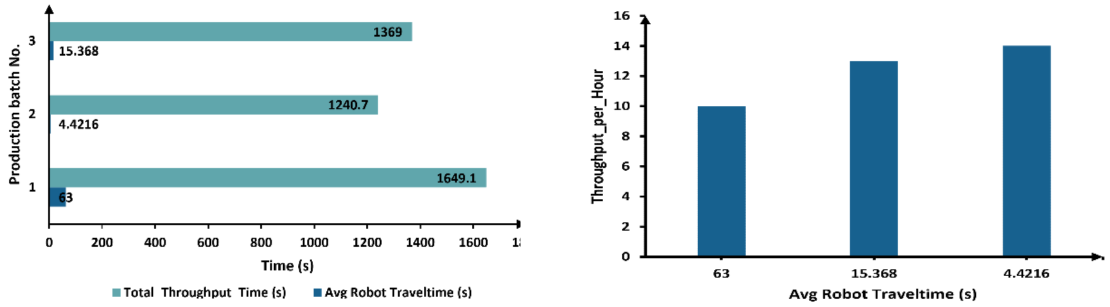
4.6.5 *Results and discussion*

Experiments carried out revealed more details on identified bottlenecks and enabled corrective maintenance and strategy proposition to improve production. Identified bottlenecks included increased friction between carriers and conveyors, delay in unloading finished products from the “Output” station, waste of process time on rejected workpieces and lost process time in heating the “Heat-tunnel” station. Figure 4.13(a & b) presents the results on the impact on *process time* and *total throughput* by the identified station with increased *travel time* due to friction on its conveyor. Figure 4.13(c & d) presents results on the impact of using the robot at varying *travel-time* on production *total throughput time*. Figure 4.13(e) presents results on the impact of the output station *storage capacity* on *throughput.* Lastly, offline simulations were carried out to determine the impact of controllable system parameters on production. Table 4.2 presents the impact of robot travel time on the total throughput time and throughput-per-hour.



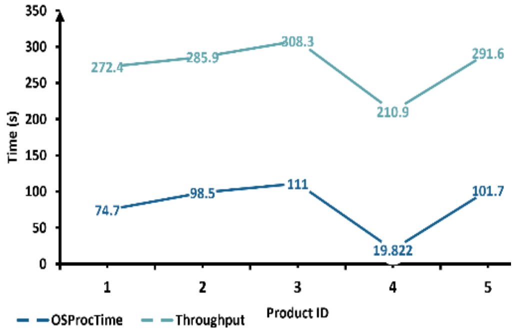
(a): The impact of *travel time on process time*

(b): The impact of *travel time* on *total throughput*



(c): Impact of robot travel time on total throughput time

(d): Impact of robot travel time on total throughput per hour



(e): The impact of the output station storage capacity on throughput

Figure 4.13: Experimental results revealing more details on identified bottlenecks and system behaviour

Table 4.2: The impact of robot *travel-time* on the *total throughput time* and *throughput-per-hour*

Avg. robot travel time (s)	**Total throughput time (s)**	**Throughput per hour**
5.467	16:36.0	18
10.467	17:26.0	17
15.467	18:16.0	16
20.467	19:06.0	16
30.467	20:46.0	14

These results supported the strategy proposed to keep its store available during production to improve the system throughput and identified optimal system configurations for production.

Benefits of the Festo smart factory digital twin: The digital twin developed has expanded the system's research/experimental capabilities for diagnostic/predictive analyses, investigating business cases and the impact of modification/upgrade decisions, and determining optimal production configurations and monitoring. It has also introduced some level of flexibility in teaching/training. The constraint of space and accessibility by a large number of students to the physical system has been tackled using the DES digital twin which can be used offline/online. Current industrial expectations like the Industry 4.0 concepts and technologies can be taught safely, especially in Covid-19-type situations where physical distancing is vital to safety.

Future work: The next phase of the project would upgrade the current digital twin to an interactive and immersive predictive digital twin, which reflects the complexities and uncertainties experienced in real manufacturing environments and possesses decision-making capabilities. The plan includes an extension of their functionalities to real-time control from the virtual space, including a more robust data layer to implement real-virtual data fusion and product-centric control.

4.7 Summary

This chapter presents an integrated product-process digital twin framework in response to the research question: *“How can a product and process digital twin be integrated to harness the dependencies between the product and its manufacturing process”.* It enables the integration of both product and process digital twin data/functionalities and the evolution of digital twin data. The application, methodology and benefits of the proposed framework were illustrated in a case study. The case study demonstrated that, within manufacturing, the DT serves as a medium for achieving cyber-physical integration through bidirectional interaction, data analytics and linking of information silos all through the product cycle. The proposed framework allows automated configuration of production setups using the virtual product specifications. Finally, technical limitations and proposed solutions for the implementation of the digital twin concept in manufacturing were discussed.

The digital twin concept is still evolving. More applicative demonstrations of the digital twin concept from different fields using the proposed integrated product-process digital twin would prove its diversified usefulness, highlight more business benefits, encourage more investment and further adoption in existing industrial infrastructures. The idea of controlling physical assets from virtual models presents more research opportunities and was considered in this research.

CHAPTER V: REAL-TIME SYNCHRONISED INTERACTIVE SIMULATION

The integrated product-process digital twin (DT) was presented as a decision-support system for the CPPS. The integration of the product and process DTs harnesses the interdependencies between the product and its production processes. In Section 5.3, a dependency rule was proposed to logically define the relationship between the product and its production processes. This formed the framework for the collaborative interaction (Section 5.4) between the asset-twin. A real-time synchronisation mechanism is presented to support the synchronised real-time interactive environment where the CPPS supports its DT simulations, analyses and visualisation with operational data and control. A case study is presented as evidence of the feasibility and effectiveness of the propositions made in this chapter.

5.1 Research contribution

The idea of using the product and the process DTs in an integrated environment is new and would present the opportunity to investigate the potential inherent in modelling the interaction between the product and its production process. To extend the benefits of the DT concept to the operational phase of manufacturing, real-time synchronised interaction between the asset-twin is needed. This is a simulation scenario where the online DT behaviour can be driven by triggers/data from the physical asset and in return, the DT can support/manage/control the physical asset based on experimental/analytical data. In line with this, two techniques for the logical modelling and implementation of the product DT-process DT connection and the asset-twin connection necessary to support a real-time data-driven synchronised asset-twin interaction, production flexibility and product customisation are presented as the novelties in this chapter. These research contributions achieve the following:

- Linking virtual products models with virtual process models based on a proposed dependency rule

- Real-time synchronized bidirectional communication between the asset-twin enabling real-time synchronised interaction
- Real-time product DT representation using the RFID technique
- Updating the product DT in real-time based on the production of its physical replica via the process DT
- Part tracking using the RFID technique

5.2 Methodology and case study

The methodology adopted in this study involved system identification to define the entity and functionalities to be analysed. A case study is then presented as evidence of the feasibility and viability of the propositions made in this chapter. These methods have been briefly introduced in Chapter 3 and detailed in Appendix C.

The rest of the chapter is structured as follows: Section 5.3 discussed the development of the integrated DT model. This includes the proposed dependency rule that describes the logical product-process interaction. Section 5.4 discussed the attributes of an integrated DT model. Section 5.5 presented capabilities unique to the integrated product-process DT if used as a decision-support system for the CPPS. A case study is presented in Section 5.6, Section 5.7 discussed the research outcome and the chapter concluded with a summary.

5.3 Development of the integrated product-process digital twin model

This section provides details on the approach adopted in integrating the product and process DTs. It discusses the DT composition of the product and processes and the interdependency rule between them. The dynamic interaction (Figure C2 & Eqn. 3.1) between the product and its production processes is modelled as a logical bidirectional interaction (Eqn. 5.1), mathematically, expressed as the dependency rule (Eqn. 5.9). Extended into the DT model, it forms the framework for the collaborative mechanism of the proposed integrated product-process DT in Section 4.4.

5.3.1 Dependency rule

The proposed dependency rule (Eqn. 5.9) defines the logical relationship between the product DT attributes and the available production services of the process DT. These dependencies are used to establish a logical relationship (interdependence) between the product-process DT and its physical asset. Mathematically, it is expressed as Eqn. 5.9 in terms of the product's attributes/features, process services and respective weights. Extended into the DT model, it forms the framework for the collaborative mechanism of the integrated product-process DT.

Dependency rule: This states that a product type $\left(P_{type}\right)$ is defined by its attributes(A) which are logically related to the services (S) of its production system (P_{c_i}) configuration $\left(Proc_{config}\right)$.

Mathematically:

$$Prod_{type} \overset{\bowtie}{\leftrightarrow} Proc_{config} \qquad \text{(Eqn. 5.1)}$$

The $Proc_{config}$ can be represented in terms of its service (S) and associated weight (W).

$$Proc_{config} = \left\{P_{c_i} | i = 1, \dots, n\right\} \qquad \text{(Eqn. 5.2)}$$

$$P_{c_i} = \left\{S_j | j = 1, \dots, q\right\}$$

Assumption: A production cell can render more than one service. Thus

$S = \left\{S_{i,j} | i = 1, \dots, n \,\&\, j = 1, \dots, q\right\}$

$W = \left\{W_{i,j} | i = 1, \dots, n \,\&\, j = 1, \dots, q\right\}$

Therefore:

$$Proc_{config} = \{(S_{i,j}, W_{i,j}) | i = 1, \dots, n \;\&\; j = 1, \dots, q\} \qquad \text{(Eqn. 5.3)}$$

Where:

i: Production cell index

j: Service index

n: Number of production cells in the production system

q: Number of services in the ith production cell

Also, to represent the product $(Prod_{type})$ in terms of its attributes (A) and associated quality (Q).

$$Prod_{type} = (A, Q) \qquad \text{(Eqn. 5.4)}$$

$A = \{A_z | z = 1, \dots, b\}$

$Q = \{Q_z | z = 1, \dots, b\}$

The quality of a product attribute (A_z) is a summation of the impact $(Q_{i,j})$of all logically associated service $(S_{i,j})$.

$$Q_z = \{Q_{i,j} | i = 1, \dots, n \;\&\; j = 1, \dots, q\} \qquad \text{(Eqn. 5.5)}$$

Where

z: Product attribute index

i: Production cell index

j: Service index

Therefore

$$Prod_{type} = \{(A_z, Q_z) | z = 1, \dots, b\} \qquad \text{(Eqn. 5.6)}$$

Where

b: Number of product attributes

A product attribute (A_z) can be worked on by one or more services. This service configuration (S_z) as shown in Eqn. 5.7 is a composition of all services of the production system associated with the attribute (A_z).

$$S_z = \{S_{i,j} \mid S_{i,j} \in S\} \qquad \text{(Eqn. 5.7)}$$

Therefore

$$(S_z, W_z) = \{(S_{i,j}, W_{i,j}) \mid \; S_{i,j} \in S \;\&\; W_{i,j} \in W\} \qquad \text{(Eqn. 5.8)}$$

By extension of the relationships in Eqn. 5.6 and Eqn. 5.8 on individual attributes and the principle in Eqn. 5.1, the dependency rule formula is formulated as shown in Eqn. 5.9.

$$(\boldsymbol{A_z}, \boldsymbol{Q_z}) \bowtie (\boldsymbol{S_z}, \boldsymbol{W_z}) \; \forall \; \boldsymbol{A} \qquad \textbf{(Eqn. 5.9)}$$

The graphical representation of the logical interaction between the product attributes and the production system services during production is shown in Figure 5.1. Based on the dependency rule (Eqn. 5.9), it presents the mapping of the services and their respective weight (S_z, W_z) to the associated product attributes and qualities (A_z, Q_z).

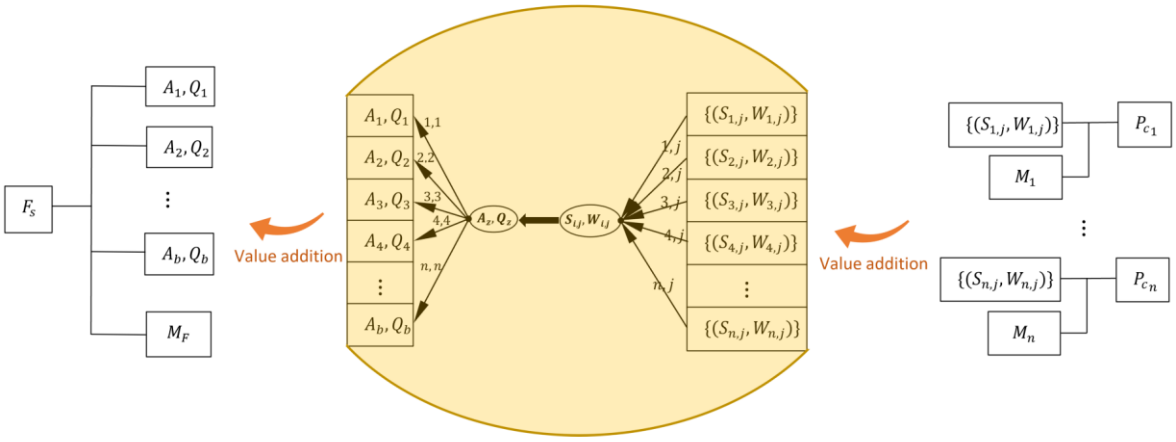


Figure 5.1: The logical interaction between the product attributes and the production system services based on the dependency rule: $(\boldsymbol{A_z}, \boldsymbol{Q_z}) \bowtie (\boldsymbol{S_z}, \boldsymbol{W_z}) \; \forall \, A$

5.3.2 Product DT composition

The product DT $\left(D_{pd}\right)$ is described to be more than a replica of the product (P_{v_x}). In addition to what attributes are been modelled, the product DT is designed to have the capacity to configure the process DT. Based on the logical relationship defined between the product and the services adding value to it, the service configurations are mapped to each of its attributes. Given several product types (x) , the product DT (D_{pd}) is represented in (5.10).

$$D_{pd} =< \{A_z, Q_z, Sc_z\}, M_F > \qquad \text{(Eqn. 5.10)}$$

Where:

A_z: zth attribute of the product

Q_z: Quality of the A_z

S_{c_z}: Service configuration for A_z

M: State of P_{v_x} (WIP, finished and rejected)

5.3.3 Process DT configuration

From a logical perspective, this research represents the production system (P_s) as an encapsulation of the internal logic and the functional composition of the production resources(R). This defines the functions of its subsystems/units (P_c), the logical interaction amongst its units and its operating environment (E_v), the services (S) it renders, the interfaces that interact with its external environment, the logistic network (L_{net}) handling material flow and communication network handling information flow.

To model the process DT (D_{pc}), the composition, structure, operations and input/outputs interfaces are identified and represented using modelling elements (material flow, information flow, user interfaces and resources). The process model is built based on the logical relationship between the production cell functions/services and that between the production cells. The geometric model forms the capsule upon which other models are anchored. This defines the type and quality of the model's visualised geometric features and kinematics of interest physic entity. The logistic/rule model describes the material flow through the model. The production cell (D_{pc}), can be represented algebraically using a six-element structure as shown in (5.11).

$$D_{pc} =< P_{c_{info}}, R, S, \mathrm{M}, L_{net}, E_v > \tag{5. 11}$$

where

P_c: The production cell

$P_{c_{info}}$: Documentation of the P_c

R: A set of the 4Ms of the 4MIE elements of P_c

S: Available P_c services

M: State of the P_c (idle, active, processing, faulty)

L_{net}: Logistic network handling material flow and storage in P_c

E_v: Operating environment of the production cell (P_c)

5.3.4 Product DT-process DT interaction

Modelling the interaction between the product and its production processes creates a bidirectional link between the product DT and the process DT (Eqn. 5.1). Based on the dependency rule, this becomes an interdependent interaction (Eqn. 5.9) where the product attributes are mapped to the respective service set. This further defines the weight of each production service on the product attribute and quality. The integration of the process and product DTs creates a virtual environment where the process DT builds the product DT and the product DT reconfigures the process DT based on the product DT's design specifications (Figure 5.2). With the dependency rule, product/process variations (as defined in Section 3.3) specific to the assets can be modelled into the DT. Also, disruptions in production in terms of product defects and deviations from predefined product specifications/behaviours can be modelled in terms of the weights of the services on the product attributes. This would involve design calibrations of the envisaged variations/disruptions based on expert knowledge.

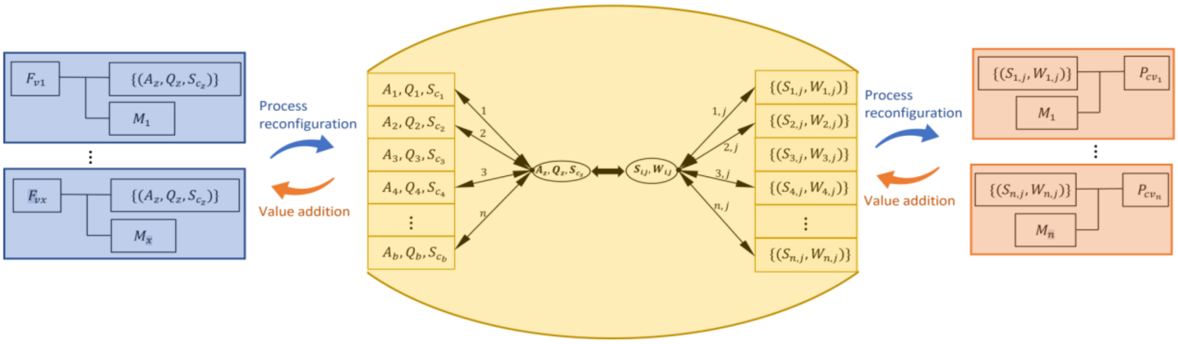


Figure 5.2: The logical interaction between the product DT attributes and the process DT based on the dependency rule

5.4 Integrated product-process digital twin for a CPPS

With a CPPS as the integrated physical asset synchronised to the integrated DT, the influence of this virtual DT interaction can be extended to the physical space. As shown in Figure 5.3, in the forward direction of the physical-virtual bidirectional connection, the physical processes build the product DT. In the reverse direction, the product DT and the process DT can reconfigure the smart processes, execute customer customisation on a product type and reschedule resources during production with no disruption to the production flow.

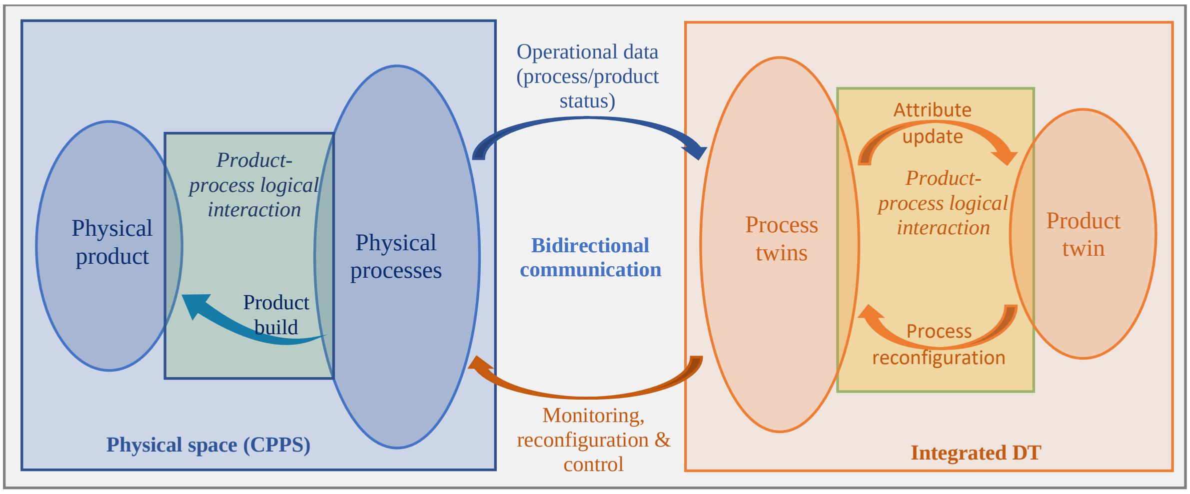


Figure 5.3: The CPPS and its integrated DT showing all interactions between elements

5.4.1 Cyber-physical integration

Integration in this research is considered a concept that allows for the interconnectivity, interaction and interdependency of related/associated components/functionalities to form a unified platform. This could include physical components like subsystems, data, control structures or layers within an architecture. Integration in production systems was considered under the following categories: virtual space integration (product and process digital twin), physical-virtual space integration

(a) Product and process DT integration

In literature, product and process DTs have been discussed independently (Haag & Anderl, 2018; Jones et al., 2020). This research attempts to integrate them and as such needs to carry out virtual space integration. This idea is based on the fact that products and their production processes are interdependent. Integrating them would create and maintain a dynamic virtual construct of the CPPS.

The dependency rule was used as the mechanism to integrate the process and product DTs. As a relational rule model, it establishes the logical connection and dependencies between the product DT data/attributes and its process DT data/services. This coupling allows the product to evolve as it passes through each process. This relationship is visualised in Figure 5.4. Model standardization/specifications stand out to be a way forward to eliminate heterogeneity in generated data. Data and resource integration within the virtual space would allow for both DTs to share resources and collaborate to improve each other's performance.

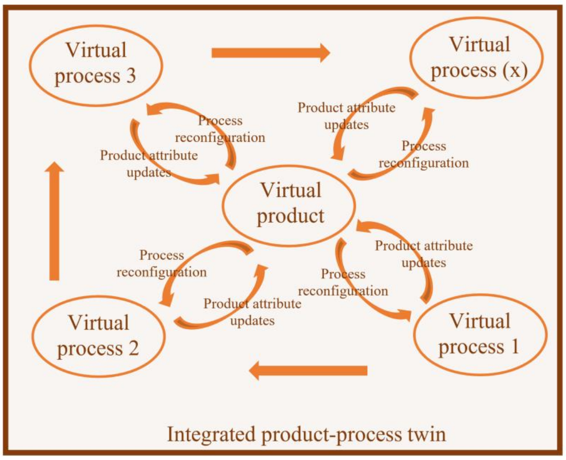


Figure 5.4: The interaction between the product DT and process DT

(b) *Physical-virtual space integration*

With a focus on the production phase of the product, the integration of both the physical and virtual space would enable the physical system to benefit from the functionalities obtainable in the virtual space in real-time. With a CPPS synchronised to the integrated DT, the influence of the virtual interaction can be extended to the physical space. When the process DT is updated with operational data from the physical process, the product-related data is then used to update the product DT information model and visual perspective. The product DT has its specifications interface which is used to manage the service performances, set process configurations, monitor the product formation and introduce customer variability in product specifications.

From the information perspective, operational data is made available to virtual analytical tools. These additional data reduce engineering estimations and errors due to uncertainties. It ultimately improves the precision of operational analyses and decisions made. Furthermore, with real-time communication applications like the OPC unified architecture (OPC_UA) protocol, operational data and data-driven control can be achieved in real-time (Pethig et al., 2017). Figure 5.5 visualises the interaction between the integrated asset-twin.

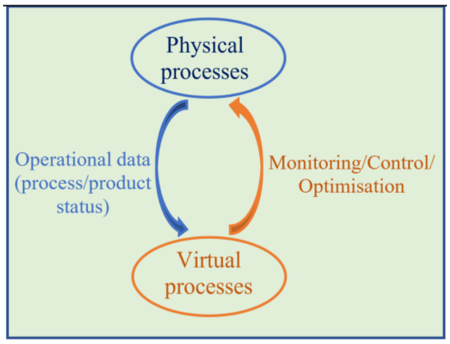


Figure 5.5: The interaction between the integrated asset-twin.

From a control and automation perspective, The virtual space expands the system control capacity by adding more interfaces for human engagement, establishing interconnectivity between independent control structures, expanding control configuration/collaborations and providing real-time data-driven control.

5.4.2 Collaborative behaviour between the integrated DT and the physical asset

Key to the cyber-physical integration concept is the real-time collaboration between the CPPS and its virtual resources. This creates a paradigm of dynamic data-driven applications systems

(DDDAS). This is an interactive simulation whereby the computation and instrumentation capabilities of the DTs are dynamically integrated into the CPPS using a data-driven analytical and decision-making feedback loop (Jiang et al., 2021). With operational data dynamically incorporated into the DT model as a functional platform for monitoring, analysis, prediction and optimization, it can implement data-driven control of the physical asset in real-time.

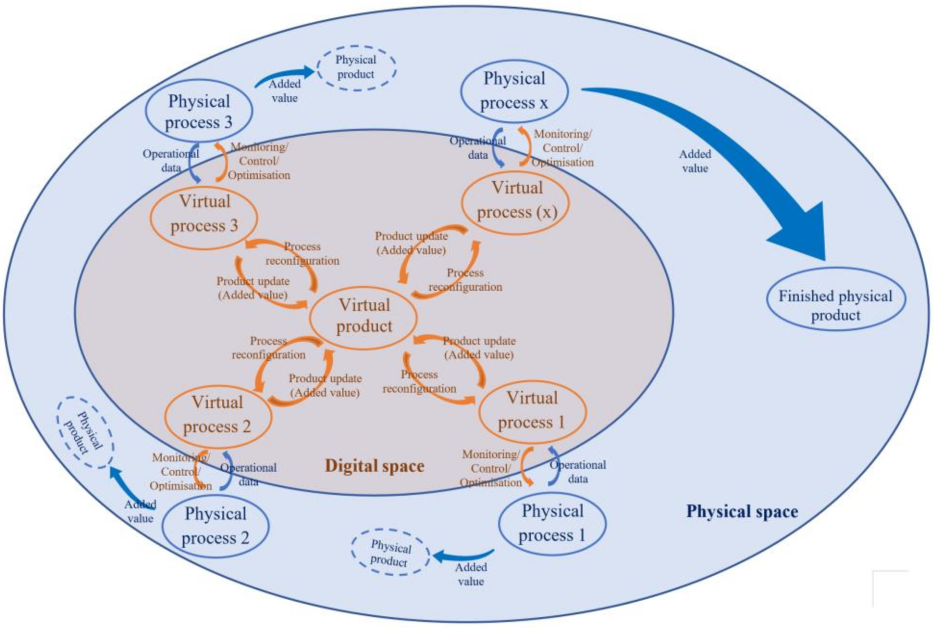


Figure 5.6: The collaboration between the CPPS and its integrated DT during production

Figure 5.6 visualises the collaboration between the CPPS and its integrated DT. The integrated DT mechanism provides a synchronised real-time interactive environment where the CPPS supports its DT simulations, analyses and visualisation with operational data and control. This enables a more accurate and faster modelling/analysis of the characteristics and behaviours of a system. It also exploits data in intelligent ways that enhance it with new capabilities as a decision-support system, with the accuracy of full-scale modelling, efficient data collection, management, and data mining (Liu, Meyendorf & Mrad, 2018). In return, these analytical results are used to manage/control production operations and support operational/managerial decisions. To achieve this collaborative behaviour between the integrated DT and the physical asset, the communication infrastructure should support a real-time synchronisation mechanism. Here a status-change event protocol/observable function active within the virtual access nodes is presented and discussed further in the next section.

5.4.3 Real-time, two-way and secure connections between the physical asset and the integrated digital twin

This section presents the proposed real-time synchronisation mechanism needed to support a synchronised real-time interactive environment where the CPPS supports its DT simulations, analyses and visualisation with operational data and control. This is the virtual access node (communication interface) associated with every functional unit within a production system. Equipped with a Status-change event protocol, it can observe and publish changes in the status of the parameters in the asset's information model. This informs and updates all connections to the virtual access nodes.

A. Real-time Synchronisation Mechanism (Virtual Access Nodes with Status-Change Event Protocol): A uniform communication interface for manufacturer-independent data exchange is an important basis for the implementation of integration as a requirement of Industry 4.0. This is also a challenge(Onaji et al., 2022). To achieve a real-time synchronisation between the asset-twin, there is the need for an established communication architecture with a real-time synchronisation mechanism. This defines a unified data structure and standardized mechanism for interaction and data accessibility within the cyber-physical environment (Blum & Schuh, 2017). The real-time synchronisation mechanism presented here is composed of the virtual access nodes (VAN) each with a Status-change event protocol. It is the standardized mechanism for collaborative interaction between the asset-twin. Collaborative interaction is achieved via the communication interfaces of the operating environment. These interfaces modelled as virtual access nodes (VAN) define the information model (parameters, data structure, communication rules) and accessibility to the resources within that operating environment. In other words, they are the access point to all obtainable virtual descriptions of the associated resources. This includes attributes, functionalities and communication standards that can be modelled.

i) Virtual Access Node (VAN): This research modelled the communication interfaces of the production system's resources as the Virtual access nodes (VAN) (Figure 5.7) in the communication network of the production system. There exists a virtual access node associated with every functional unit within a production system. If all access nodes have a unique identification, unified data structure and communication protocol, then the communication network of the operating environment would be composed of standardised and robust bidirectional communication channels that support faster data transmission irrespective of the source/vendor. Figure 5.7 presents the communication framework between the asset-twin using the Virtual access nodes.

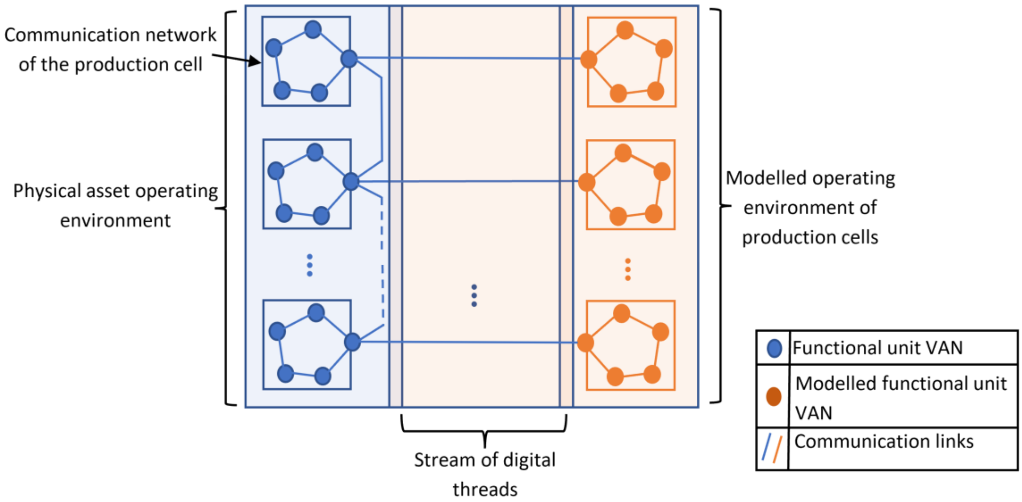


Figure 5.7: Modelled cyber-physical environment showing an integrated communication network of the virtual access nodes (VAN).

ii) Status-change event protocol: Crucial to an interactive simulation of the asset-twin is a

Status-change event protocol active within the virtual access nodes. This observes and publishes changes in the status of the parameters in the asset's information model. This informs and updates all connections to the virtual access nodes. Having modelled the virtual access nodes in the DT, coupling the DT to its physical asset allows for a real-time response to changes from either space. With this approach, the DTs are more accurate and faster in modelling and analysing the behaviours/characteristics of the physical asset. How fast it does that depends on how often data is pulled from the physical asset.

iii) Interaction and evolution of the asset-twin quantities: The physical system exists in high-dimensional space; therefore it is complex and difficult to be fully modelled. As such the physical asset's information model is a composition of all obtainable virtual descriptions of the associated resource Cheng et al., 2020, Jiang et al., 2021). These include all observable data (physical states, operational data) and control inputs/outputs. The integrated DT information model is a composition of all parameters useful for the use case. This translates to the digital states, quantities of interest (process and product's attributes and weights) and performance metrics.

A dynamic bidirectional communication network with its real-time synchronisation mechanism between the coupled asset-twin is presented in Figure 5.8. This illustrates the interaction and continuous evolution of the asset-twin. An expansion of the virtual access node of the physical production unit (P_c) shows its information model. It comprises the observable data set (O), control input set (U) and the Status-change event protocol. On the virtual side, you have the process DTs (D_{pc}), product DT (D_{pd}), integrated DT information model and an Analytical unit (K) of algorithms networked to process information, interact and share data. The integrated DT information model consists of both extractable operational data (O) and virtually engineered data (S, A, W, Q, K, U) logically linked for constructing useful information. This information can be stored and kept handy for analytics. The symbols (S, A, W, Q) have been defined in Section 5.3.

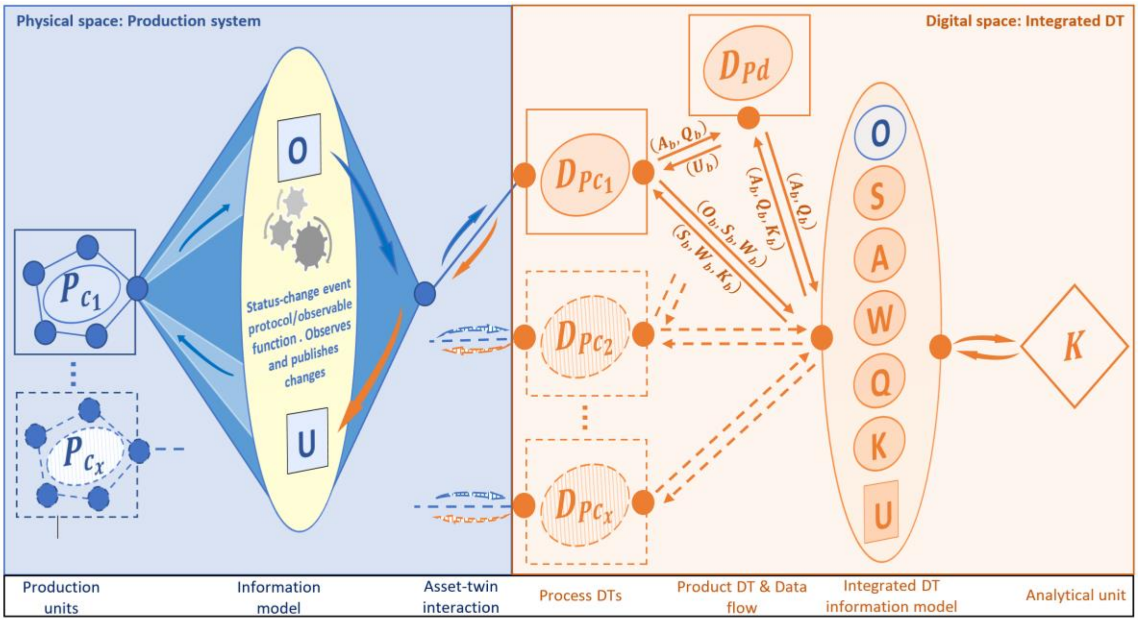


Figure 5.8: The interaction and evolution of the integrated asset-twin quantities

With the DTs coupled to the physical asset in real-time, it is expected to synchronously reflect the status of the physical asset and evolve with it. Using data-driven logical/physics models, its simulation actively assimilates the behaviour and state of its physical asset using acquired observable data. This is a scenario where the instantaneous status of the process DTs and the product DT are a reflection of the current status of the physical assets. Also, they can implement data-based virtual control strategies in real-time.

5.5 Integrated product-process digital twin as a CPPS decision-support system

This section presents capabilities unique to the integrated product-process DT if used as a decision-support system for the CPPS.

5.5.1 The function of the product DT

A major contribution of the product DT to the integrated environment is the added capacity to the CPPS to virtually reconfigure the production system to suit product specifications (Figure 5.9). This can be done in the preparatory stage or even during production thus reducing most of the manual involvement during reconfiguration processes. Other benefits include improved monitoring/production supervision, quality evaluation and product customisation.

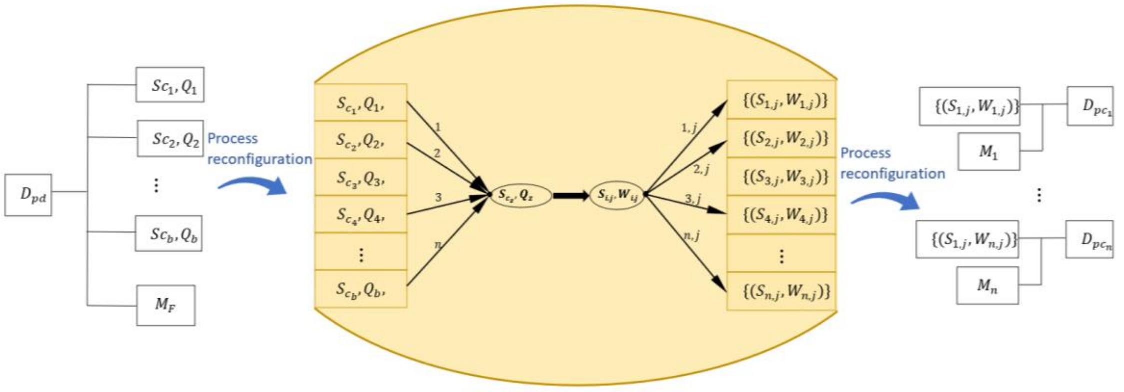


Figure 5.9: The process DT system reconfiguration (Sc_b) by the process DT

Production monitoring: The product DT presents the virtual framework of the product in making. Having its make-up (composition/attributes) constructed in real-time, based on the production data of its physical replica, it presents a more measurable and valuable view of the actual product. With technologies like the RFID, products/product components are identified and tracked with unique identification numbers (IDs), and the WIP status/attributes at each production phase can be monitored and weighed with the design specification. For example, the actual processing time and quality compared to production specifications. This production information becomes data available to manage the production efficiency during production, evaluate the system performance and determine or predict scheduled maintenance.

Product quality evaluation: The product DT being used to define the product specification can monitor the product quality while in production. The product attributes' qualities at each production phase can be weighed with the design specification. This approach would save time, resources and costs used for quality assurance after production. This also reduces waste due to rejected products not identified and removed from the system in time or correctable defaults not handled on time.

Product customisation: The connection between the product attributes and process services can be harnessed to support the autonomous variability of product specifications. Serving as an interface for more human involvement in the production control, product specifications can be managed to suit customer specifications with less obstruction to the production flow. This concept can be automated and variability in specifications can be inputted during preparatory stages thus reducing human intervention in real-time.

5.5.2 *The function of the process DT*

The process DT provides the platform to monitor and manage the CPPS from the virtual space. In a real-time simulation, the process DT builds the product DT with captured production data constructs as the physical product is manufactured. In offline scenarios, the process DT service configuration is used to build the product DT attributes (Figure 5.10). Where virtual control is implemented, collaborations between the process DT and the physical control structure can be used to manage the production process as well as the quality of the product.

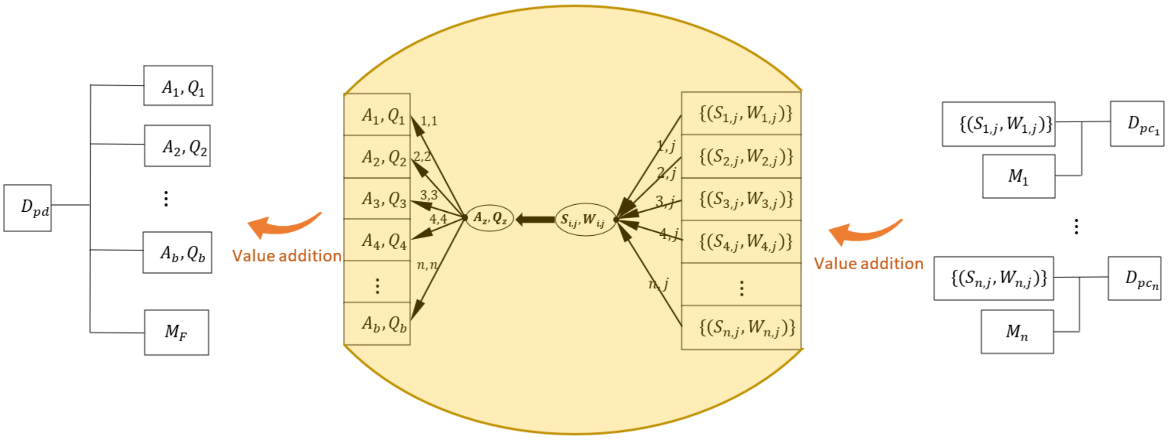


Figure 5.10: The product DT attributes (A_b) defined by the process DT services

5.5.3 Benefits of a Real-time Synchronised Interaction between the Asset-twin

Implementing a real-time synchronised integrated manufacturing DT on a CPPS comes with the following advantages:

1) The product twin is built in real-time using factual production data of its physical twin. This effectively represents the production status/condition of the product instances
2) The process DT serves as an interface for managing/monitoring the production process. Its simulation behaviour being driven by its physical asset reflects the current status of the production operation
3) The integrated DT utilises more effectively the cyber-physical environment as the product DT can be used to reconfigure the production processes via the process DT which is bidirectionally connected to the physical asset. This promotes production flexibility and product customisation during production
4) The virtual resources utilise the dynamic interaction to manage the production resources, scheduling and services to improve system performance and product quality
5) This digital structure creates a conducive environment for design, experimental simulations, analytics and information extraction. This virtual results of the production impact on the product can be used to improve industrial operations within the physical space. The utility of these virtual results in real-time is constrained by the issues in the interconnectivity and heterogeneity of the virtual and physical space. Integrating the product and process twins reduces these communication constraints.

5.6 Case study

5.6.1 Experimental setup: Festo Cyber-physical smart factory

In Chapter 4, a supervisory DT of the case study was presented. In this phase of the research, a Festo cyber-physical smart factory DES DT of a higher threshold (interactive and immersive predictive digital twin) is developed. This was designed to include variability in the product and processes as discussed in Section 3.3.

5.6.2 Conceptual model elements

(a) Process chart

The *ASME* symbols adopted to represent the following categories of activities include: arrows reveal transport activities, circles represent value-adding operations, the square represents inspection, inverted triangles represent storage and the teardrop symbol represents manual transfer operations. Material flow analysis of the production processes generated sufficient information for developing the process chart in Figure 5.11. This graphically presents the conceptual model in much detail.

Strategic points in the production line with sensors/actuators

1. Stations: entry and exit
2. Conveyors: entry and exit
3. Buffers: entry and exit
4. Bridges: entry and exit

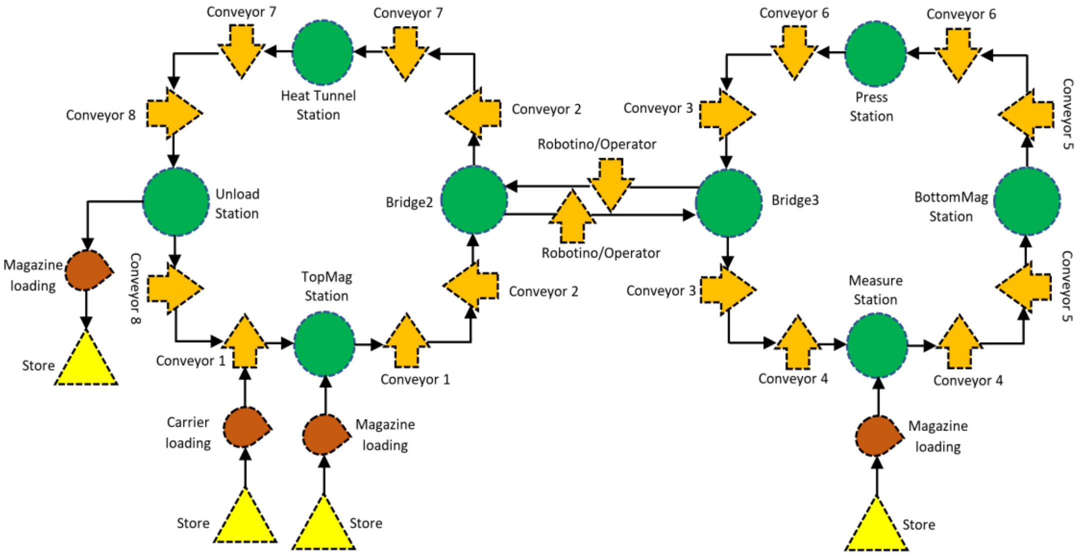


Figure 5. 11: Process chart of the system under investigation (SUI)

Figure 5.12 presents the high-level functional flowchart of the proposed interactive integrated product-process DT of the Festo CP smart factory. This included a virtual MES, station reconfiguration and product customisation functionalities. The bidirectional communication across the OPC_UA connection can support virtual control of the asset. It was explored in Chapter 6.

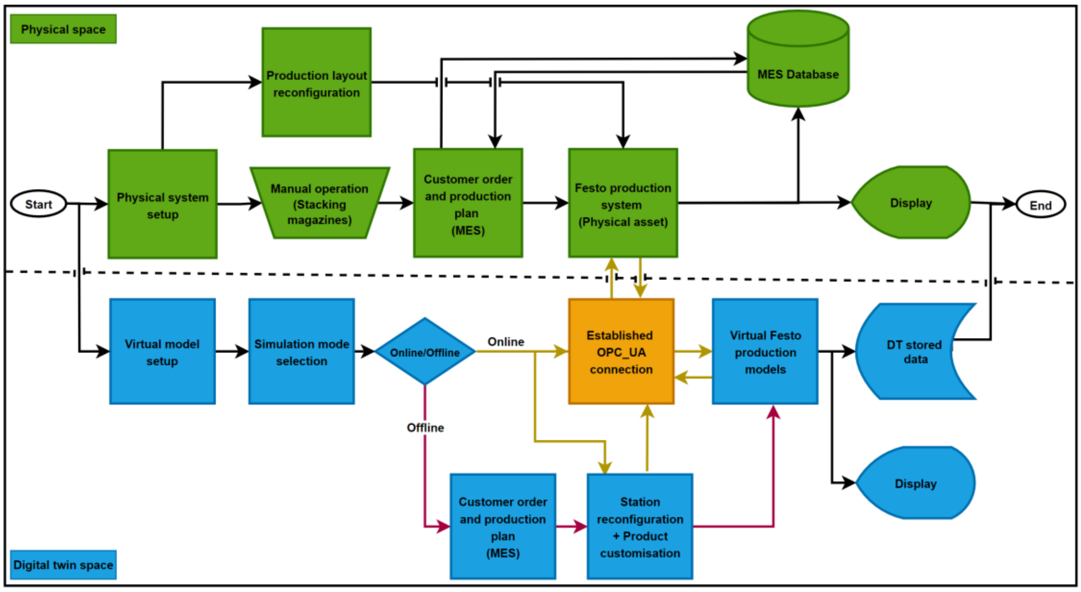
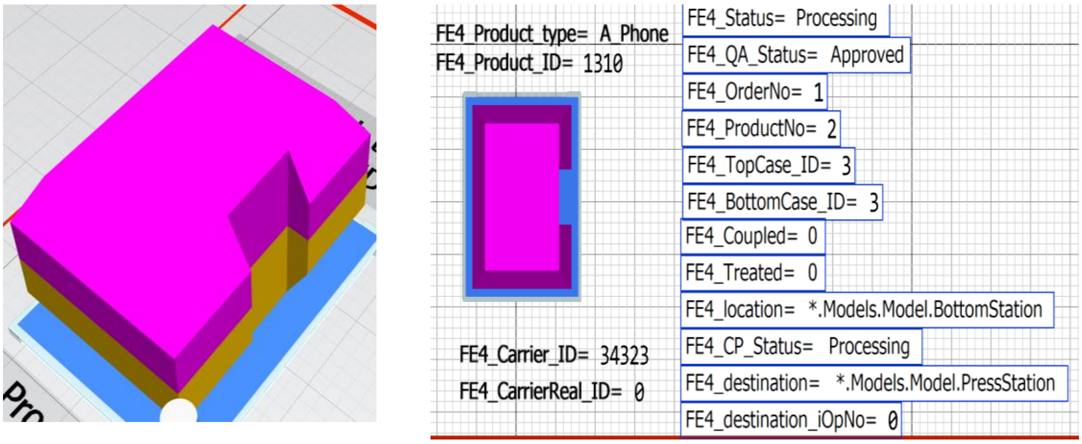


Figure 5.12: Functional flowchart showing a closed-loop DT set-up and the digital connection between the asset-twin

5.6.3 *Developed integrated DT*

(b) Product DT

Datasheets on the product and the material flow analysis provided details on the services and attributes that can be modelled. These were then mapped and visualised. The RFID data contains transferable information on the production of the flow entity. This makes it possible to build and update the product DT (Figure 5.13) as the real product is built.



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FE4_Carrier_ID= 34323
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FE4_Status= Processing
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FE4_Treated= 0
FE4_location= *.Models.Model.BottomStation
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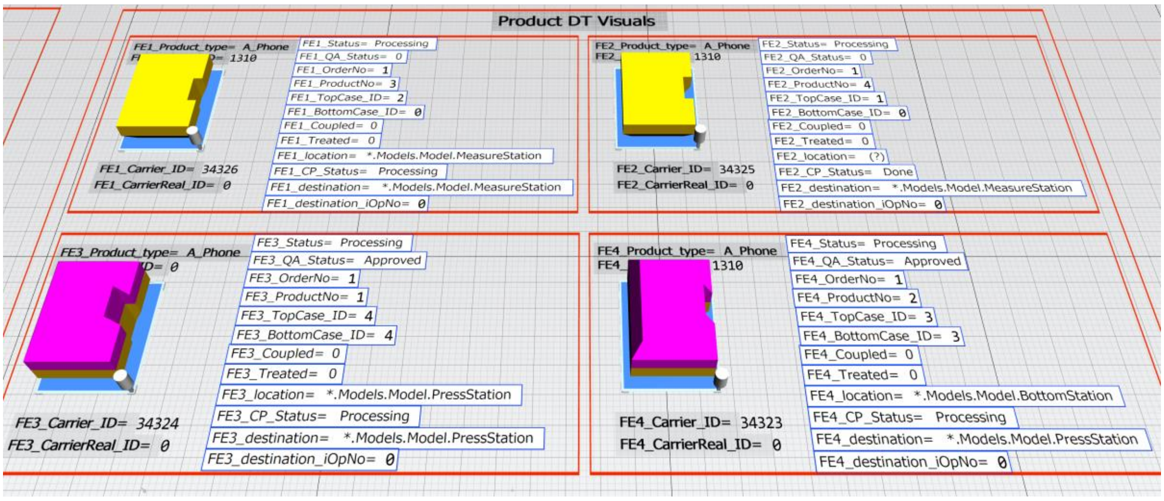
FE4_destination_iOpNo= 0

(a) Product geometric model (b) Extract from product DT information model



Product DT Visuals

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FE1_QA_Status= 0
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FE1_ProductNo= 3
FE1_TopCase_ID= 2
FE1_BottomCase_ID= 0
FE1_Coupled= 0
FE1_Treated= 0
FE1_location= *.Models.Model.MeasureStation
FE1_CP_Status= Processing
FE1_destination= *.Models.Model.MeasureStation
FE1_destination_iOpNo= 0

FE2_Product_type= A_Phone
FE2_ 1310
FE2_Carrier_ID= 34325
FE2_CarrierReal_ID= 0
FE2_Status= Processing
FE2_QA_Status= 0
FE2_OrderNo= 1
FE2_ProductNo= 4
FE2_TopCase_ID= 1
FE2_BottomCase_ID= 0
FE2_Coupled= 0
FE2_Treated= 0
FE2_location= (?)
FE2_CP_Status= Done
FE2_destination= *.Models.Model.MeasureStation
FE2_destination_iOpNo= 0

FE3_Product_type= A_Phone
D= 0
FE3_Carrier_ID= 34324
FE3_CarrierReal_ID= 0
FE3_Status= Processing
FE3_QA_Status= Approved
FE3_OrderNo= 1
FE3_ProductNo= 1
FE3_TopCase_ID= 4
FE3_BottomCase_ID= 4
FE3_Coupled= 0
FE3_Treated= 0
FE3_location= *.Models.Model.PressStation
FE3_CP_Status= Processing
FE3_destination= *.Models.Model.PressStation
FE3_destination_iOpNo= 0

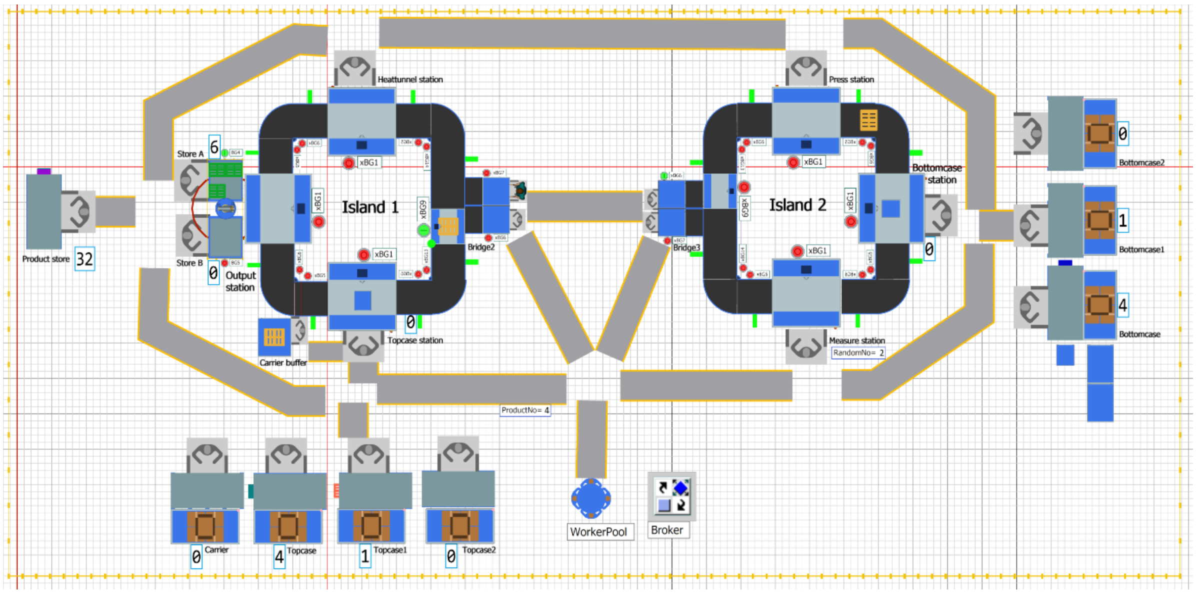
FE4_Product_type= A_Phone
FE4_ 1310
FE4_Carrier_ID= 34323
FE4_CarrierReal_ID= 0
FE4_Status= Processing
FE4_QA_Status= Approved
FE4_OrderNo= 1
FE4_ProductNo= 2
FE4_TopCase_ID= 3
FE4_BottomCase_ID= 3
FE4_Coupled= 0
FE4_Treated= 0
FE4_location= *.Models.Model.BottomStation
FE4_CP_Status= Processing
FE4_destination= *.Models.Model.PressStation
FE4_destination_iOpNo= 0

(c) Product DT model showing all 4 workpieces in production

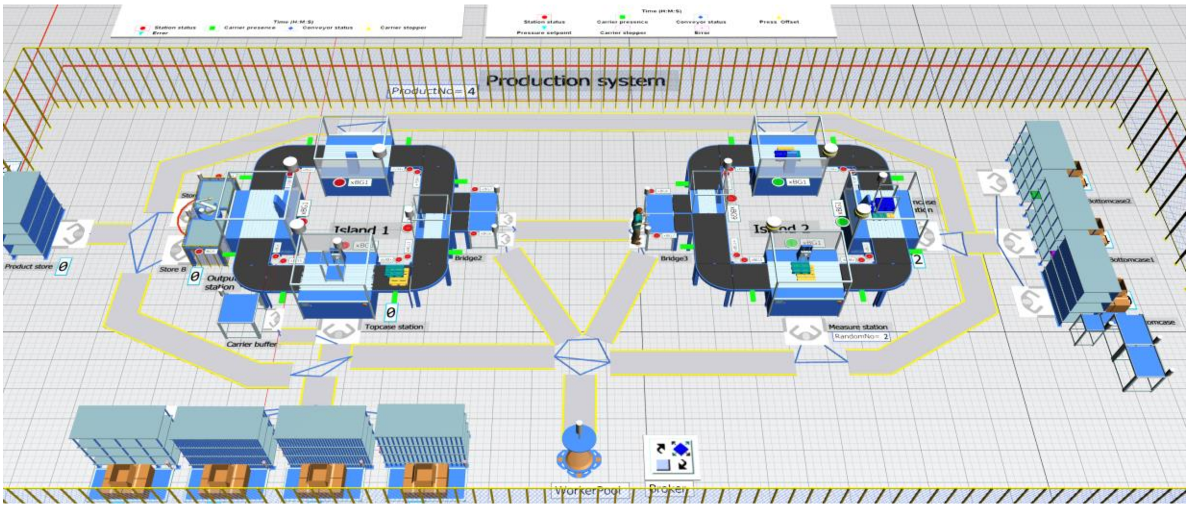
Figure 5.13: Product DT of the Festo CP smart factory

(c) *Process DT*

Using the available modelling elements of the DT platform, the production system was modelled consisting of the 4MIE components (man, machine, material, method and its operating environment). These include the workstations, robots, operators, logistic networks and digital connections like the sensors and actuators. Figure 5.14 presents the process DT with virtual sensors and state indicators showing active states when green. The model is designed to simulate four variable products. During Offline simulation, this variability is initiated in the virtual MES. In an Online simulation, details on the product and production plan are transferred to the DT during production.



(a) 2D view



(b) 3D view

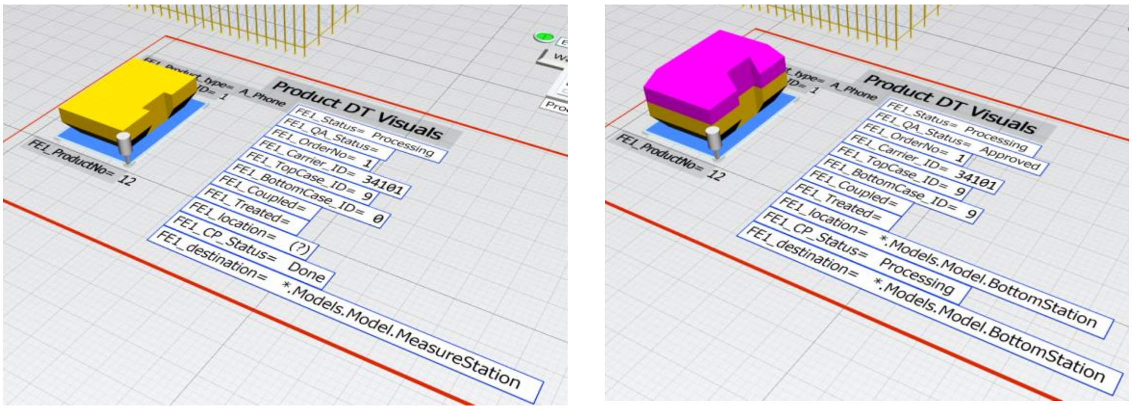
Figure 5.14: Festo CP smart factory DT model

5.6.4 An integrated product-process digital twin of the Festo CP system

Integration in production systems was considered under the following categories: physical asset integration, virtual space integration (product and process DT), and physical-virtual space integration. The physical asset is a CPPS.

(a) Connecting the product DT to the product

The physical product is connected to its DT using the RFID technique in conjunction with the OPC_UA connection. The RFID technique enables product/part tracking, and product-related generated data to be stored and passed on along the production line in real-time. Extracted RFID data makes it possible to track the production flow and update the DT with reliable real-time operational information. As shown in Figure 5.15, when the physical product is assembled, its virtual counterpart is updated as it passes through the production line.



FE1_Product_type= A_Phone
ID= 1
FE1_ProductNo= 12
FE1_Status= Processing
FE1_QA_Status=
FE1_OrderNo= 1
FE1_Carrier_ID= 34101
FE1_TopCase_ID= 9
FE1_BottomCase_ID= 0
FE1_Coupled=
FE1_Treated=
FE1_location= (?)
FE1_CP_Status= Done
FE1_destination= *.Models.Model.MeasureStation

_type= A_Phone
ID= 1
FE1_ProductNo= 12
FE1_Status= Processing
FE1_QA_Status= Approved
FE1_OrderNo= 1
FE1_Carrier_ID= 34101
FE1_TopCase_ID= 9
FE1_BottomCase_ID= 9
FE1_Coupled=
FE1_Treated=
FE1_location= *.Models.Model.BottomStation
FE1_CP_Status= Processing
FE1_destination= *.Models.Model.BottomStation

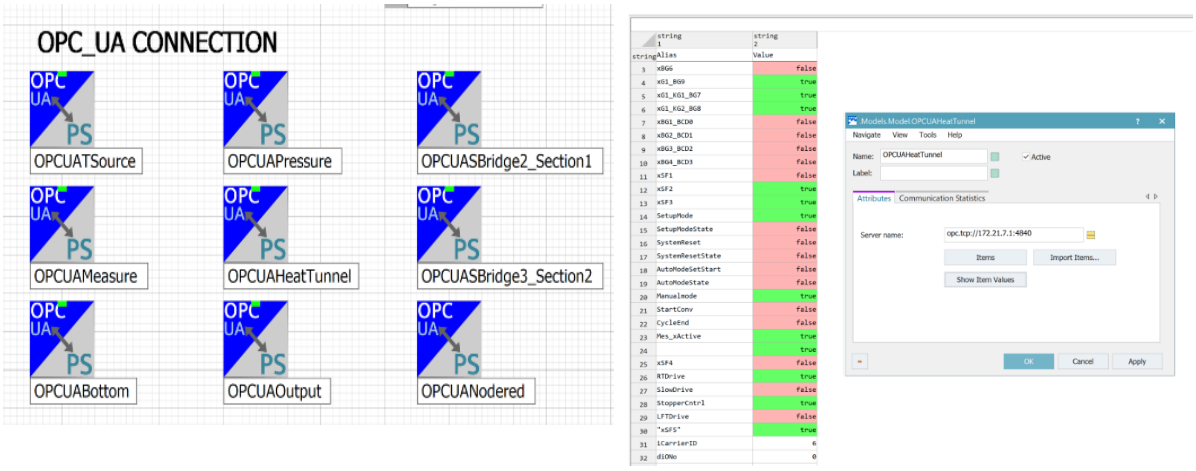
(a) (b)

Figure 5.15: (a) Top case loaded on the carrier at Topcase station (b) Bottomcase mounted on Topcase at Bottom station

(b) Connecting the process twin to the physical system

The process DT comprises simulation models whose granularities were defined by the functionalities and modular structure identified within the physical system. It was built based on the identified processes to be digitised, accessible operational data, and process behaviour/functionalities to be modelled/visualised.

The communication system of the physical system is built on TCP/IP/Ethernet protocol. Upon this communication structure, the OPC_UA protocol provides a standardised and robust channel to establish a bidirectional communication link, generate and transmit data in a unified format irrespective of the source/vendor. Based on a server-client structure, the physical system is configured to be a server and the DT a client (Figure 5.16a). Both communicate via the OPC_UA table (information model). (Figure 5.16b). These tables are a list of dynamic tags of the physical system mapped to virtual alias called in the virtual space. A change in the values or states of these tags is used to trigger virtual activities. Also, virtual activities can be used to update the values/states of these tags which in turn trigger activities within the physical systems. (This reverse path was explored for virtual control of the asset in the next chapter).



	string 1	string 2
string	Alias	Value
3	xBG6	false
4	xG1_BG9	true
5	xG1_KG1_BG7	true
6	xG1_KG2_BG8	true
7	xBG1_BCD0	false
8	xBG2_BCD1	false
9	xBG3_BCD2	false
10	xBG4_BCD3	false
11	xSF1	false
12	xSF2	true
13	xSF3	true
14	SetupMode	true
15	SetupModeState	false
16	SystemReset	false
17	SystemResetState	false
18	AutoModeSetStart	false
19	AutoModeState	false
20	Manualmode	true
21	StartConv	false
22	CycleEnd	false
23	Mes_xActive	true
24		true
25	xSF4	false
26	RTDrive	true
27	SlowDrive	false
28	StopperCntrl	true
29	LFTDrive	false
30	"xSF5"	true
31	iCarrierID	6
32	diONo	0

Name: OPCUAHeatTunnel ☑ Active

Label:

Server name: opc.tcp://172.21.7.1:4840

(a) (b)

Figure 5.16: (a) OPC_UA interfaces for each workstation and (b) Real-time interaction. Green values indicate an active change in status

Figure 5.17 presents a structured operational data flow from the asset to the DT. It also shows the structured real-time influence of the physical asset on the simulation behaviour of the DT, resulting in real-time synchronised interaction between the asset-twin during production online simulation.

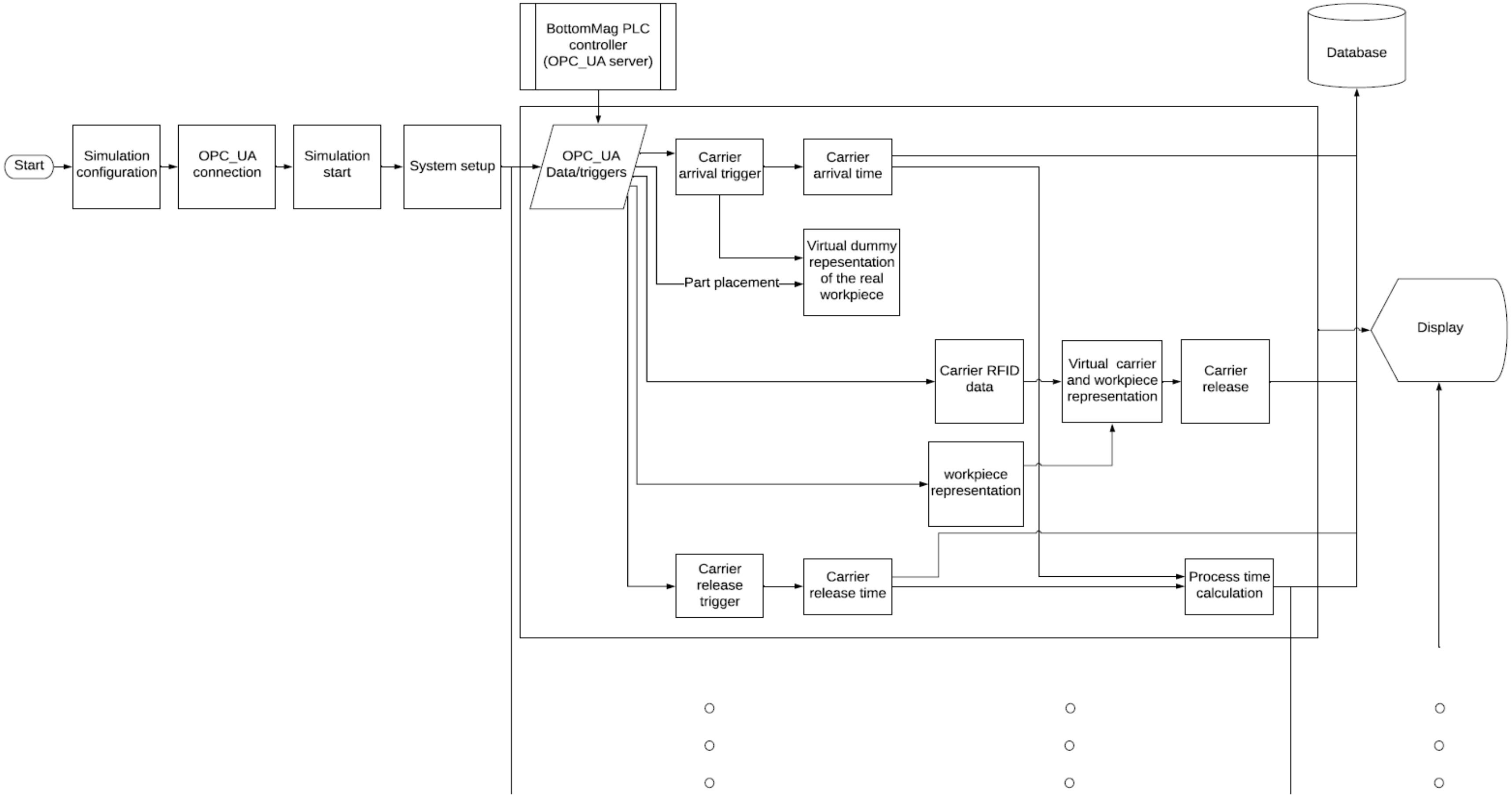
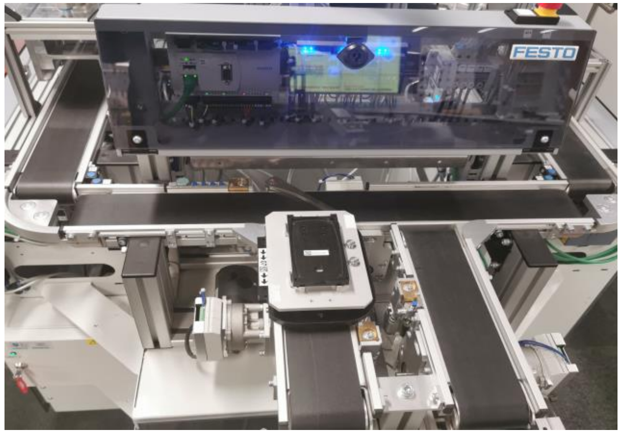
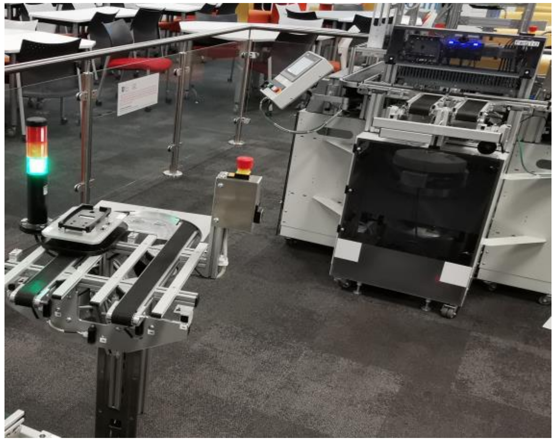


Figure 5.17: Functional flowchart showing a real-time structured operational data flow from the physical asset that influences the real-time synchronised behaviour of the DT.

Figure 5.18 presents captured DT online behaviour mirroring the physical asset's activity instances during production.

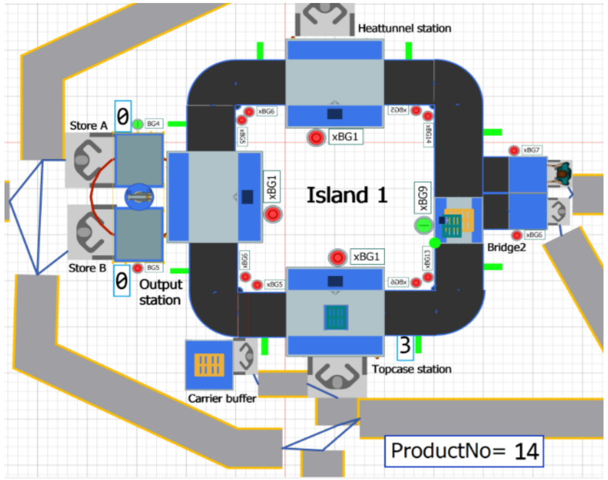


Transfer bridge 2

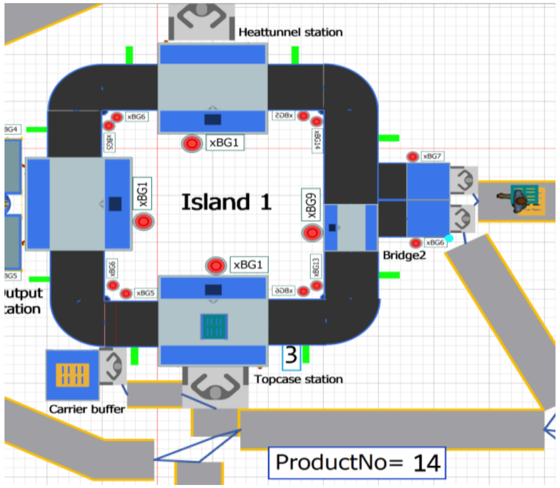


Robotiono

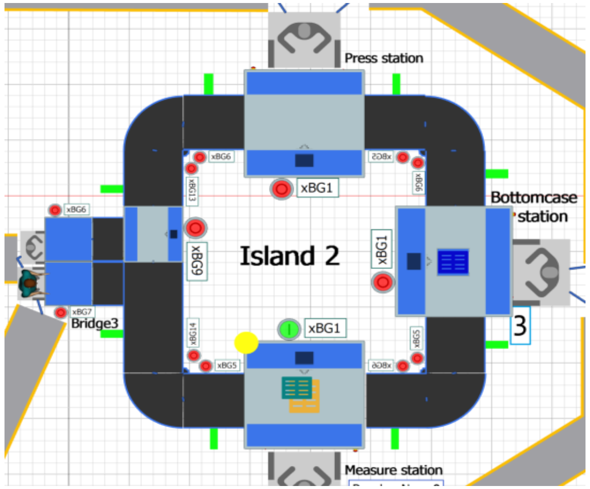
Measure station



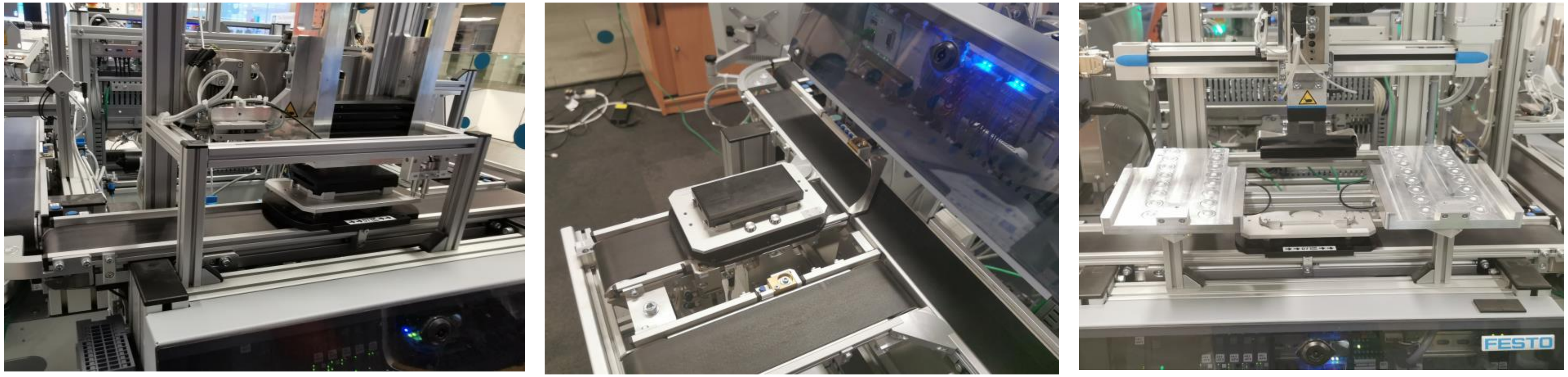
(a) Workpiece at the Transfer bridge



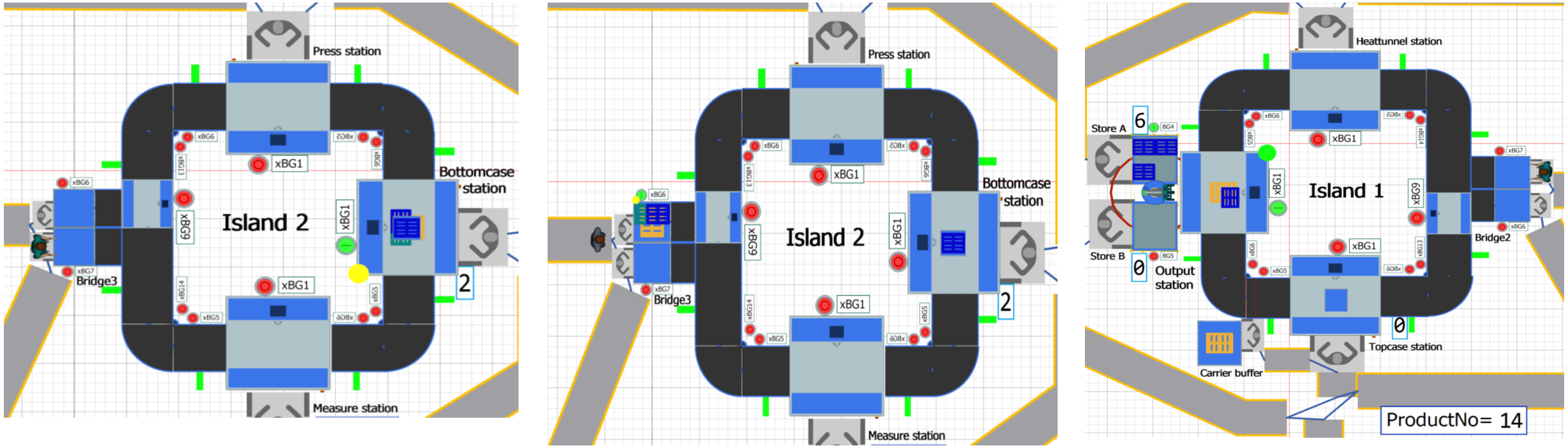
(b) Workpiece transported by Robotino



(c) Workpiece in Measure station



Bottomcase station Transfer bridge 3 Output station

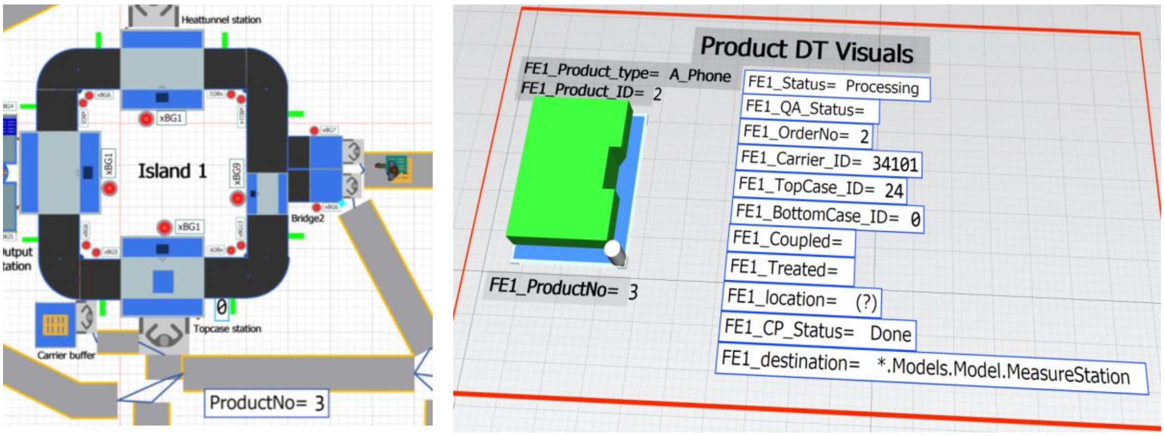


(d) Workpiece in Bottomcase station (e) Workpiece at the Transfer bridge 3 (f) Finished product in Output station

Figure 5.18: Real-time synchronised interaction between asset-twin. DT behaviours triggered by actual physical twin activities

(c) Connecting the product twin to the process twin

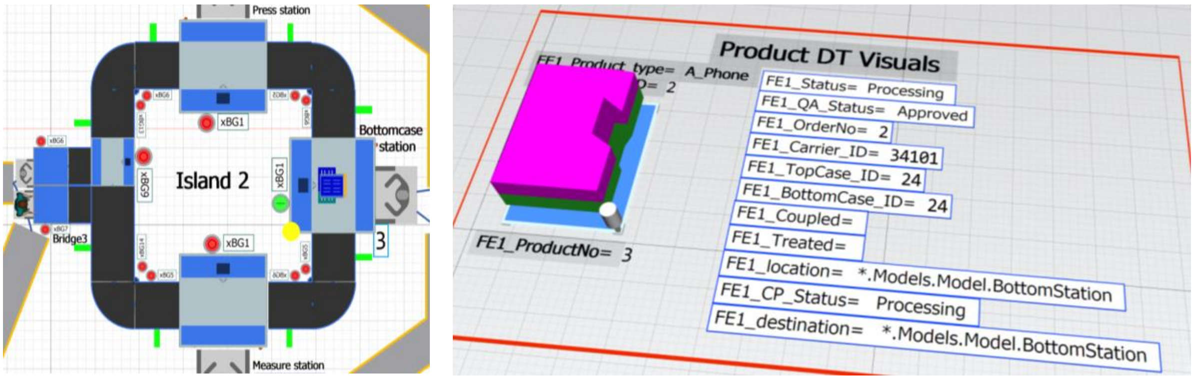
A product type determines its production work plan which is a description of the product attributes and the configuration of its production flow. This also gives details of the resources to be used (workstations, processes and respective process attributes). For example, heating temperature setpoint, drilling depth and processing time. In the virtual space, the product DT's properties are mapped to the related processes that are responsible for adding them to the product. This plays a key role in the data structure created within the DT database. Figure 5.19 shows the assembling of the product DT as the workpiece travels along the process DT.



ProductNo= 3

FE1_Product_type= A_Phone
FE1_Product_ID= 2
FE1_ProductNo= 3
FE1_Status= Processing
FE1_QA_Status=
FE1_OrderNo= 2
FE1_Carrier_ID= 34101
FE1_TopCase_ID= 24
FE1_BottomCase_ID= 0
FE1_Coupled=
FE1_Treated=
FE1_location= (?)
FE1_CP_Status= Done
FE1_destination= *.Models.Model.MeasureStation

(a) The carrier transporting TopCase. This is reflected in the product DT



FE1_Product_type= A_Phone
FE1_Product_ID= 2
FE1_ProductNo= 3
FE1_Status= Processing
FE1_QA_Status= Approved
FE1_OrderNo= 2
FE1_Carrier_ID= 34101
FE1_TopCase_ID= 24
FE1_BottomCase_ID= 24
FE1_Coupled=
FE1_Treated=
FE1_location= *.Models.Model.BottomStation
FE1_CP_Status= Processing
FE1_destination= *.Models.Model.BottomStation

(b) Carrier loaded with both Topcase and Bottomcase. This is reflected in the product DT

Figure 5.19: Simulation showing coordination between process and product DTs to build product DT

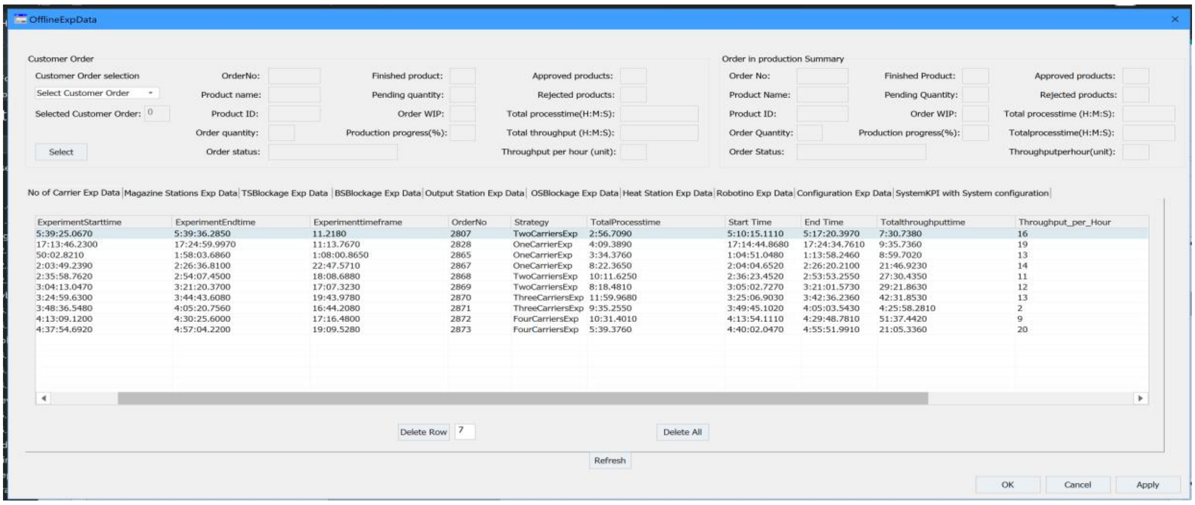
A relational rule model based on the dependency rule was used to map the product DT data to the relevant process data. This model manages the workpiece path through the process DT and the formation of the production data.

5.6.5 Simulation results and discussion

This section presents the results of both offline and online simulations. The real system configuration was extracted and used to set up the model for offline simulation.

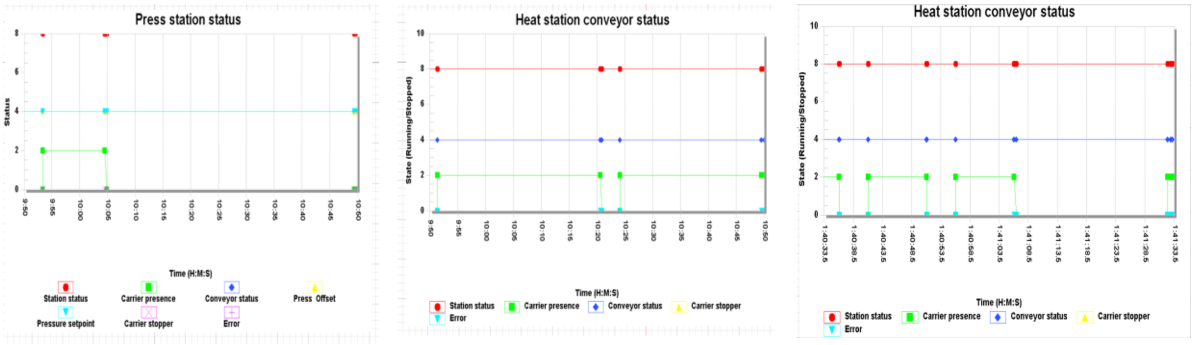
(a) Offline simulation (Experimentation and analysis)

The offline simulation results in Figure 5.20 shows the behaviour of the production systems when certain parameters are changed. In this case, the number of carriers in operation varied between 1, 3 & 4. Figure 5.20a shows system performance in terms of Throughput-per-Hour and Total throughput-time. Figure 5.20(b-g) presents the traffic flow during production, and Figure 5.20(h-j) shows the distance covered by the robot and operator. Observably, the robot works more with an increased number of carriers. Lastly, Figure 5.20(k-p) presents the stations' operational usage as (The portion of states) during production.



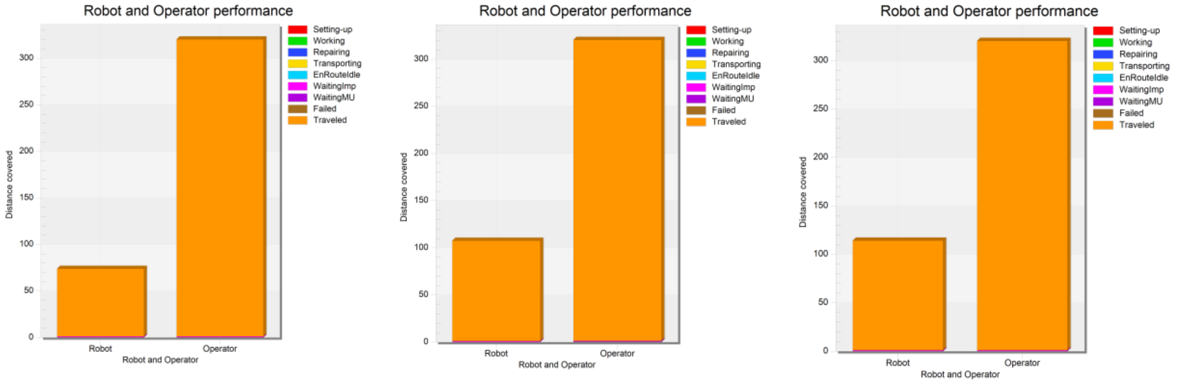
ExperimentStarttime	ExperimentEndtime	Experimenttimeframe	OrderNo	Strategy	TotalProcesstime	Start Time	End Time	Totalthroughputtime	Throughput_per_Hour
5:39:25.0670	5:39:36.2850	11.2180	2807	TwoCarriersExp	2:56.7090	5:10:15.1110	5:17:20.3970	7:30.7380	16
17:13:46.2300	17:24:59.9970	11:13.7670	2828	OneCarrierExp	4:09.3890	17:14:44.8680	17:24:34.7610	9:35.7360	19
50:02.8210	1:58:03.6860	1:08:00.8650	2865	OneCarrierExp	3:34.3760	1:04:51.0480	1:13:58.2460	8:59.7020	13
2:03:49.2390	2:26:36.8100	22:47.5710	2867	OneCarrierExp	8:22.3650	2:04:04.6520	2:26:20.2100	21:46.9230	14
2:35:58.7620	2:54:07.4500	18:08.6880	2868	TwoCarriersExp	10:11.6250	2:36:23.4520	2:53:53.2550	27:30.4350	11
3:04:13.0470	3:21:20.3700	17:07.3230	2869	TwoCarriersExp	8:18.4810	3:05:02.7270	3:21:01.5730	29:21.8630	12
3:24:59.6300	3:44:43.6080	19:43.9780	2870	ThreeCarriersExp	11:59.9680	3:25:06.9030	3:42:36.2360	42:31.8530	13
3:48:36.5480	4:05:20.7560	16:44.2080	2871	ThreeCarriersExp	9:35.2550	3:49:45.1020	4:05:03.5430	4:25:58.2810	2
4:13:09.1200	4:30:25.6000	17:16.4800	2872	FourCarriersExp	10:31.4010	4:13:54.1110	4:29:48.7810	51:37.4420	9
4:37:54.6920	4:57:04.2200	19:09.5280	2873	FourCarriersExp	5:39.3760	4:40:02.0470	4:55:51.9910	21:05.3360	20

(a) Simulation data including production performance

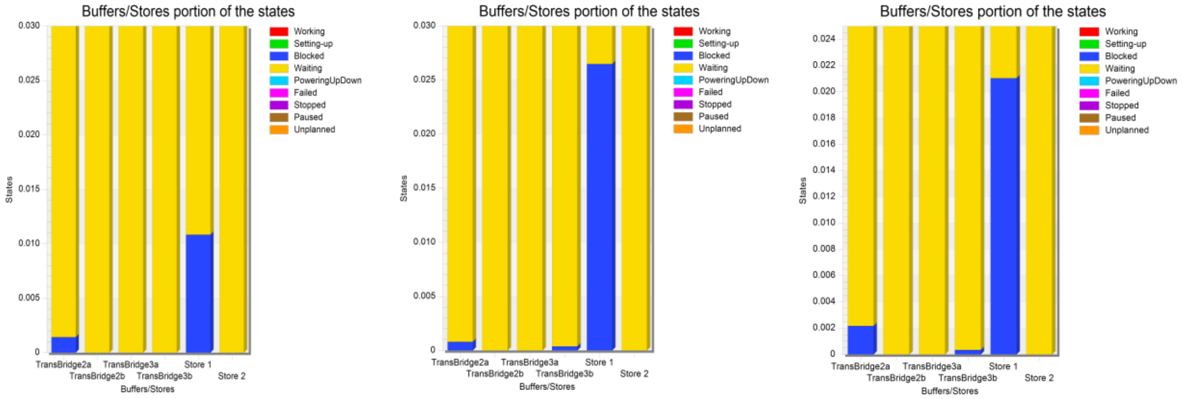


(b) 1 carrier in operation (c) 2 carriers in operation (d) 4 carriers in operation

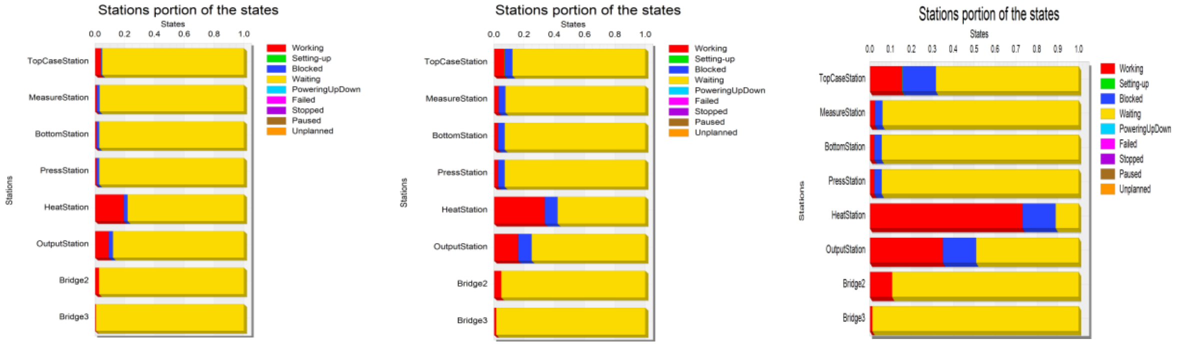
(e) 1 carrier in operation (f) 2 carriers in operation (g) 4 carriers in operation



(h) 1 carrier in operation (i) 2 carriers in operation (j) 4 carriers in operation



(k) 1 carrier in operation (l) 2 carriers in operation (m) 4 carriers in operation

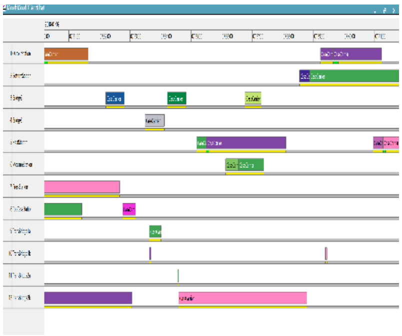


(n) 1 carrier in operation (o) 2 carriers in operation (p) 4 carriers in operation

Figure 5.20: Simulation results and analyses using asset configuration

(b) Online simulation (Production real-time monitoring and operational data extraction)

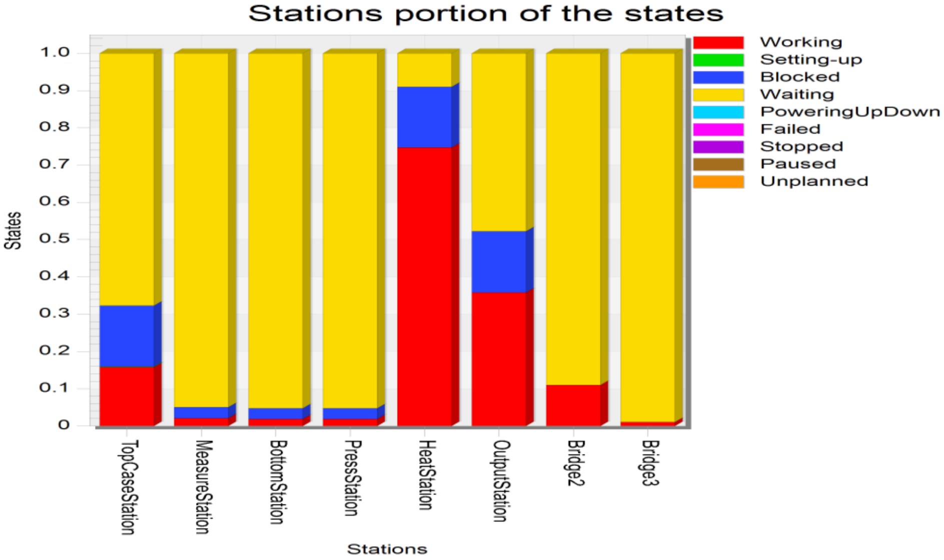
Statistical and analytical tools of the DT were used to observe the behaviour of the physical asset. Figure 5.21 presents the observable behaviour of the asset. Figures 5.21 (a-c) present Gantt charts showing the production flow traffic when the number of carriers is varied. Figure 5.21d presents the stations' operational usage as (The portion of states) during production, and Figure 5.21e presents the template used for extracting the asset configuration data. Figure 5.21f presents a summary of the asset performance during a production cycle and Figure 5.21g presents an extract of the production data linking the product instances to all associated production data.



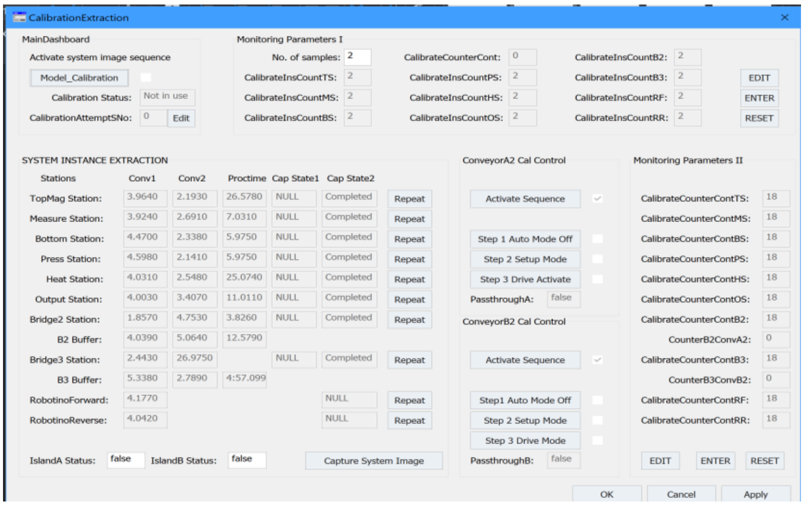
(a) 1 carrier

(b) 3 carriers

(c) 4 carriers



(d) Workstations utilisation during production



Calibration Status: Not in use
CalibrationAttemptSNo: 0

No. of samples: 2
CalibrateInsCountTS: 2
CalibrateInsCountMS: 2
CalibrateInsCountBS: 2
CalibrateCounterCont: 0
CalibrateInsCountPS: 2
CalibrateInsCountHS: 2
CalibrateInsCountOS: 2
CalibrateInsCountB2: 2
CalibrateInsCountB3: 2
CalibrateInsCountRF: 2
CalibrateInsCountRR: 2

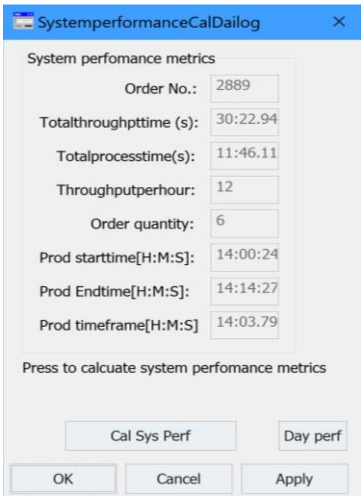
Stations	Conv1	Conv2	Proctime	Cap State1	Cap State2	
TopMag Station:	3.9640	2.1930	26.5780	NULL	Completed	Repeat
Measure Station:	3.9240	2.6910	7.0310	NULL	Completed	Repeat
Bottom Station:	4.4700	2.3380	5.9750	NULL	Completed	Repeat
Press Station:	4.5980	2.1410	5.9750	NULL	Completed	Repeat
Heat Station:	4.0310	2.5480	25.0740	NULL	Completed	Repeat
Output Station:	4.0030	3.4070	11.0110	NULL	Completed	Repeat
Bridge2 Station:	1.8570	4.7530	3.8260	NULL	Completed	Repeat
B2 Buffer:	4.0390	5.0640	12.5790			
Bridge3 Station:	2.4430	26.9750		NULL	Completed	Repeat
B3 Buffer:	5.3380	2.7890	4:57.099			
RobotinoForward:	4.1770				NULL	Repeat
RobotinoReverse:	4.0420				NULL	Repeat

IslandA Status: false
IslandB Status: false

PassthroughA: false
PassthroughB: false

CalibrateCounterContTS: 18
CalibrateCounterContMS: 18
CalibrateCounterContBS: 18
CalibrateCounterContPS: 18
CalibrateCounterContHS: 18
CalibrateCounterContOS: 18
CalibrateCounterContB2: 18
CounterB2ConvA2: 0
CalibrateCounterContB3: 18
CounterB3ConvB2: 0
CalibrateCounterContRF: 18
CalibrateCounterContRR: 18

(e) Template used for system configuration data extraction

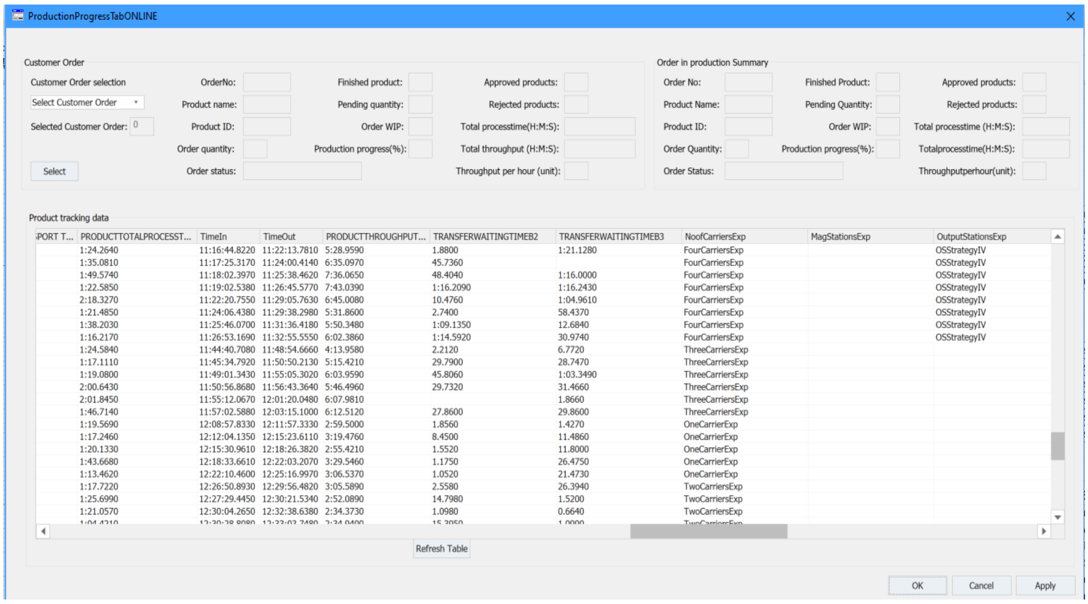


System perfomance metrics

Order No.: 2889
Totalthroughpttime (s): 30:22.94
Totalprocesstime(s): 11:46.11
Throughputperhour: 12
Order quantity: 6
Prod starttime[H:M:S]: 14:00:24
Prod Endtime[H:M:S]: 14:14:27
Prod timeframe[H:M:S] 14:03.79

Press to calcuate system perfomance metrics

(f) System performance



Selected Customer Order: 0

Product tracking data

PORT T...	PRODUCTTOTALPROCESST...	TimeIn	TimeOut	PRODUCTTHROUGHPUT...	TRANSFERWAITINGTIMEB2	TRANSFERWAITINGTIMEB3	NoofCarriersExp	MagStationsExp	OutputStationsExp
	1:24.2640	11:16:44.8220	11:22:13.7810	5:28.9590	1.8800	1:21.1280	FourCarriersExp		OSStrategyIV
	1:35.0810	11:17:25.3170	11:24:00.4140	6:35.0970	45.7360		FourCarriersExp		OSStrategyIV
	1:49.5740	11:18:02.3970	11:25:38.4620	7:36.0650	48.4040	1:16.0000	FourCarriersExp		OSStrategyIV
	1:22.5850	11:19:02.5380	11:26:45.5770	7:43.0390	1:16.2090	1:16.2430	FourCarriersExp		OSStrategyIV
	2:18.3270	11:22:20.7550	11:29:05.7630	6:45.0080	10.4760	1:04.9610	FourCarriersExp		OSStrategyIV
	1:21.4850	11:24:06.4380	11:29:38.2980	5:31.8600	2.7400	58.4370	FourCarriersExp		OSStrategyIV
	1:38.2030	11:25:46.0700	11:31:36.4180	5:50.3480	1:09.1350	12.6840	FourCarriersExp		OSStrategyIV
	1:16.2170	11:26:53.1690	11:32:55.5550	6:02.3860	1:14.5920	30.9740	FourCarriersExp		OSStrategyIV
	1:24.5840	11:44:40.7080	11:48:54.6660	4:13.9580	2.2120	6.7720	ThreeCarriersExp		
	1:17.1110	11:45:34.7920	11:50:50.2130	5:15.4210	29.7900	28.7470	ThreeCarriersExp		
	1:19.0800	11:49:01.3430	11:55:05.3020	6:03.9590	45.8060	1:03.3490	ThreeCarriersExp		
	2:00.6430	11:50:56.8680	11:56:43.3640	5:46.4960	29.7320	31.4660	ThreeCarriersExp		
	2:01.8450	11:55:12.0670	12:01:20.0480	6:07.9810		1.8660	ThreeCarriersExp		
	1:46.7140	11:57:02.5880	12:03:15.1000	6:12.5120	27.8600	29.8600	ThreeCarriersExp		
	1:19.5690	12:08:57.8330	12:11:57.3330	2:59.5000	1.8560	1.4270	OneCarrierExp		
	1:17.2460	12:12:04.1350	12:15:23.6110	3:19.4760	8.4500	11.4860	OneCarrierExp		
	1:20.1330	12:15:30.9610	12:18:26.3820	2:55.4210	1.5520	11.8000	OneCarrierExp		
	1:43.6680	12:18:33.6610	12:22:03.2070	3:29.5460	1.1750	26.4750	OneCarrierExp		
	1:13.4620	12:22:10.4600	12:25:16.9970	3:06.5370	1.0520	21.4730	OneCarrierExp		
	1:17.7220	12:26:50.8930	12:29:56.4820	3:05.5890	2.5580	26.3940	TwoCarriersExp		
	1:25.6990	12:27:29.4450	12:30:21.5340	2:52.0890	14.7980	1.5200	TwoCarriersExp		
	1:21.0570	12:30:04.2650	12:32:38.6380	2:34.3730	1.0980	0.6640	TwoCarriersExp		

(g) Extracted production data. Integrated product-process data

Figure 5.21: Simulation results and analyses of the asset in real-time

The next phase included implementing the product-centric control method using control functionalities/loops that harnesses this product-process relationship to achieve data-driven control. This added process reconfiguration flexibility makes it possible for the product DT to manage its production, including product customisation.

5.7 Discussion

The proposed dependency rule presented the logical connection of the product attributes to the services of the production system. Modelling this in the DT creates a two-way interaction whereby the product DT can be used to reconfigure the production system to achieve product customisation. In reverse, the product quality can be monitored and production managed. The dynamic interaction between the assets-twin was addressed with the proposition of a virtual access node. These are seen as tangible nodes/access points with data structure and communication protocols for standardised interaction with the functional unit. A status-change protocol is modelled to keep the interaction near-real-time as changes in observable parameters are updated in all connected loops. It is near-real-time because there is a lagging digital representation due to the transmission speed of the network and simulating platform. The OPC_UA protocol equipped with this functionality in conjunction with programming codes used to subscribe or publish parameter status was used in the case study to achieve an interactive online simulation.

In a traditional simulation model, simulation parameters are a product of statistical and engineering estimations. As shown in the case study, with the synchronised connection of a DT, these simulation parameters are gotten automatically from the physical asset. On the other hand, during online simulations, analytical results can be used to manage/monitor production. For an integrated product-process environment, part tracking was achieved using the communication structure of the processes in conjunction with the RFID technique thus, the virtual product is updated intermittently as it moves from one process/station to another. Whatever value has been added to the physical product through processing is reflected on the virtual product via the link established with the virtual process. Geometric product variations were represented in the product DT using colourations and the size of product parts (Figures 5.15 & 5.19). Online simulations/analytics constructively present the production performance, and product quality evaluations can be done to reduce waste due to quality assurance procedures. For instance, from the case study, workpieces not properly placed are identified and taken out before completing the production cycle. More orders are timely made to replace such faulted workpieces.

A closed-loop interactive integrated DT was developed for the Festo CP smart factory. The forward direction of the bidirectional communication established between the asset-twin has been utilised to mirror the production system for monitoring/supervisory purposes, real-time operational data collection and analytics. The DT of the Festo CP system is a real-time synchronised closed-loop integrated product-process DT. Its online simulation is managed using operational data and should be able to execute virtual control/management of the physical asset. The product-process DT integration was achieved using a collaboration mechanism that defines and manages the logical dependency of the product on its production processes. The process services were mapped to the respective product attributes they influence. Product and production data are logically connected such that the product is progressively built during production and in reverse, the product DT can influence the system configuration based on product specifications.

The next phase of the project would be to upgrade the current DT functionalities to an immersive predictive DT. The plan includes an extension of their functionalities to real-time control from the virtual space, including a more robust data layer to implement real-virtual data fusion and product-centric control. This would consider the complexities and uncertainties experienced in real manufacturing environments and possesses decision-making capabilities.

5.8 Summary

The work presented here contributes to the modelling of the production system and its product as an integrated DT to primarily harness the logical relationship between the product and its production processes. This modelled process-product dependency was used as a collaborative mechanism between the product and process DTs. To achieve a synchronised interactive simulation between the asset-twin, a real-time synchronisation mechanism was proposed. The virtual access to these logical interdependencies provides more control over the metrics that contribute to the quality of the product and the management of the resources. With the integration of the product and process asset-twin, production can be actively monitored such that under-delivered services and their impact on the flow entity can be identified on time and reviewed. Also, product customisation can be implemented without necessarily obstructing operations. Model standardization/specifications stand out to be a way forward to eliminate heterogeneity in generated data (Onaji et al., 2022). Data and resource integration within the cyber-physical space would allow for components to share resources and collaborate to improve system performance.

Having created an active bidirectional communication link that supports real-time interaction and data collation, strategies that would support the asset-twin control integration (cyber-physical control structure) needed to be explored. This would be good to test control strategies like the product-centric control method using control functionalities/loops that harness this product-process relationship to achieve data-driven control. This would add process reconfiguration flexibility that makes it possible for the product DT to manage its production, including product customisation.

CHAPTER VI: DIGITAL TWIN CYBER-PHYSICAL CONTROL STRUCTURE

This chapter presents a proposed cyber-physical control structure for a CPPS DT and an implementation strategy. The framework integrates the DT control structure with the physical asset's control system over a real-time bidirectional communication link. Equipped with the logical connection for virtual control of the physical asset, the integrated DT can execute real-time control, production management and product customisation. A case study was presented as applicative evidence of the usefulness of the cyber-physical control structure in production management and product customisation.

6.1 Research novelty and contribution

The integration at the control level is also a digital twin expectation that needs attention. Achieving this has been a challenge due to the lack of implementation methods. This research makes its contribution by proposing a novel cyber-physical control that supports the following:

- Virtual control strategies for manufacturing
- Real-time analyses for production performance improvement and data-driven control
- Real-time product customisation using the product-centric control method

This proposed cyber-physical control structure using closed-control loops at multiple granularities would integrate and expand the control system to support collaborative control between the asset-twin. This equips the DT to influence production in real-time and as a decision-support system executes control/production decisions based on analytical results.

6.2 System control identification

This section presents the procedure for the systems control identification and modelling adopted in this research.

6.2.1 Industrial control structures

According to IEC62264-3, the manufacturing control system has five functional levels. Represented using the ISA95 automation pyramid (Figure 6.1) they include the field, direct control, plant supervisory, production and production scheduling levels (Rojko, 2017). The field level consists of field devices like sensors and control elements such as actuators, drives and control valves. The control level contains controllers like PLCs and microcontrollers with associated input/output modules. The plant supervisory levels equipped with the MES, consist of computers that collect information from the control level and give access to the operator. The production control and scheduling levels are the ERP levels. They do not directly control the production processes but are concerned with high-level tasks like production management, monitoring and scheduling (Zezulka et al., 2016).

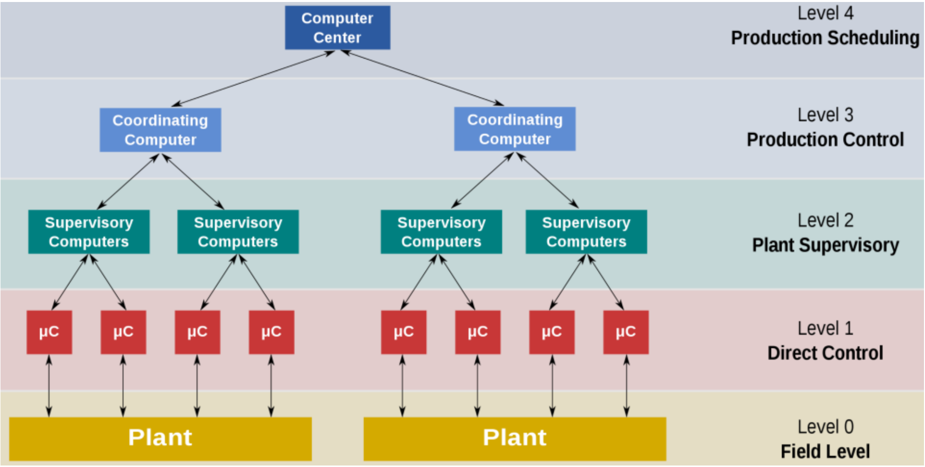


Figure 6.1: Manufacturing control system showing five functional levels (ISA95 automation pyramid). Source (Wikimedia, 2014)

For continuously modulated control, a feedback controller is used to automatically control a process or operation. The control system compares the value or status of the process variable (PV) being controlled with the desired value or setpoint (SP) and applies the difference as a control signal to bring the process variable output to the same value as the setpoint.

6.2.2 Physical control structure

Key to the development of this control system is the identification of macro-control functionalities and the disintegration of these macro entities to the least possible independent micro-entities/control subroutines/functionalities.

(a) Control parameters (I/O)

The functional controller can be modelled as shown in Figure 6.2. This presents the controller in terms of its control input parameters, control function/algorithm and output parameters. Its functionality defines the service/task it renders. This could be as simple as switching ON/OFF a power supply or a routine that automates a process or series of processes.

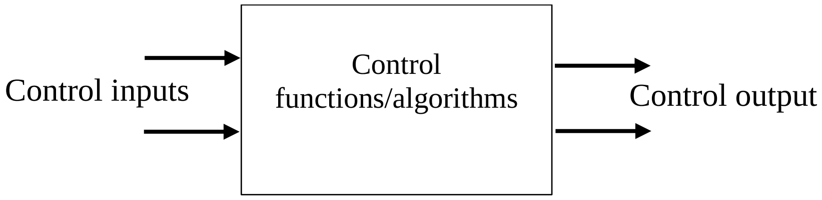


Figure 6.2: Schematics of a basic model of a controller

(b) Control algorithms(routines/functions)

The controller functionality is a composition of sub-functions/routines with inputs and outputs. From Figure 6.3, it can be seen that the controller algorithm could be a composition of subroutines/functions, of which some could be independent of one another and/or are interdependent such that subroutine outputs, can become inputs to other subroutines. Its functionality can be expanded to create independent sub-functions based on defined services/tasks/purposes.

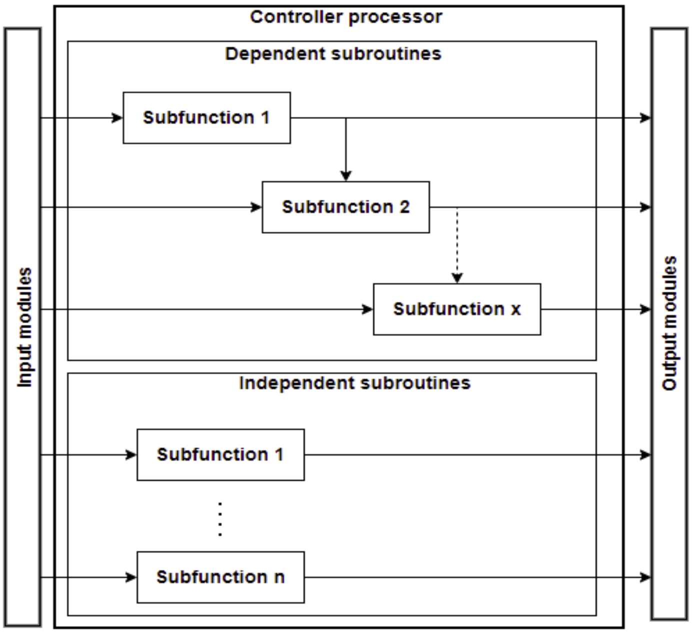


Figure 6.3: A more detailed model of a controller showing subroutines.

(c) Digital access

To describe the digital access of the control system, the discrete control structure of a distributed control network can be viewed from the systems and component levels. At the systems level, it is visualised as a network of control nodes. Each unique controller is represented as a control node. This includes its functionality and input/output composition. Furthermore, a control node can be subdivided into sub-nodes which represent the subroutines and their input/out compositions.

The DT is expected to utilise the bidirectional communication established between the asset-twin. The forward direction enables the DT to access operational data for simulation and experimental analytics. The reverse direction enables the DT to implement virtual control instruction based on the results of its analytics. The absence of a real-time synchronised connection between the asset-twin makes this virtual control impossible.

The proposed collaborative mechanism equips the integrated DT with the capability to execute control/production management. It would enable real-time modification of production setup to implement variation in product specifications and manage the product quality while in production.

6.2.3 *Applicable control techniques*

i. *Implementation of the push-pull control approach:* Efficient time management and timely decision-making are paramount to the overall efficiency of the logistic operations and production management system. The real-time coupled integrated product-process DT serving as a decision-support system can provide needed information for operators and top management to observe production performance and make timely factual strategic decisions. The pull-push control approach when implemented in the DT enables it to optimise logistics as it facilitates (push) the distribution of resources based on demands (pull) and logistic network (Garetti et al., 2016). Operators can manage resources as they are demanded and consumed along the production network using up-to-date information from the production site.
ii. *Implementation of the product-centric control approach:* Product-centric control uses control instructions to manage all associated resources tagged with unique identification. It takes advantage of the dynamic interaction between the product and the process to configure the resources to be used for its production. During production, the product/workpiece directly requests materials/material handling services from service providers within the supply chain (Lyly-Yrjanainen et al., 2016). Implementing this in an integrated product-process DT equips the product DT with the capacity to

assemble/select the raw materials to be used and reconfigure the production line. This approach simplifies material handling, control, product customisation and information usage within the supply chain**.**

6.3 The proposed cyber-physical control structure for digital twin

6.3.1 Background

This research presents a cyber-physical control structure for CPPS integrated product-process DT. The integration of data and control is an expectation of digital twinning in manufacturing (Zhuang, Liu & Xiong, 2018). Integration at the control level would imply an expansion of the CPPS control structure to the virtual space. This involves the modelling of the control system of the physical asset as a component of the DT and equips the DT with control capabilities to implement data-driven control strategies based on its analytic results. At a higher level, an integrated product-process DT with such a control structure would be able to implement data-based production management strategies and also enable real-time implementation of product customisation by using the product DT to manage system configurations based on its product specifications.

6.3.2 Cyber-physical control structure

A closed-loop cyber-physical control structure (Figure 6.4) of a manufacturing DT consists of a physical control system integrated with its virtual modelled replica over a bidirectional communication protocol that supports real-time interaction, for example, the OPC_UA protocol. Identified control data and functions are linked to the respective digital replica enabling simple ON/OFF controls, system-level controls and production control strategies that can be triggered and managed from the DT and vice versa. The bidirectional communication link consists of a feedback control loop that allows for the virtual status update of executed control instructions, thus the DT is constantly aware of the physical asset's response to control.

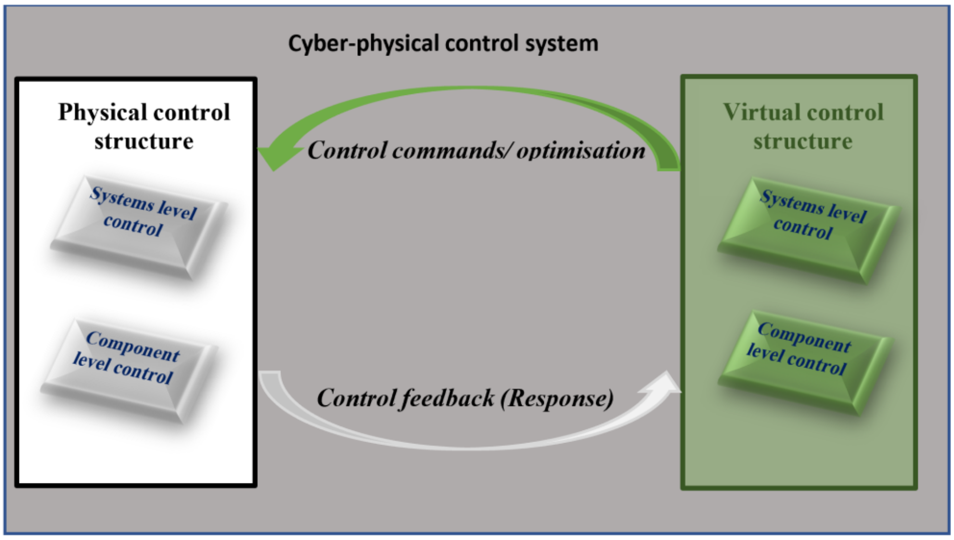


Figure 6.4: Cyber-physical control structure showing the interaction between the physical control system and virtual control structure of the digital twin

Figure 6.4 presents the proposed cyber-physical control structure/architecture. This shows the interaction between the physical control system and the virtual control structure of the DT. It integrates the first three levels of an ISA95 automation pyramid (Field level, direct control and supervisory level). Figure 6.5 presents an expanded flowchart of the proposed control structure whose design is based on the premise that the physical asset control structure is a distributed control system with each controller having a communication interface that supports bidirectional communication like the OPC_UA protocol.

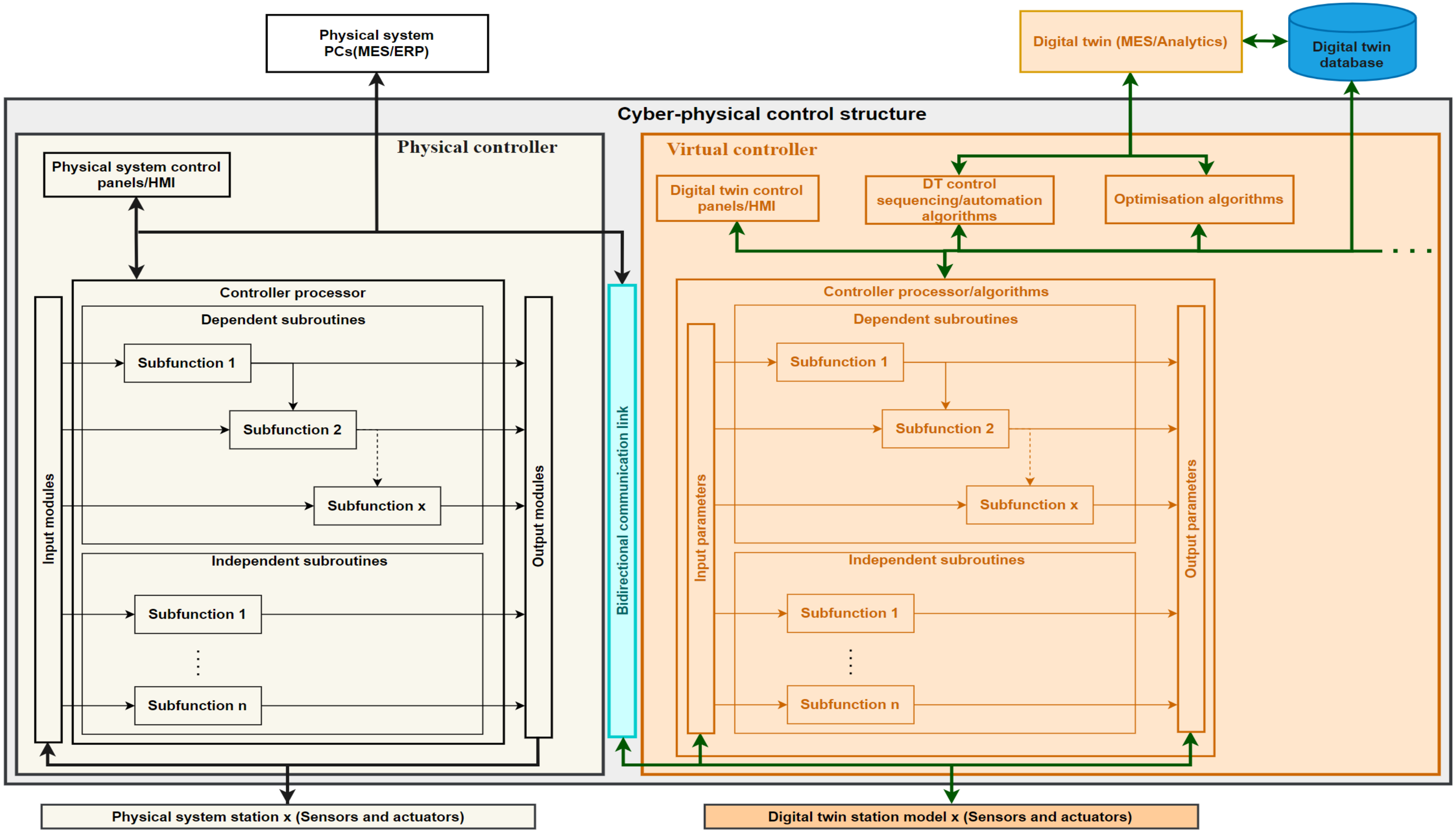


Figure 6.5: Flowchart of the CPPS cyber-physical control structure showing interconnections and communication between the asset-twin.

The physical control system is modelled as a composition of subroutines, input/output modules connected to sensors and other control elements. This virtual control structure is a composition of soft sensors and control elements like manipulators, and control algorithms with input/output parameters logically mapped to the physical asset control system. The control algorithms are a definition of all required control routines of the controller asset and an extension of other possible digital functionalities. With a real-time logical closed-loop connection between the physical control system and its virtual replica, the DT can virtually initiate control commands/routines of the controller and virtually manipulate the physical asset depending on the digital accessibility of the physical system. In return, the physical asset updates the DT with its response to control. The DT with such a control structure and operational and analytical data can support the production control task of monitoring, managing, and scheduling production resources/activities as a decision-support system.

6.3.3 Components of the cyber-physical control structure

(a) The physical control system of a cyber-physical production system

Control systems are designed to manage/regulate the behaviour of other devices/systems using control instructions. This could range from simple ON/OFF light switches to large industrial control systems used to control a network of production processes and resources. The focus here is on industrial control systems and structures that support the CPPS. The CPPS as an aggregate model of logically related scalable and modular cyber-physical systems (CPS) has a distributed control structure (DCS) (Ward et al., 2021).

Industry 4.0 proposes production lines built with cyber-physical systems. These are operational machine networks integrated with ICT components and sensors. This new paradigm of intelligent systems possesses both learning and cognitive capabilities enabling them to think, make/support decisions, autonomously execute, determine and implement improvement strategies (Rojko, 2017). Systems being able to monitor their state through their lifecycle enhances proactive maintenance strategies. This is a progressive step towards flexibility, and increased productivity with the more efficient use of resources and energy (Abramovici et al., 2018).

(b) Virtual control model

The virtual control structure of the DT is the virtual replica of the selected functionalities of the physical control system. This consist of the identified control data and functions modelled to replicate the designated behaviour and effect of the physical control system on the physical production system. In addition, it provides the extended digital functionalities defined by the DT objectives to achieve control integration, the collaboration between the asset-twin, production management and optimisation. Figure 6.6 shows the virtual control model of a distributed control system consisting of individual virtual controllers modelled with individual communication links and a centralised DT control for sequencing/automation and optimisation algorithms.

(c) Bidirectional communication link

There communication link that connects the physical asset with the DT should support real-time interaction. This is based on the premise that it operates on a communication protocol that supports a unified data structure, and standardised communication mechanism for seamless data accessibility, and interaction between elements of the cyber-physical environment. Prominent in the literature and machining industry are the OPC_UA and MTConnect protocols used in TCP/IP/Ethernet communication architectures (Pethig et al., 2017).

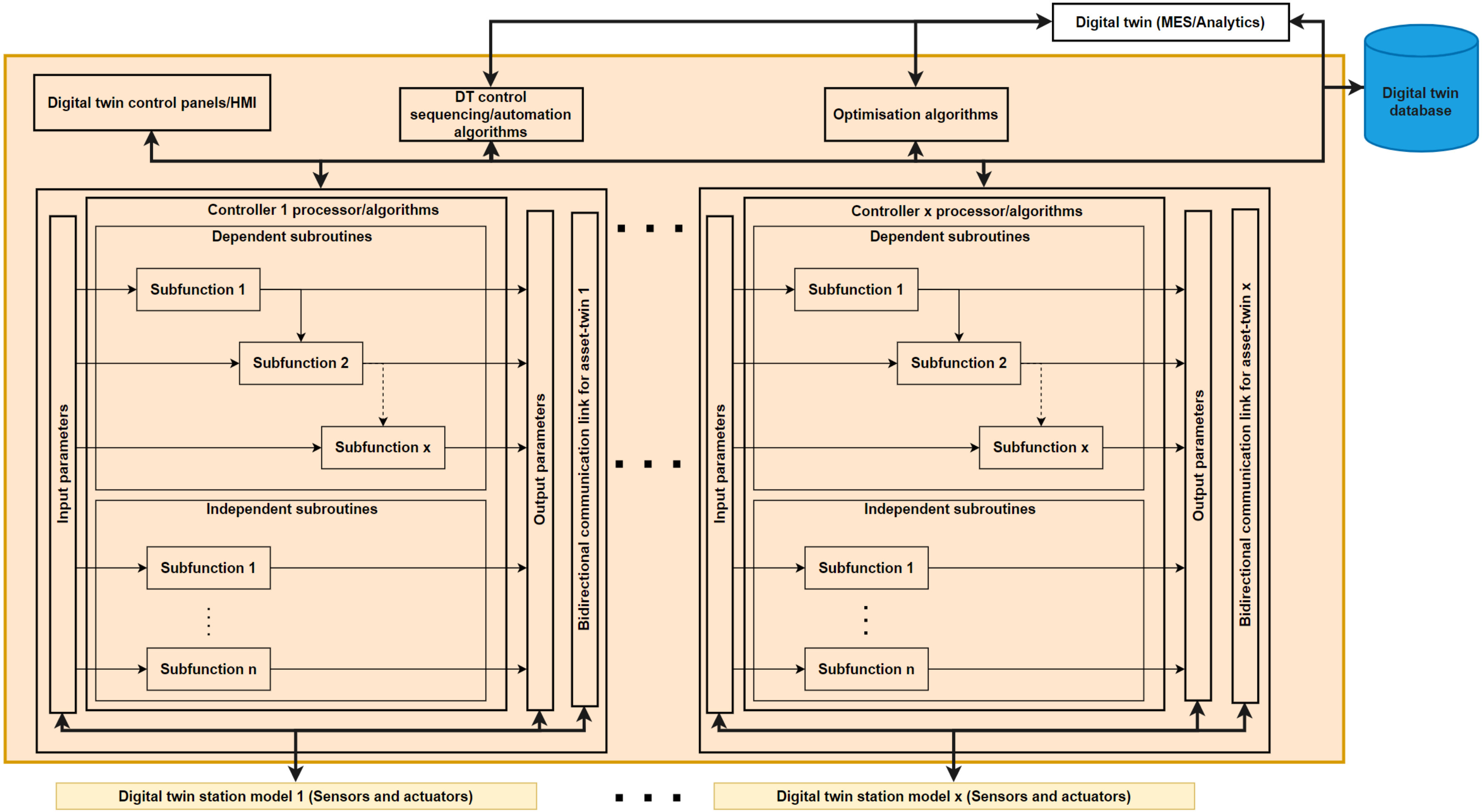


Figure 6.6: Flowchart of the virtual control structure of the DT

6.3.4 Control strategies for the cyber-physical control structure

The proposed cyber-physical control infrastructure was designed upon a bidirectional communication link. This enabled a virtual control of the physical asset and at the same time, provided a virtual representation of the control activities as the DT behaviour is manipulated in real-time by the asset behaviour. Three channels were proposed and illustrated in Figure 6.7. They include the:

(a) Forward channel

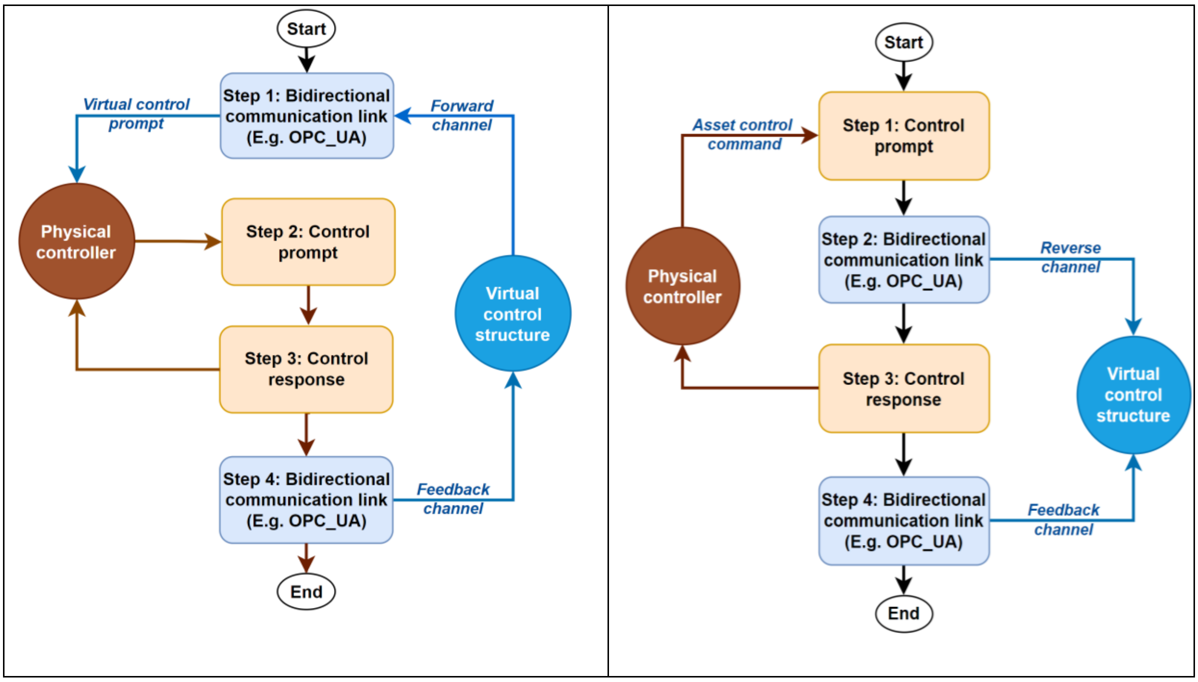
This refers to the channel through which virtual control signals are sent to the physical system controllers to initiate control at the component and systems levels. At the systems level, it is connected to the model for the automation of control routines. This can also be connected to the physical control panel for operator interaction. This is illustrated in Figure 6.7a.

(b) Reverse channel

This refers to the connection (Figure 6.7b) which informs the virtual model when a control command is triggered from the physical asset controller. This also serves as the channel through which control actions in the physical system are duplicated in the virtual model.

(c) Feedback channel

The feedback channel (Figure 6.7) is the feedback route that informs the virtual controller if a prompted control command has been executed. This is the feedback control signal from the physical system to the physical controller informing it of its response to the control command. This is vital in the management of virtual controlled automated routines as the digital twin is updated on the impact of its decisions.



(a) (b)

Figure 6.7: Diagram showing (a) The Forward channel (Asset to DT) and (b) The Reverse channel (DT to asset) between the asset control systems and the DT virtual control system

When control is triggered either from the physical controller/system or DT, the DT model gets feedback that informs it of the outcome of that control prompt. This approach keeps the cyber-physical control system updated and enables an interactive collaboration between the asset and its DT. With expert knowledge of the control program, this approach can be used to transverse through the physical asset controller structure taking into consideration the use of interlocks and control loops interdependencies.

6.3.5 Control modelling strategies for the cyber-physical control structure

To develop the proposed cyber-physical control structure of a DT that supports a CPPS, there is a need to identify the control loops (data and functionalities) of the physical system and decompose them to the least possible independent control granularities that can be modelled. The modelled virtual control structure should consist of control strategies and codes to link the physical system control to the DT and implement data-driven control strategies to manage the physical twin from the virtual platform.

The control modelling strategy involves the identification and implementation of control at the systems and component levels. The field devices (sensors and actuators) are modelled as virtual sensors and control elements, the controller is modelled using a combination of sub-functions and control inputs/outputs parameters. Three strategic levels of connection are defined within the cyber-physical control structure. (i) connection between the control parameters, (ii) connection between control routines/functions and (iii) control collaboration: the supervisory strategy by the DT to manage the production flow.

(a) Control input/output (I/O) parameters/function triggers

The first approach to integrating the asset-virtual control structure is using the control input/output parameters/function triggers. The control I/O parameters are identified and mapped between the asset-twin to give the DT access to trigger control functions in the physical controller.

(b) Duplicating control functions

The control functions are granulated to create sub-functional loops. These functions can be modelled in the DT. It can be called to execute such functions in place of the physical controller. The output of such sub-functions is updated at the output models or relevant interface where they are needed to trigger the next required control action/system response.

(c) Control collaboration: Digital twin automation/optimisation sequence

At the systems level, both control systems can work together to manage the production. With the DT being smart, it monitors the production operations like control and logistics, evaluates its performance and can assist with certain processes/functionalities/decisions to ensure the performance is optimal. The DT based on design should have production management/optimisation algorithms that can utilise real-time operational and analytical data to supervise/optimise the production processes. For instance, optimisation algorithms can be used to optimise the logistics of material flow and resource utilisation resulting in improved production performance and resource efficiency. New automation algorithm sequences can be created without disrupting the original control design/program. This saves cost in the redesign of existing infrastructures.

6.4 Methodology for developing and implementing the cyber-physical control structure

6.4.1 Identification of the level of granularities and impact on the level of system control

Identifying the least possible independent control loops has proven to be of advantage. This is because they can be reused as part of several independent control loops and are easy to debug/manage to ensure expected design/modelling objectives are met. From an object-oriented programming (OOP) perspective, the concept of encapsulation is used in the bundling/categorization of data and the control functions that operate on them to define unique DT control capabilities. This concept enables the designer to create DT functionalities that increase the capabilities of already existing control systems. For instance rearranging/creating control sequences to create new control flows.

6.4.2 Investigation of the link between the level of granularities and the use of engineering models vs data model-driven models

In pursuit of data-driven control, there are benefits to using independent control loops with related data. These benefits can be more harnessed by breaking the control routines into the least useful independent control subroutines. This enables the control system to respond to relevant data-driven instructions without obstructing other control activities/sequences. Engineering/physics models are based on engineering principles and estimations. Activities that are unique or consistent in behaviour or/and demand precise response are better represented with these physics models. For such uniqueness/consistency/precision in control response, engineering models are better. Errors due to engineering estimations can be reduced using relational operational data to support these model responses. Data-driven models generate information that informs the model of its real status, this includes operational uncertainties which help instruct the model on the most effective response. Having a distinct/unique control response to a piece of operational information is a boost to the system efficiency and optimisation strategy.

6.4.3 Control implementation between product and process digital twins

Control is necessary between the product and process DTs. The virtual control communication link creates the digital threads needed to influence/manage product quality during production monitoring. The control strategy here is based on the interdependencies between the product and its production processes. The configuration of the processes defines the product attributes, and constraints on the processes are reflected in the product attributes. Digitally, this can be in reverse, where the product DT triggers the reconfiguration of the production processes based on its defined attributes.

6.4.4 Control implementation between process DT and physical asset

The process DT configuration is a mirror of the physical asset. Its attributes (behaviour, control parameters) are mapped to its physical asset such that process reconfigurations are transferable between each other. On one hand, the DT can send control commands, change control parameter values, and trigger control sequences. On the other hand, the physical assets can update the DT with the system response to its control commands. This control feedback to the DT is used to update the DT control status. A modulated production layout enables a modulated virtual control structure. This is systematic and within a virtual environment, these distributed controllers can be managed centrally by the DT sequencing/automation/optimisation algorithms.

6.4.5 Techniques to achieve virtual control of physical assets and to update the virtual control from physical assets

The identification of all possible digital access points of the physical control systems is vital here. The first approach proposed here involved mirroring the digital access points of the physical control interfaces (for instance HMIs, pushbuttons and sensors) of the physical system. This digital connection enables the virtual controller to initiate basic control sequences permitted from such control interfaces. The second approach was to identify control functions/algorithms/sequences that can be recreated in the DT. This could involve optimisation operations where the DT in a computer would be faster or can implement more complex algorithms to improve performance/accuracy. The third approach was to identify control functions/sequences that can be triggered from the DT. For all three approaches, the input, output, interlock and safety parameters of the modelled control function(s) become digital access points for virtual control. These digital access points become digital threads with feedback channels for the asset-twin control structure. They become an extension of the physical control system(s) connected to the DT. The feedback channels inform the virtual controller of the response of the physical system. It enables the virtual controller to reflect the real status of the physical controller and the controlled aspect of the physical system on the DT.

6.4.6 Establish closed control loops at multiple granularities using real-time synchronisation between the processes and the process DT

Modern manufacturing systems with modular structures and distributed control systems facilitate categorising system compositions into meaningful controllable granularities. With a modular structure and distributed control system, control sequences can be identified and categorised into the least possible independent entity based on predefined modelling objectives/functionalities. This increases the feasibility of modelling control loops. Therefore:

- Simple control loops include start/stop, ON/OFF, activate/deactivate control sequences. More complex ones involve the automation of related process-controlled executions.
- Existing control loops can be modelled, and new control interactions between control loops and processes can be created depending on the nature of the physical system and modelling objectives.
- At the intelligent level, automated control sequences and data-driven control can be implemented. The distributed control network can be managed centrally resulting in dependencies among the station behaviours.
- The DT at the control level is an extension of the physical control system interface. Fundamentally, it creates more options for operator interaction and system control.

The DT control is used to support the physical control system in a closed loop. Where the system fails the DT can assist in such situations by having a replica of the control functionality.

With the DT control structure, automation can be programmed and tested without necessarily changing the control system. Automatic sequences can be managed using the DT.

6.5 Case study

This phase of this research improved the capability of the case study DT to include a bidirectional control. The DT being able to run in real-time and also integrate operational data (as shown in chapter 5), would have the capacity to control the real system and vice versa. The DT virtual control infrastructure serves as an extension of the distributed control network and establishes connectivity and dependencies between the independent modular controllers. Data driven-control was implemented to optimise resource management-specifically energy and production time.

6.5.1 Festo cyber-physical (CP) smart system control structure

This Industry 4.0 system is built with a modular concept and has a distributed control structure to support some level of flexibility and factory layout reconfiguration. Each station and bridge has a PLC controller managing its operation independent of each other. The MES application manages production as it communicates with the controllers and the robotino robot.

6.5.2 Festo CP smart factory DT

The supervisory DT of the Festo CP smart factory presented in Chapter 4 was upgraded in Chapter 5 to a variable product-process DT (Figure 5.12 & 5.13). This reflects the variability in the product attributes and the process configurations. The DT (Figure 5.13) needs a control infrastructure to have a direct influence on production. It needed a platform to implement process reconfiguration and product variability for customised products. data-based designed automation scenarios and to equip the operator with the connectivity and access to implementing optimisation decisions.

6.5.3 Festo CP smart factory DT cyber-physical control

The implemented control structure is composed of the physical system control infrastructure, the virtual control framework and a real-time bidirectional communication link. The physical control system is a distributed network of PLC controllers managing each module. The virtual control framework is composed of the control parameters and the control algorithms that mirror the identified control routines and provide the extended digital functionalities defined by the DT objectives. The bidirectional communication link is built on the TCP/IP/Ethernet communication that supports OPC_UA communication real-time accessibility.

6.5.4 Key steps

The methodology used in implementing the control infrastructure proposed in Section 6.4 involved the following steps: conceptual control infrastructure design, virtual control infrastructure development, control panel development, data layer development, intelligent layer development and lastly, a verification and validation process. This approach allows the gradual build-in of the complexity of the existing physical control system and the automation sequencing/optimisation algorithms.

a) *Conceptual model design*: This involved the definition of the project objective, control system identification and the design of a control strategy. The project objective in this case is to establish a bidirectional control strategy. Operational data processed and analysed by the DT can be used to manage the production flow in real-time. The DT control functionalities were identified and mapped to the relevant technical requirements. This entails the identification of the existing control loops, controllable parameters, control-related operational data, process behaviour/functionalities that can be controlled and lastly, investigating the accessibility of the existing system architecture to identify how it can be virtually controlled.

b) *Virtual control infrastructure development*: This includes the modification of the existing model to include algorithms and variables for control simulation. The physical system which is modular and structured and implements distributed control would require the virtual system to mimic such levels of granularity. Identified controllable physical configurations were implemented on the DT and the physical counterparts were connected via the OPC_UA interfaces. The three aforementioned control strategies in subsection 6.3.5 were implemented.

c) *Control panel development*: This stage involves the addition of control elements like pushbuttons linked to control instructions/algorithms of the virtual model, input, output/display elements like indicators for data. These graphic user interfaces (GUI) elements provide the point for human interaction/inclusion in the virtual space. This controls the virtual simulation, online simulation and the physical system. This also allows for the implementation of different control applications based on the control strategies.

d) *The data layer development:* This involves the inclusion of data storage elements like tables, global and local variables and display channels like pop-up windows and indicators for operator notifications. Both operational and virtual data were stored for analytical use. Control data is generated and available for analysis and used to improve data-driven control.

e) *Intelligent layer development*: This involves the inclusion of algorithms to monitor the production flow/status of the physical system and manage DT simulation and control sequences/automation and optimisation strategies using relevant accessible data. The operator can be notified of changes and certainly designed responses can be triggered based on analytical results. This extracted information can be used to manage or improve the operation of the physical system. In addition, algorithms needed to centrally manage the entire production processes and run certain control scenarios were developed including a product customisation application using the product-centric control method.

f) *Model verification and validation*: These steps are carried out intermittently all through the development stages. All logic and modelled operations are debugged and tested to ensure they are error-free and built following the project design.

6.5.5 Modelling results

(a) Identification of control granularities

Evaluation of the control structure used in the physical system identified the following control loops that can be modelled:

1) Conveyor control-start/stop/speed-Slow and Normal speed/direction
2) Station operational mode-Automatic and Setup mode, MES mode and default
3) Carrier stopper control: Actuator control-Hold/release carrier
4) Heat-tunnel station: Heating-start/stop and Heater power selection
5) Press station control: Offset pressure, Setpoint pressure
6) Station process time

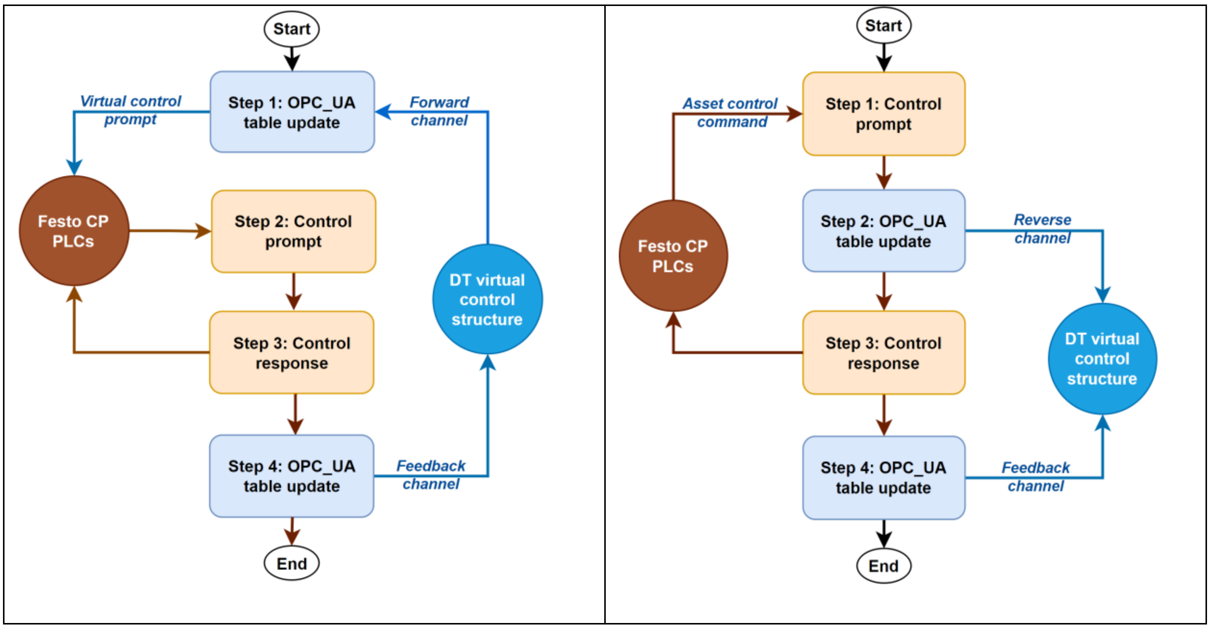
(b) Implementation of control: from virtual to physical and vice versa

The identified control loops were modelled and linked to the Festo CP control system (PLCs configured as OPC_UA servers) via the OPC_UA interface. With expert knowledge of the PLC control programs, the DT virtual control structure (OPC_UA client) was developed taking into consideration the use of interlocks and control loops interdependencies. The necessary controller parameters (interlocks, input and output tags) were identified and mirrored in the virtual controller. These parameters formed the connecting links for the forward, reverse and feedback channels. As shown in Figure 6.8, virtual control and collaboration between the physical asset control system and the digital twin were achieved based on the communication channels created:

*Forward channel***:** It is the asset-twin OPC_UA connections through which the DT virtual control signals are sent to the PLC controllers of the Festo CP smart factory enabling control both at the component and systems levels. The systems-level connection allowed for the implementation of automated virtual control routines. This is shown in Figure 6.8a.

Reverse channel: This OPC_UA channel (Figure 6.8b) informs the DT model when a control command has been prompted from the physical control system. It enables the necessary virtual representation of the control as the expected DT simulation. The signal could be a control command from an HMI panel or an automated control sequence triggered at the systems level.

Feedback channel: This refers to the asset-twin OPC_UA connections consisting of digital access points that inform the virtual model when a control command is being executed. The feedback signal from the physical system (for example an actuator) informs its controller of the status of the triggered control operation. This same control status duplicated in the DT updates its controller and simulation response/behaviour towards such control actions. This is shown in Figure 6.8.



(a) Forward path (b) Reverse path

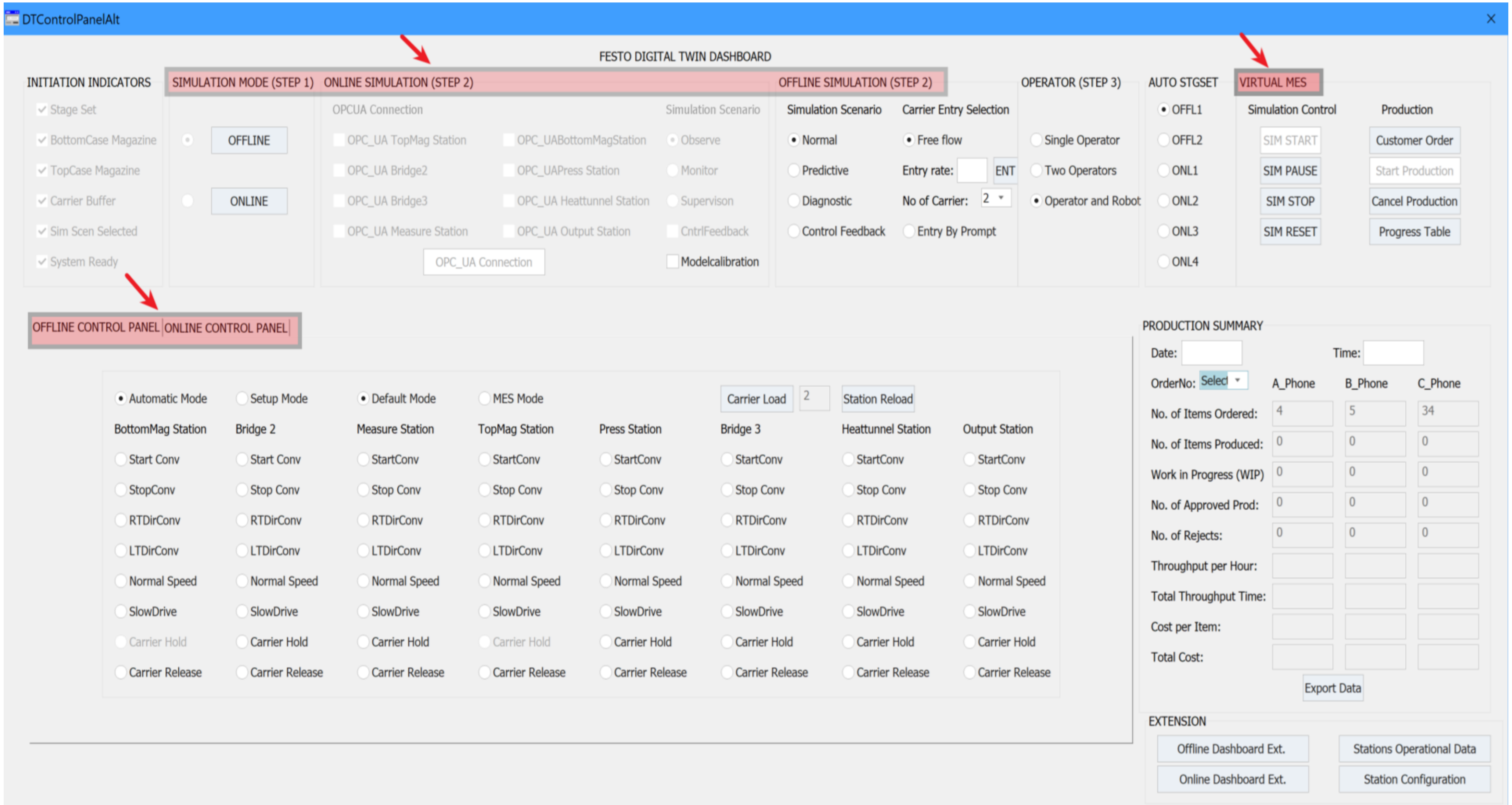
Figure 6.8: Diagram showing the paths between the PLCs of the Festo CP smart factory and its DT virtual control system

Control was implemented in both simulation modes:

- *Offline Simulation:* Control operations of the asset that were of interest were modelled on the virtual model to support control experimentation and analyses
- *Online Simulation:* The real system was controllable from the virtual platform. This includes conveyor control-start/stop, speed selection-slow/normal, conveyor direction-forward/reverse, Operation mode-automatic, set-up mode, MES/default mode. This also supports online simulation, data-driven control and analytics.

(c) Virtual control of Festo CP smart factory

Control sequences could be triggered from the DT control panel and designed control scenarios were executed from the DT. The DT as a closed-loop interactive component of the CPPS monitors production and trigger warnings to the operator to prevent downtimes during production. Figure 6.9 presents the virtual control main screen.



☑ Stage Set
☑ BottomCase Magazine
☑ TopCase Magazine
☑ Carrier Buffer
☑ Sim Scen Selected
☑ System Ready

● Normal
● Free flow
No of Carrier: 2
● Operator and Robot
● OFFL1
● Automatic Mode
● Default Mode
Carrier Load 2

Date:
Time:
OrderNo: Select

	A_Phone	B_Phone	C_Phone
No. of Items Ordered:	4	5	34
No. of Items Produced:	0	0	0
Work in Progress (WIP)	0	0	0
No. of Approved Prod:	0	0	0
No. of Rejects:	0	0	0
Throughput per Hour:			
Total Throughput Time:			
Cost per Item:			
Total Cost:			

Figure 6.9: DT control panel showing the Simulation setup, control panel and virtual MES

(d) Control from Festo physical asset to the virtual platform

The DT in online simulation mode is updated with control activities triggered and executed from the physical system platform through the feedback channel. Virtual sensors/actuators are used to visualise these (Figure 6.10). The DT model responds to this feedback by reflecting the status of the controlled component/system. When executing automated control routines, this feedback is used to inform the DT's next action/decision.

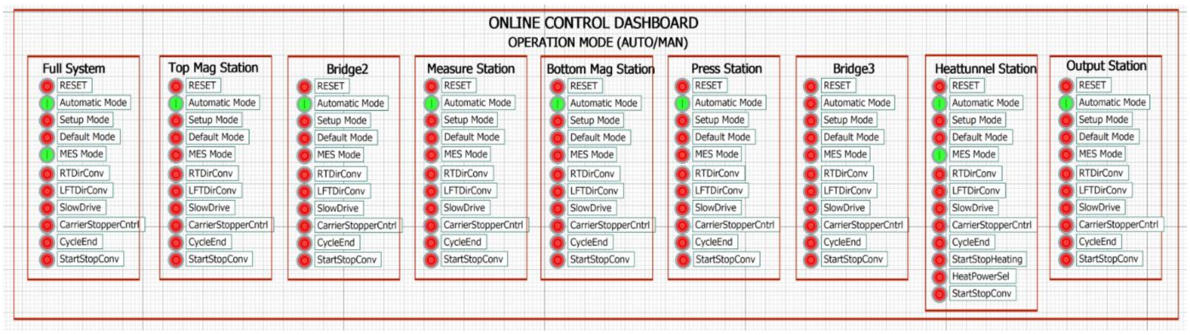


Figure 6.10: Virtual sensors of the various stations reflecting the status of control actions. Green indicates an active state and red indicates an inactive state

(e) Production scenarios

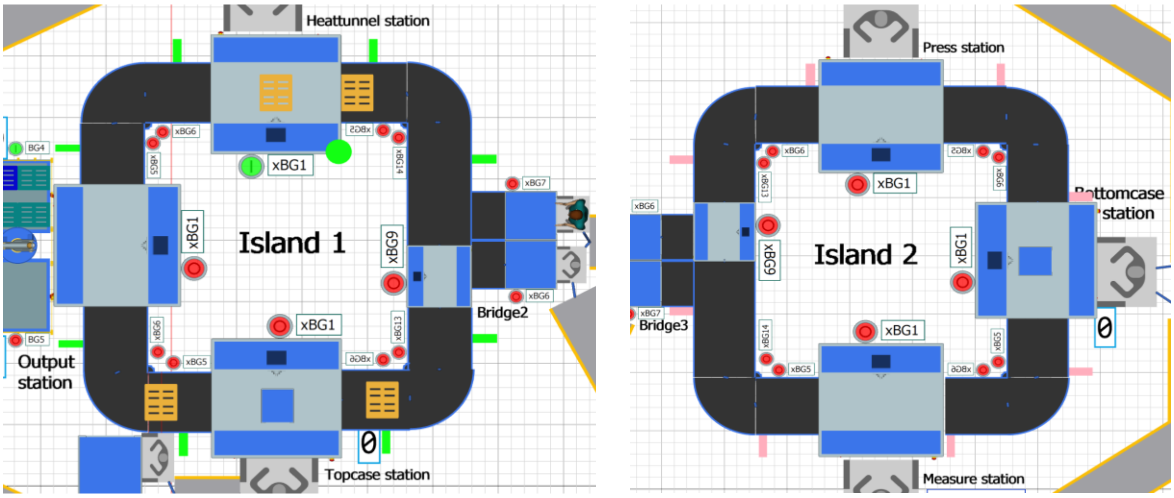
Eco production: One of the selling points of digitisation is effective resource management and energy saving. Eco production is simply production in a more economical way. Finding ways of doing the same thing with less energy. The production flow was analysed and areas of waste were identified and strategies were put in place to reduce waste.

Identified areas:

i. Conveyors running when the station is idle
ii. Output station adding waiting time to throughput time when the store is full
iii. Magazines stations have a longer setup time when magazines are empty during production

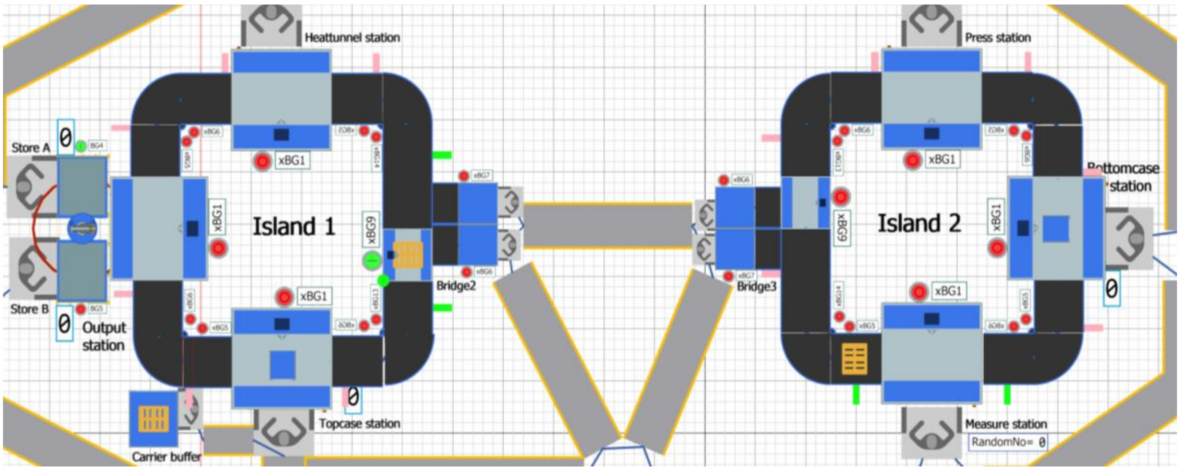
iv. Heating station waiting to be heated only when workpiece arrives

Idle conveyors: Waste due to idle stations when there is no ongoing production was tackled. The DT saves electrical energy by stopping all conveyors from running. It also can identify idle conveyors during production and stop them to save energy. Figure 6.11(a-c) shows the conveyor indicators are red meaning the conveyors are turned OFF/inactive. Green indicator light means the conveyors are running/active.

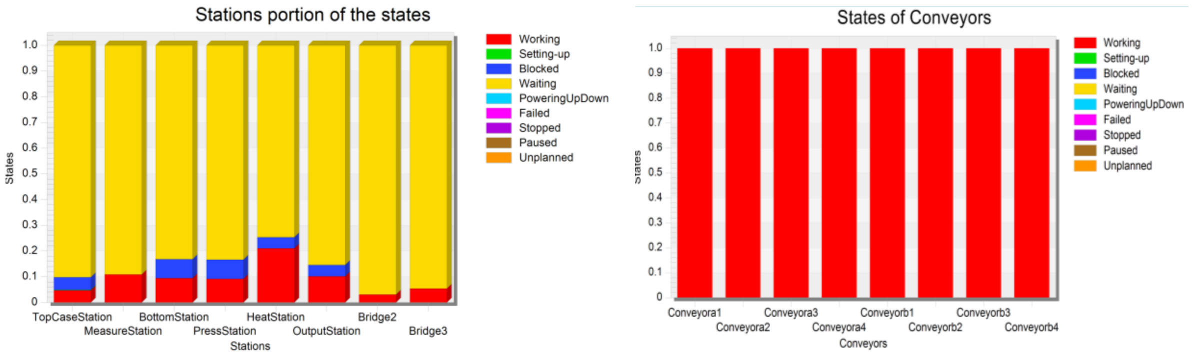


(a) Conveyors running as carriers are available in Island 1(Green conveyor status bar)

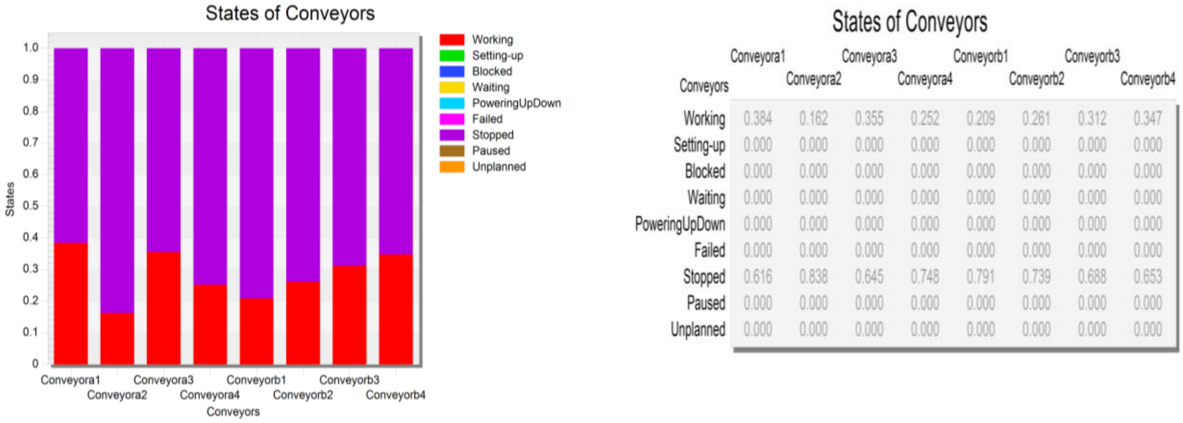
(b) Conveyors stopped as Island 2 stations are idle (Red conveyor status bar)



(c) DT model shows resource management as idle station conveyors are stopped to save energy



(d) Energy consumption at normal operation (Stations and conveyors)



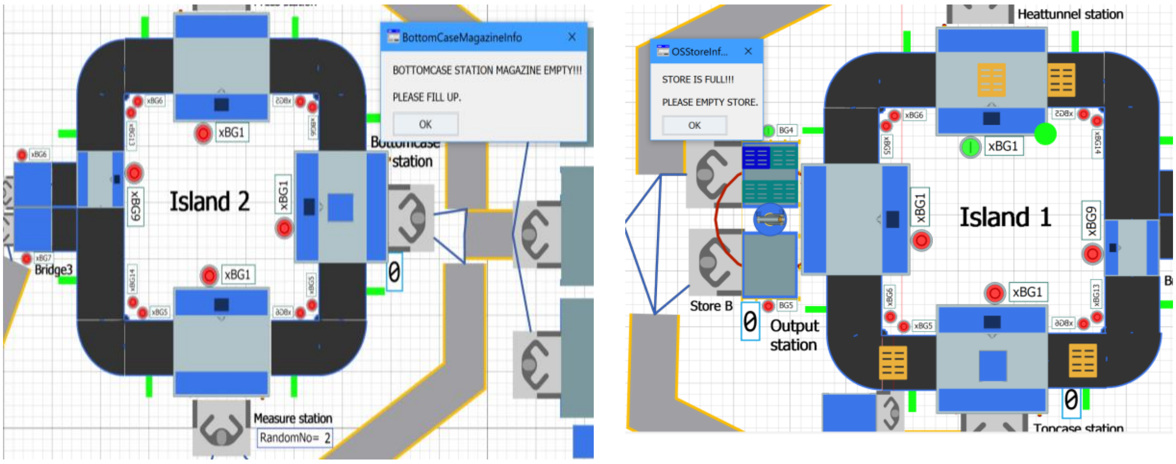
Conveyors	Conveyora1	Conveyora2	Conveyora3	Conveyora4	Conveyorb1	Conveyorb2	Conveyorb3	Conveyorb4
Working	0.384	0.162	0.355	0.252	0.209	0.261	0.312	0.347
Setting-up	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Blocked	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Waiting	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
PoweringUpDown	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Failed	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Stopped	0.616	0.838	0.645	0.748	0.791	0.739	0.688	0.653
Paused	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Unplanned	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

(e) Energy consumption using virtual control strategy (Conveyors statistics)

Figure 6.11: Charts showing the impact of DT control on the energy usage of conveyors.

Figure 6.11(d-e), presents a comparison between energy consumed at normal operation and when the virtual control strategy was implemented. The control strategy by stopping conveyors from idle stations enables the physical asset to save approximately 71.48% of electrical energy consumed by the conveyors. This also increases the useful life of the conveyor system.

Magazines and Output stations: Production is stalled when the output stations are full or the Top/Bottom part magazines are empty resulting in unplanned. The operator needs to empty the storage units or refill the magazines. These situations are monitored and averted by the DT. Figure 6.12a shows, that it alerts the operator before they trigger delays resulting to waste due to waiting. Figure 6.12b shows a pop window informing the operator of the status of the storage unit.



BOTTOMCASE STATION MAGAZINE EMPTY!!!

PLEASE FILL UP.

STORE IS FULL!!!

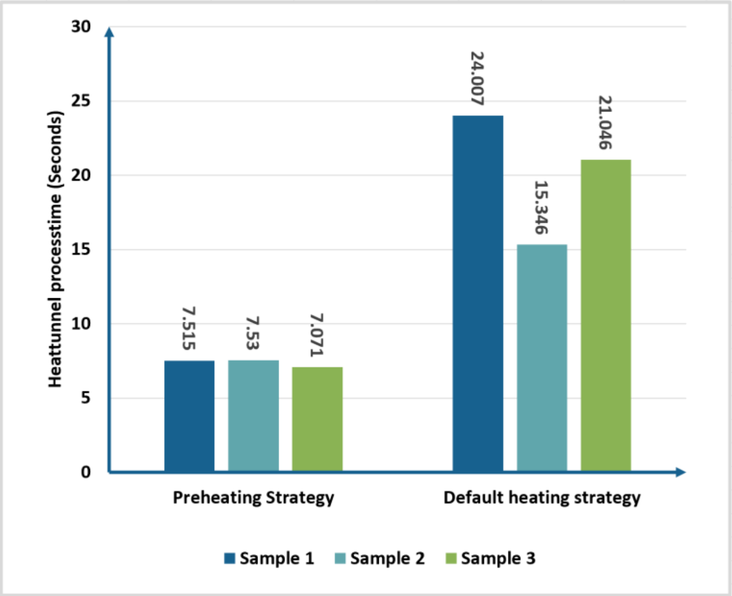
PLEASE EMPTY STORE.

(a) Magazine station monitoring (b) Output station storage unit monitoring

Figure 6.12: Production monitoring with pop-up notifications

Heating strategy: One area identified to improve throughput was to manage the heating process. The Heat-tunnel needs to be preheated to a predefined temperature setpoint. This sequence is only triggered when the workpiece arrives (Figure 6.13a). The heat station can be preheated when a workpiece is approaching (Figure 6.13b). The DT harnesses data from all modules and can trigger the heat station ahead of an arriving workpiece. This reduced the processing time in the heat station by an average of 63.38% and the effect improved the throughput performance of the system (Figure 6.13c).

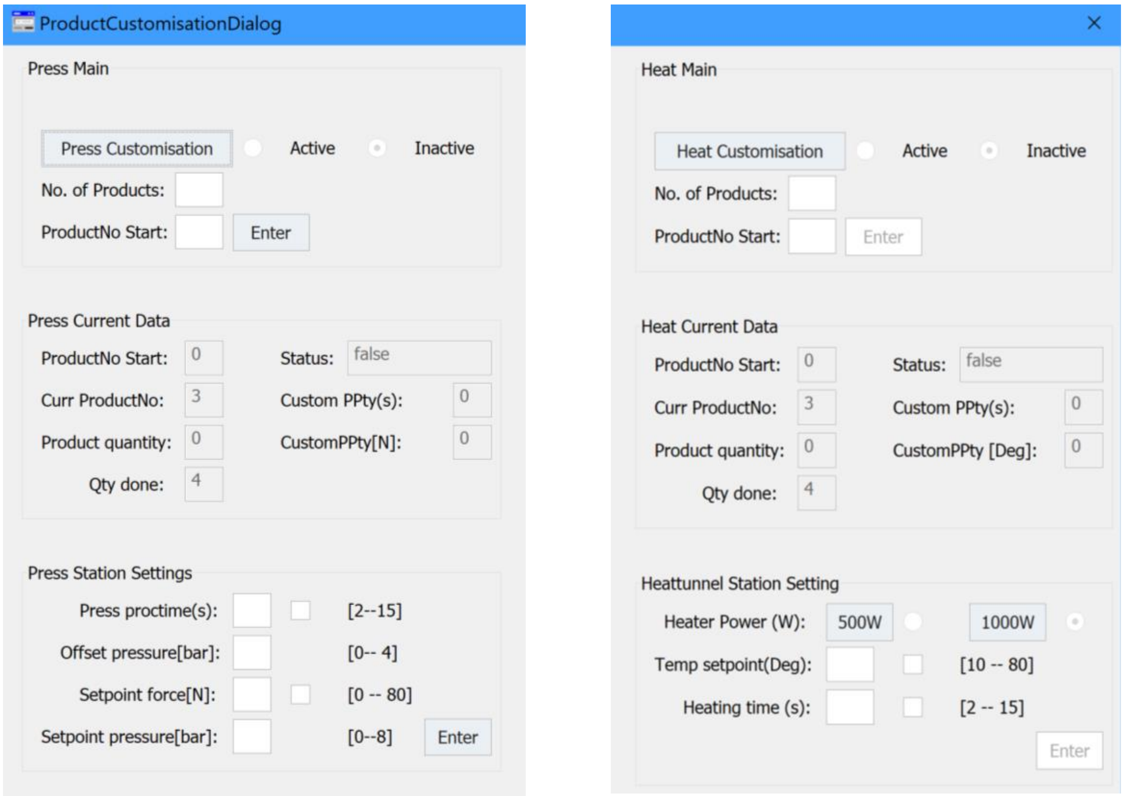
(a) Heating on workpiece arrival (b) Heating strategy-Preheating Heat-tunnel



(c) Impact of Heating strategy on System performance-Heattunel process time

Figure 6.13: Impact of heating strategy on station performance. (Heat station *process time* and *throughput time*

Product customisation: The concept of product customisation in this case study involved the variation in the attributes of the product to suit predefined descriptions. This involved altering the process settings for the press and heat stations in real-time using the product customisation interface connected to the product twin. The selected workpieces are tracked using RFID data and the respective stations are reconfigured to predefined settings to process those workpieces. After which the DT reconfigures the stations to the default production settings. Figure 6.14 presents the DT menu for inputting variability in the product using the process DT.



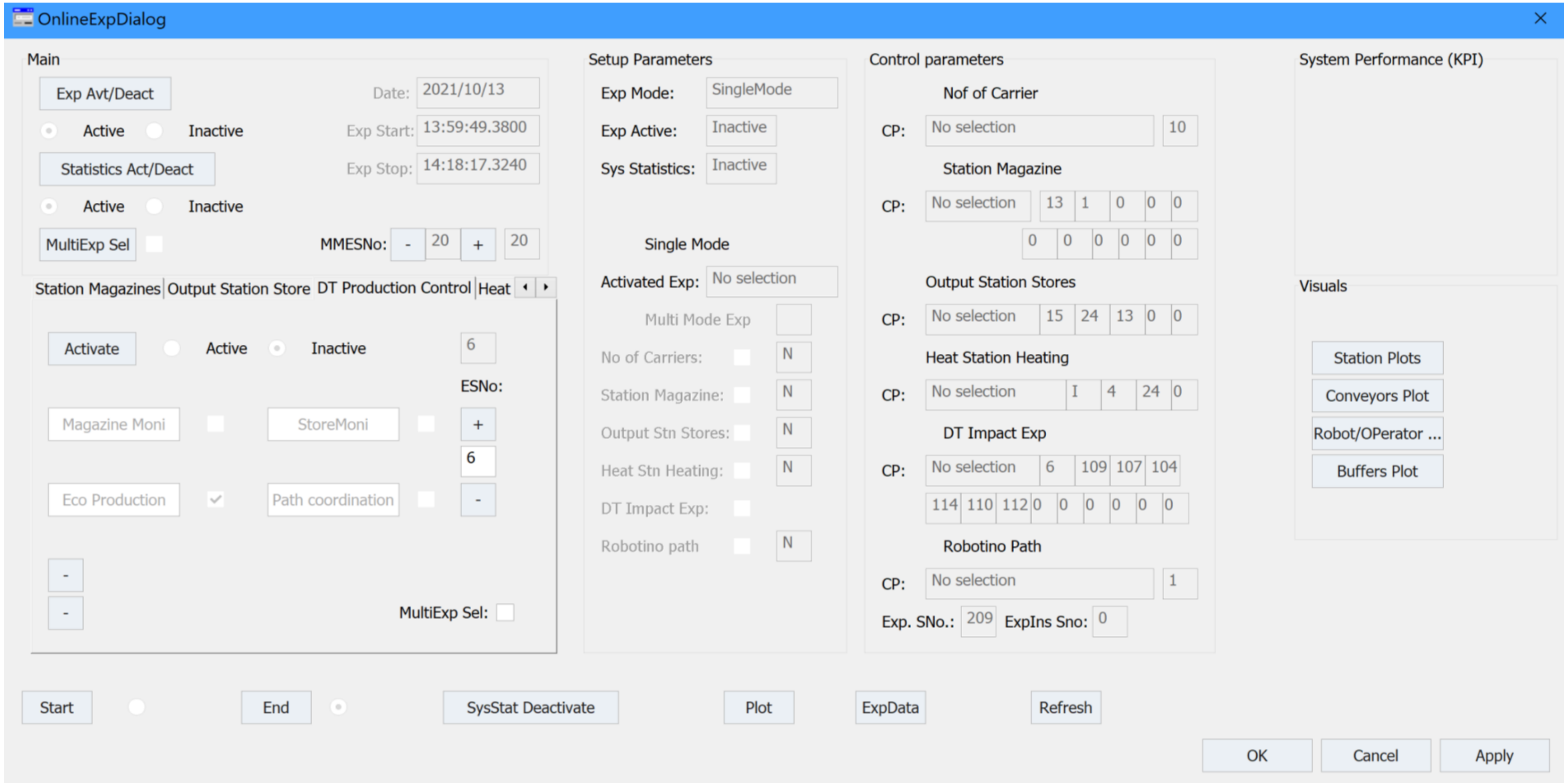
Press Current Data
ProductNo Start: 0
Status: false
Curr ProductNo: 3
Custom PPty(s): 0
Product quantity: 0
CustomPPty[N]: 0
Qty done: 4

Heat Current Data
ProductNo Start: 0
Status: false
Curr ProductNo: 3
Custom PPty(s): 0
Product quantity: 0
CustomPPty [Deg]: 0
Qty done: 4

(a) Press station menu (b) Heat-tunnel station menu

Figure 6.14: DT-panel used in imputing product attributes during production

Online/offline experimentation: The control infrastructure enables online/offline experimentations where virtual control is implemented. Several production configurations were tested and viable configurations were implemented. Figure 6.15 presents the control panel for experimentations.



Main

● Active ○ Inactive

● Active ○ Inactive

MultiExp Sel ☐

Date: 2021/10/13

Exp Start: 13:59:49.3800

Exp Stop: 14:18:17.3240

MMESNo: - 20 + 20

○ Active ● Inactive 6

ESNo: + 6 -

Magazine Moni ☐ StoreMoni ☐

Eco Production ☑ Path coordination ☐

MultiExp Sel: ☐

Setup Parameters

Exp Mode: SingleMode

Exp Active: Inactive

Sys Statistics: Inactive

Single Mode

Activated Exp: No selection

Multi Mode Exp

No of Carriers: ☐ N

Station Magazine: ☐ N

Output Stn Stores: ☐ N

Heat Stn Heating: ☐ N

DT Impact Exp: ☐

Robotino path ☐ N

Control parameters

Nof of Carrier

CP: No selection 10

Station Magazine

CP: No selection 13 1 0 0 0

0 0 0 0 0 0

Output Station Stores

CP: No selection 15 24 13 0 0

Heat Station Heating

CP: No selection I 4 24 0

DT Impact Exp

CP: No selection 6 109 107 104

114 110 112 0 0 0 0 0 0

Robotino Path

CP: No selection 1

Exp. SNo.: 209 ExpIns Sno: 0

Start ○ End ●

Figure 6.15: HMI panel for experimentation showing the Main menu, setup parameters and Control parameters

6.6 Discussion of results

The design configuration for the designed CPPS integrated DT is a closed-loop synchronised interaction between the asset-twin. This means there is a real-time collaborative interaction between the asset-twin. The bidirectional communication link between them equipped with a synchronisation mechanism for real-time data access makes it possible for the integration of data and control. The implemented cyber-physical control infrastructure creates the needed control flexibility, interconnectivity and integration of the interactive closed-loop connection between the asset-twin. While all associated data, including operational data, is harnessed, stored and processed by the DT, the cyber-physical control infrastructure makes available the required control connectivity and mechanism for responsive interaction/implementation of decisions/recommendations arrived at by the DT and the operator/users.

The implemented DT differs from a model predictive controller in that it is multifunctional and is an integration platform. Beyond applying data-driven predictive operations, it has its basic simulation and analytical functionalities and integrates all these functionalities on a single platform. The three levels of implementable control strategies presented reflect the level of complexity that can be modelled into the DT. Strategically, more dynamic control operations can be implemented without interfering with the physical asset control infrastructure. The case study shows how to implement a cyber-physical control that enables virtual control of the physical asset and the implementation of automation/improvement scenarios. Despite the successful implementation, some challenges were faced during the implementation of the control infrastructure. They included:

i. The digital access to the controller: This proposed control infrastructure is suitable for CPPS. Existing controllers may lack Industry 4.0 digital connectivity capabilities that support real-time synchronisation, for example, OPC_UA with read/write permissions. Some PLCs did not have write permissions, thus virtual control was not feasible.

ii. The availability of needed technical skills: Control and programming knowledge and skills are vital. Proficiency in these skills and knowledge would improve the results of the implementation and save time. More training and collaborations between schools and industry should be encouraged to cultivate needed knowledge/skills.

iii. The controller algorithm structure/design is a determining factor in the categorisation of identifiable control subroutines/functions into feasible least independent granularities: This affects the modelling of the virtual controller and the level of collaboration between the asset's controller and its DT control structure. New control designs should take into consideration the need for DT connectivity and collaborations at the control level.

6.7 Summary

The integrated process-product DT could implement real-time responsive interaction with both the operator and the asset as a support-decision mechanism. This increases the DT's capability to implement management and control decisions. Also, this control infrastructure reduces the rudimentary human involvement in correction procedures during production. A systematic approach to identifying and modelling real system control infrastructure would improve the implementation of control in manufacturing DTs. This is a step in actualising the Industry 4.0 expectations in the digitisation of manufacturing processes. Though the case study is a laboratory infrastructure, it is a composition of real industrial components and production processes. The challenges highlighted can be mitigated in future industrial infrastructures to create a more digital connection to the CPPS.

CHAPTER VII: DIGITAL TWIN AS A DECISION-SUPPORT SYSTEM

This chapter presents work done on addressing the research objective "How can the DT concept support decision-making across the RAMI4.0 automation Hierarchy level?". The DT was used to further integrate data from the various Hierarchy levels of the RAMI4.0 automation architecture and made it available to interest groups like the operations management, customers and suppliers of the business chain. This section presents a CPPS DT decision-support system (CPPS_DTDSS) that connects the DT built for the first 4 levels of the RAMI4.0 architecture to access/share resources at the other levels. A case study was presented to validate this proposition. Customer order data was incorporated into the DT data and the customer was always updated on its order status using the customer API.

7.1 Research contribution

This chapter presents a framework that positions the CPPS integrated product-process DT as a decision-support system. The novelty in this chapter is the proposed CPPS DT decision-support system (DTDSS) framework which supports:

- The integration and storage of all associated data across the Hierarchy levels of the RAMI4.0 automation architecture
- The accessibility of DT data to cloud-based analytical tools
- The accessibility of DT analytical results to support production management, business strategic decisions, and inform customer and supply chain associates.

A case study was used to test these propositions and available technologies.

7.2 Digital twin as a decision-support system

This section analyses the prospect of using the CPPS DT as a decision-support system. It addresses four main functionalities supported by the DT concept projected in this research. The developed DT is interactive and multifunctional; it forms a closed-loop system with the physical asset. This closed-loop makes it possible for a continuous flow of operational data to all decision-making processes within the DT. The DT becomes a decision-support system as it provides a continuous process of optimisation sequences that improves product design, production activities and value chain performances. This newly created value chain becomes available to support both supervisory/operational and business levels decisions/strategies.

In an industrial environment, decisions are constantly made. This can be observed at the various hierarchical levels of the business structure. The operator needs to ascertain that operation is in order, the lines manager needs to ensure the production is on schedule, the marketer needs to tell his customer what is obtainable at the moment, and the CEO needs to make policies or strategies to push his business forward. Some of these choices/decisions are spontaneous and thus are made based on some level of presumptions/assumptions. The DT as an analytical platform, wherewith the influx of data from all levels of the system, can assist in providing more fact-based information and recommendations to the operator, line manager or any other interest group. From the operational level, an interactive DT can provide information on the resource performance relative to production schedules and targets.

7.2.1 Simulation and experimentation

Simulations inherit the behaviours of their physical asset into the virtual environment for detailed analysis (Onaji et al., 2019). A synchronised interactive DT can provide simulation functionalities both in offline and online modes. Through offline simulation, design decisions, and production strategies can be tested early enough before they are launched into the physical asset (Tao, Cheng et al., 2018). Using online simulations, implemented strategies can be monitored and analysed in real-time. This creates room for authentic observations and adequate responses resulting in improvements. Decisions made here are factual and event-based using the DT resources.

7.2.2 Real-time data-driven operations

A digital twin-based cyber-physical production system for autonomous manufacturing supports real-time data-driven operations. Data analytics has been a significant tool used for evaluating past incidences and the prediction of the future state (Schuh & Blum, 2016). Data is continuously processed and analysed to provide optimal responses to the daily needs of the production system. Some specific-based functionalities programmed into the DT as a support decision system include the following:

Production management and health monitoring: The DT provides more insight into the dynamic operation of the production system. As shown in Figure 4.5, the DT framework enables the inclusion of both operational and environmental data for analytics (Rosen et al. 2015; Catapult, 2018). These additional data reflect the real state of the manufacturing infrastructure. When the DT is employed in health monitoring systems, the inclusion of such information in analyses reduces the impact of presumption or engineering estimations. This would facilitate the enhancement of manufacturing efficiency leading to a more lean and competitive establishment (Onaji et al., 2019; Schuh & Blum, 2016).

Disruptions and failures management: The DT used in this capacity, enables last-minute changes to production and flexible response to disruptions and failures caused by suppliers, machine failures or unplanned maintenance schedules. AI algorithms can make good use of available production data to support operation and reduce foreseeable downtimes and waste.

Applying rescheduling, customisation and optimisation: Using the DT to implement waste management techniques like the Kaban hybrids to achieve rescheduling, customisation and production optimisation eliminates overproduction, reduce waste and cut storage cost. This would improve the coordination of raw material flow, production flow and overall resource management. The use of AI algorithms increases the performance of such specific based digital functions and overall system performances.

The adaptability of the production system using DTs: Real-time digital communication between the asset-twin creates the implementation convenience of product variability and customisation. Production resource reconfiguration can be done digitally as the DT handles logistics tasks like routing/rerouting, and production services like production scheduling. From the maintenance perspective, the DT as a responsive system can coordinate the systems to handle breakdowns, schedule maintenance or even unplanned maintenance.

7.2.3 Digital twin data: Data generation, storage, model update and data visualisation in the context

Data, in this case, could include design and development data, operational data (static and real-time), health monitoring/maintenance, process sequence and parameter relationships, experimentation and analytics. Managing DT data would involve the following processes:

(a) *Data generation:* Algorithms are written to generate data that reflects the model's behaviour in terms of actions/responses. These data can be in different formats-timestamps and quantities/states.

i. *Operational data from the real system:* Two approaches have been adopted to extract operational data.
   - *Extraction by physical system*: Here, the data is generated by the physical system and stored in the controller. This is then pooled and stored in the model.
   - *Virtual data generation using physical system triggers:* Data describing operational activities is generated in the model based on triggers from the physical system. Data generating algorithms are triggered by signals from the physical system.

ii. *Virtual data generation from virtual operations and sensors:* Virtual data not triggered by the physical system includes virtual activities needed to generate desired digital information. It also includes activities that cannot be directly extracted from the physical system but are modelled and inform the virtual replicas of the physical system. Examples include virtual product attributes and production flow data.

(b) Data integration: To generate data during production, data is pulled from several sources like the MES, stations and products. The DT data is built based on the established collaborative dependencies between the asset-twin. These dependencies establish the connection between the operational data, virtual data and the resultant information constructs. The RFID techniques if employed provide the mechanism to transport product and production data along the production line, thus enabling a real-time mapping and updating of the production data.

(c) Data storage: All data pulled into the virtual platform should be done using unified data semantics. Based on the collaborative dependencies between the asset-twin, all production-related data on the product and processes can be linked and constructively stored such that the business chain data is built and made accessible to all associated groups.

(d) *Model update:* In online mode, the operational data is extracted via the digital channels connected to the sensors and actuators via the controller. This stored information is used to update the DT model. These instances reflect the physical system configuration and behaviour in real-time.

(e) *Data visualisation in context:* Information constructs are contextual, thus, front-end APIs, analytical tools and visualisation interfaces with access to the DT data would provide design-based contextual information. These visualisation tools can operate in real-time such that results/information are readily made available using charts and other visual tools to all connected groups on need-know bases.

(f) *Cloud-based data services:* Cloud technology today presents enormous benefits to users even as an independent entity or as a part of an ecosystem (Yang et al., 2017). DT data can also be pushed to the cloud for storage or made accessible to cloud-based analytical/visualisation tools. Subscribing to the cloud platform for data services provides the following benefits to the digital twin platform:

- Connectivity to other hierarchy levels/resources
- Access to data across the hierarchy level
- Access to more sophisticated front-end APIs
- Access to more digital space for data storage, processing and analytics
- Access to more computer power and reliability.

7.2.4 Benefits of the digital twin as a decision-support system

This section highlights potential benefits added to the CPPS when an integrated product-process DT is used as a decision-support system. This has been considered under offline and online simulation.

(a) Offline services

As an analytical system, it helps with providing more evidence-based information using operational data in its diagnostic, descriptive and prognostic analyses. This improves the understanding of both the current status and futuristic behaviour of the physical asset and supports decision-making on its future.

i. *Accelerated risk assessment and production time:* The DT makes it possible to test new products/processes with little cost before they exist. This makes it possible to identify bottlenecks/design/operational failures on time. Through disruptive testing, different scenarios can be tested to investigate system reactions enabling the provision of the corresponding mitigation strategies. This improves risk assessment and production reliability.
ii. *Data analytics:* Real-time synchronised interaction and integration between the asset-twin make operational data available for real-time data analyses. The real-time inclusion and analyses of operational data improve the analytical results and promote the timely usage of these results in operations. This gives better insight into all aspects of the production system and processes involved. Businesses through diagnostic/descriptive analyses can identify root causes and provide evidence-based recommendations for improvement. Prognostic analyses, identify potential problems before they occur, and provide insight into future outcomes based on known parameters or experimental scenarios. They also provide needed information to support more effective predictive maintenance. These should optimise system performance, increase profitability and lower maintenance cost.
iii. *Better team collaboration:* The integration of the business chain data and the management of such data increases the accessibility of all project-related data (design, historical, real-

time and analytics results) to all interest teams. This fosters inter-team collaboration with improved productivity and operational efficiency.

iv. *Better business decision-making:* The availability of operational data reduces errors due to estimations/assumptions, and the integration of all related data and advanced analytics has equipped businesses with more efficient decision-making mechanisms. The virtual platform makes it possible to test and evaluate such business decisions before implementing them.

(b) Online services

i. *Increasing the level of integration between unconnected systems:* Based on the type of the DT, independent units (equipment, stations, sites) can be integrated. Modular infrastructures and distributed control structures are key approaches to smart production lines. The DT plays a central role in creating a unified operational platform through the integration of control and data from these heterogeneous networks.

ii. *Real-time remote monitoring:* Having a real-time in-depth view of production systems has been a near-impossible task. This is because of communication challenges and the high dependence on engineering estimations in virtual models. The concept of digital twinning makes possible, the remote access of such systems from anywhere, thus it enables real-time monitoring and control of the system performance. This provides a deeper understanding of the existing dynamic interaction between components of the production line and the impact of its operational environment on production.

iii. *Enhancing product traceability processes:* Industry 4.0 technologies like the RFID techniques enable a more efficient tracking method of resources along the supply chain and products during production. The digital twin makes it possible to keep track of and utilize such information to manage production and product quality.

iv. *Cyber-physical control:* The emergence of bidirectional communication establishes a closed-loop control structure that provides feedback to the virtual control models. This makes it possible to enhance existing control operations. Data analytics provides insights that enable data-driven control, automate control sequences, support decision-making processes and implement solutions.

v. *The utilisation of product-process interaction during production:* There exists a dynamic interaction between the product and its production processes during production. This dynamism if well managed reflects in the product quality and resource management. An integrated product-process DT supports flexibility in production. The product DT using the cyber-physical control network can automate the dynamic recalibration of equipment, processes, work stations or production lines. This promotes product customisation by making use of the product DT to incorporate customer variability during production.

7.3 The proposed framework of the CPPS_DTDSS

7.3.1 Background

Across the manufacturing, business chain lies disconnected silos of information. This spans from the design stage to the final retrieval of a product/resources from active service (Tao, & Zhang, 2017; Macchi et al, 2018). These isolated data need to be integrated for effective management of the product/resources across its life span. For instance, a machine can be tracked from the design stage through useful life to its retirement. Data from its useful life can be used to inform/improve its design and functionality. Also, proper record enables an effective process to retire the machine from service to reduce waste due to increased inefficiency. One of the research objectives in implementing the DT concept is the integration of all Hierarchy levels of the RAMI4.0 automation architecture using data. Eliminating the disconnectivity between information silos across the business chain makes information readily accessible to all interest groups.

The DT platform has provided the needed virtual environment to integrate operational data with other production data and create a more accurate digital context of the shop floor conditions for analysis and visualisation (Onaji et al., 2022). This platform can be explored further beyond simple simulations and operational functionalities. It can make use of data across the RAMI4.0 Hierarchy levels and other external specialised or more sophisticated analytical tools to create more useful information that becomes profitable across the manufacturing business chain. Aligned to this benefit is the prospect of generating a more holistic picture of the business situation and the submission of more proactive evident-based business/strategic decisions.

7.3.2 The proposed framework of the CPPS_DTDSS

This section presents a CPPS Digital twin decision-support system (CPPS_DTDSS) framework (Figure 7.1) that makes use of the internet and cloud services to connect the integrated product-process DT to the ERP/MES, the customer and supply chain. This gets closer to the expectations of an integrated RAMI4.0 architecture Hierarchy levels structure using data. Also, a digital environment is created that makes several services and resources across the various levels accessible to the DT and the users of the entire system.

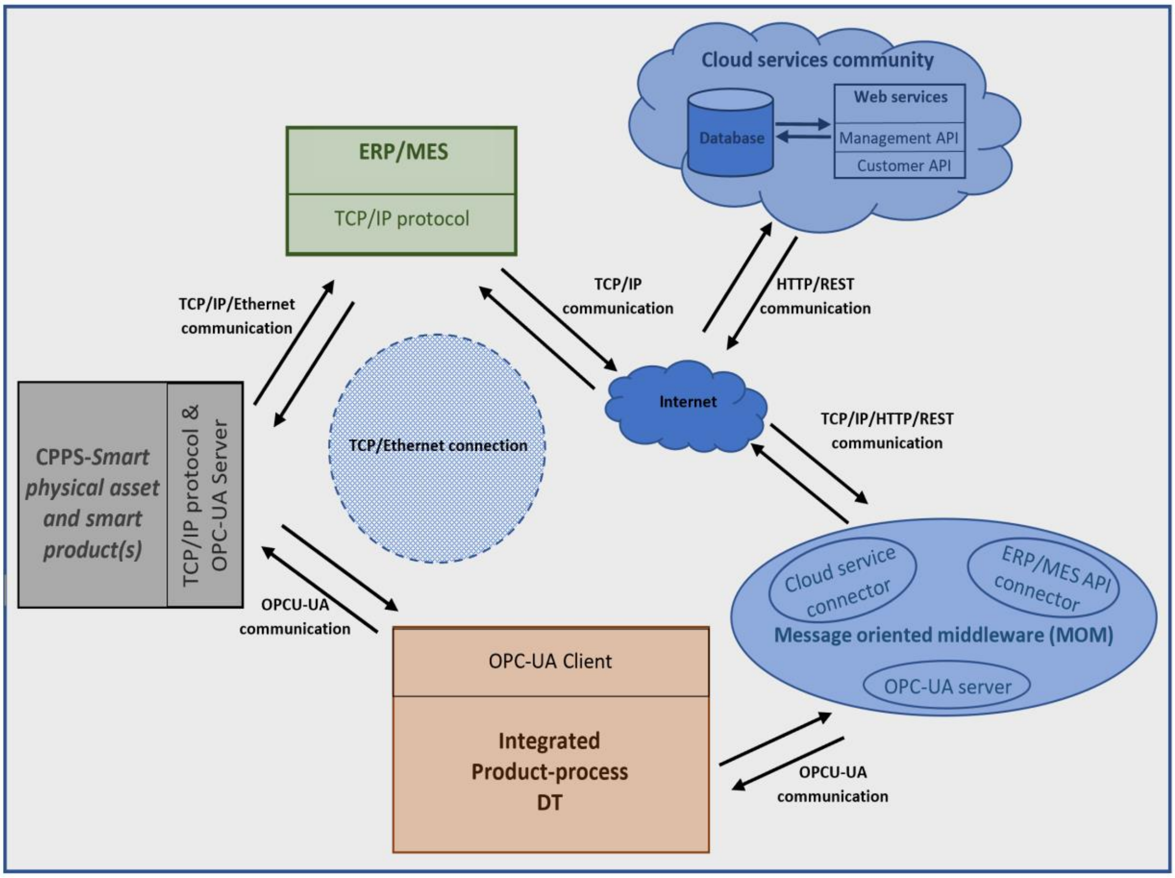


Figure 7.1: Proposed framework of the CPPS_DTDSS connecting all Hierarchy levels of the RAMI4.0 automation architecture

7.3.3 Components of the proposed CPPS_DTDSS infrastructure

(a) CPPS-Smart physical asset and smart product

These are enhanced intelligent autonomous integrated, adaptable production systems possessing both learning and cognitive capabilities (Konstantinov et al., 2017). Allowed to interact with digital models, they can think, make/support decisions, autonomously execute, determine and implement improvement strategies. This has been discussed as an integrated physical asset in Section 3.8.

(b) Integrated product-process digital twin

This is an integrated product-process DT that supports both data and control integration, real-time interactive simulation in a closed-loop synchronised cyber-physical environment with its physical asset. This has been discussed in detail in Chapters 4 and 5.

(c) Message-oriented middleware (MOM)

The concept of edge computing paves way for communication via the internet, establishes interconnectivity within a heterogeneous network, unifies data semantics, and reduces computing work on remote systems using cloud facilities (Yang et al., 2017). This project used the Node-RED application as a channel to communicate and interconnect IoT components of the framework through the internet. More information on MOM can be found in Appendix D.

(d) Cloud service community

This could be any cloud-based platform that renders computing services like servers, databases, storage/networking across IoT devices, software like front-end applications, analytics and intelligence over the internet (Yang et al., 2017). Objectively, these services are meant to be faster, flexible with resources and economical. Examples include Siemens Mindsphere, Amazon AWS and Microsoft Azure. In an industrial/manufacturing environment, it collects and makes operational data accessible to connected users who make use of front-end applications to extract factual information used for daily decisions.

(e) ERP/MES

The ERP/MES level is equipped with efficient digital tools for its services. The idea of having a DT for this level is not viable here but having the asset-twin access its resources extends the digital and integration platform across these Hierarchy levels. The MES has efficient mathematical models for scheduling/production management and maintenance management.

All these high and specific based analytical tools can be extended to the DT through a collaboration where data and tools are shared. The DT interfacing with a virtual MES can extend its simulation functionality to the MES to support smart scheduling and material flow. Scheduling principles like first-thing-first-out and first-thing-last-out can be merged as a hybrid scheduling approach. The DT can also support in evaluating the impact of rescheduling methods like rescheduling orders (new, existing) or rescheduling new orders according to due time, process time and travel time (New Order, simple rule).

(f) ICT infrastructure that supports bidirectional communication between IoT

The ICT infrastructure needs to be robust, reliable and secured in service (linkage, internet, transport and applications). The ProfiNet/TCP/IP communication infrastructure has been noted to be efficient in providing a secured, reliable communication service. It comprises the link, internet and transport layers of the communication layer (Nazarenko et al., 2020). This is proposed as the communication service provider for the CPPS_DTDSS as it uses IP addresses to provide unique identification for IoT devices within the network. It also supports different types of application (APIs) protocols and interfaces (Examples include MQTT, AMQP, RESTful, OPC_UA, and HTTP). The MOM as a distributed communication layer is used in this infrastructure to enable APIs modules distributed across heterogeneous IoT devices/platforms to communicate (Curry, 2005).

7.3.4 Interaction loops between the digital twin and associated architecture

One challenge of current industrial infrastructure is the disconnection between the various layers. This is physical and virtual because they are built with components (hardware/software) predefined to suit specific purposes and from different vendors. As such, one tends to find issues with communication due to variations in data semantics and system architectures.

(a) Digital twin and CPPS

One of the main concerns of the connection between the DT and the CPPS is the robustness of the connection to support seamless bidirectional communication and guaranteed cyber security of the infrastructure. This is needed to ensure control is efficient, operational safety meets the required standards and the infrastructure is not compromised by cyber threats. A remote TCP/IP/Ethernet network is proposed here, upon which the OPC_UA protocol is implemented to establish a fast and secured bidirectional communication link. The OPC_UA provides fast standardised and secured access to industrial systems, machines and other related devices enabling manufacturer-independent control and data exchange (Pethig et al., 2017). Figure 7.1 shows this connection between the asset-twin. This enables the transmission of data and implementation of cyber-physical control.

(b) Digital twin and ERP/MES

The ERP/MES is most often established in a separate digital base from the production asset-twin. The connection between the ERP/MES and other components of the manufacturing network would most likely span across a TCP/IP/Ethernet network, which may be internet-connected. To ensure cyber security and reliability over the internet, a more suitable communication interface would most likely be the TCP/IP protocol. The DT using the standard OPC_UA protocol as a client through the MOM would be able to interact with the ERP/MES using the TCP communication node. The DT can share data with the ERP/MES or be designed to influence MES operations like production orders, and scheduling (operator, orders, maintenance). A DT can have a virtual MES, which is linked to the main MES. This pulls MES services closer to the operator managing the DT activities. At the ERP level, DT data accessed by ERP analytical tools/APIs can provide more informed business insights as production information is readily made available.

(c) Digital twin and Cloud services

The cloud service community is a web-based infrastructure. The DT as an OPC_UA client uses the OPC_UA protocol to access the MOM OPC_UA server node. The MOM provides the specific HTTP/REST API node for communication to the cloud service community in use.

This forms the connection to the connected world. The customer and other supply chain users have access to production data (DT data) and in turn, make available other associated production data (For instance, customer input based on product usage and preferences, resource supply chain inputs, administrative strategic policies and insights). The DT as an integration platform can create a more holistic image of the business as it accesses more data and specific analytical tools to provide specific business insights that enhance informed business decisions.

7.3.5 Benefits of the digital twin as an extended decision-support system across the RAMI4.0 automation architecture hierarchy levels

The key concept here is the interconnectivity and integration of the RAMI4.0 automation architecture. This enables collaboration between the Hierarchy levels of the architecture. What makes the DT a unique tool for interconnectivity and integration is the real-time synchronised interaction and data accessibility. At the asset-twin level, the continuous evolution of the DT data supports the real-time data-based responses to production needs and the autonomous implementation of analytical results. Stretched across the RAMI4.0 Hierarchy levels, more factual production information can be provided to support business decisions, marketing reviews, and customer recommendations. Information from the customer and management can be easily incorporated into daily production activities and product design. Figure 7.2 gives a view of the interconnection and benefits obtainable across the various Hierarchy levels when the proposed CPPS_DTDSS is implemented.

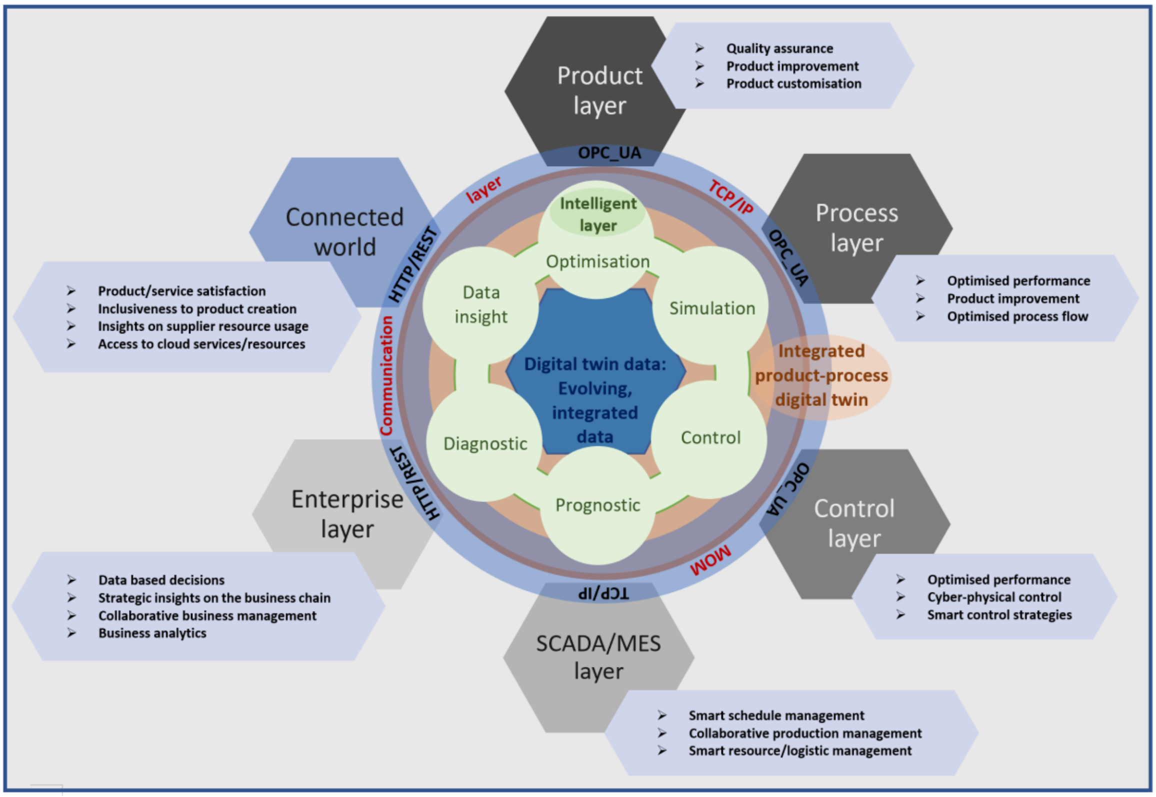


Figure 7.2: Schematics showing connectivity and benefits of the collaborative interconnections between the integrated product-process DT and the RAMI4.0 automation architecture Hierarchy levels

The integration and evolution of all associated production data (design, planning, operations, usages, maintenance, business/customer/supply chain, and analytics) provide sufficient information to generate a holistic lifecycle informative image of the business investment. This DT data is continuously updated thereby creating interaction and convergence of all accessible historic, real-time data and analytical results. This DT data becomes available to all associates of the business chain based on the given access privileges. For instance, the operator gets up-to-date information on the production system, maintenance, performances and resources management. The business manager can request analytical results to investigate a business case for production investment or business strategy. The supply chain is well informed of how their services are been used and how the efficiency of the resource logistics affects production and customer satisfaction.

Using the integrated product-process DT as an extended decision-support system across the RAMI4.0 automation architecture is envisaged to benefit the DT and all connected levels. This DT interconnection approach is symbiotic in service. First, the DT has access to data and other specific based analytical and front-end APIs of these levels thus expanding its database. Also, it increases its functional capacity as its intelligent layer is extended across the hierarchy. It has more applications, computing base, data and analytical tools. On the other hand, the information and communication gap across the Hierarchy levels is bridged. The interdependence between the various participants of the business chain gets to be harnessed to improve everyone's performance as resources/information are made accessible and usable.

7.4 Case study

7.4.1 The DTDSS of the Festo CP smart factory

The Festo CP smart factory's integrated product-process DT has been developed and introduced in the previous chapters. In line with the current industrial expectations, the business case explores the benefits of connecting the integrated product-process DT with the other RAMI4.0 Hierarchy levels. Therefore, the DT should have access to the MES, customer API/data, issue production orders, and push DT data to the cloud database for use across the business chain. The resources used here are considered an extension of what is obtainable in the industry. The Festo CP smart factory utilises the standard TCP/IP/Ethernet communication infrastructure and all resources here are industrial-based applications. Communication between the physical system and the MES computer is not part of this research work. All other connections between the components of the proposed CPPS_DTDSS were done by this research.

7.4.2 Key Steps

The methodology used in implementing the CPPS_DTDSS infrastructure involved the following steps: conceptual CPPS_DTDSS infrastructure design, Component development, Communication infrastructure setup and lastly, the verification and validation process. This approach allows the gradual build-up of the design objective as one works around the available resource constraints.

(a) Conceptual CPPS_DTDSS infrastructure design

This involved the definition of the project objective and system identification including the definition of the component's functionality and the design of the communication network. The objectives of this phase of the project included the:

- Connection of the MES component of the DT to the ERP/MES system to enable production orders from the DT and retrieve production order details from the MES
- Connection of the DT to the Siemens Mindsphere cloud database for DT data storage and accessibility to all associated parties for business analyses
- Connection of the DT to the customer API to access customer orders made from the customer API and inform customers of the status of their order

The communication between the DT, the ERP/MES system and the Mindsphere cloud services was established across the internet.

(b) Component development

This included the modification of the existing DT model to include algorithms and variables for organising DT data to be pushed out, pushing production orders to the MES and receiving data from the MES and the customer API. Other needed components included the IoT message-oriented platform (MOM), Cloud service platform and customer API. The MOM platform used in this case study is the Node-RED. Algorithms were designed and implemented to manage the connectivity between connected IoT elements/Nodes and GUI interfaces were created to manage the platform resources. The Mindsphere cloud service was configured to create the digital twin

(c) Communication infrastructure setup

This stage involved the installation and configuration of the communication interfaces. The OPC_UA interface in the DT, the OPC_UA in the Node-RED, the Siemens Mindsphere agent in the Node-RED for Siemens Mindsphere connectivity and the Siemens Mindsphere connectivity.

(d) Model verification and validation

These steps are carried out intermittently all through the development stages. All connectivity and modelled operations are debugged and tested to ensure they are error-free and built under the project design.

7.4.3 Festo CP smart factory CPPS_DTDSS infrastructure

Figure 7.3 presents the developed CPPS_DTDSS for the Festo CP smart factory. The ICT communication techniques/technologies adopted were based on the digital accessibility of the resources available.

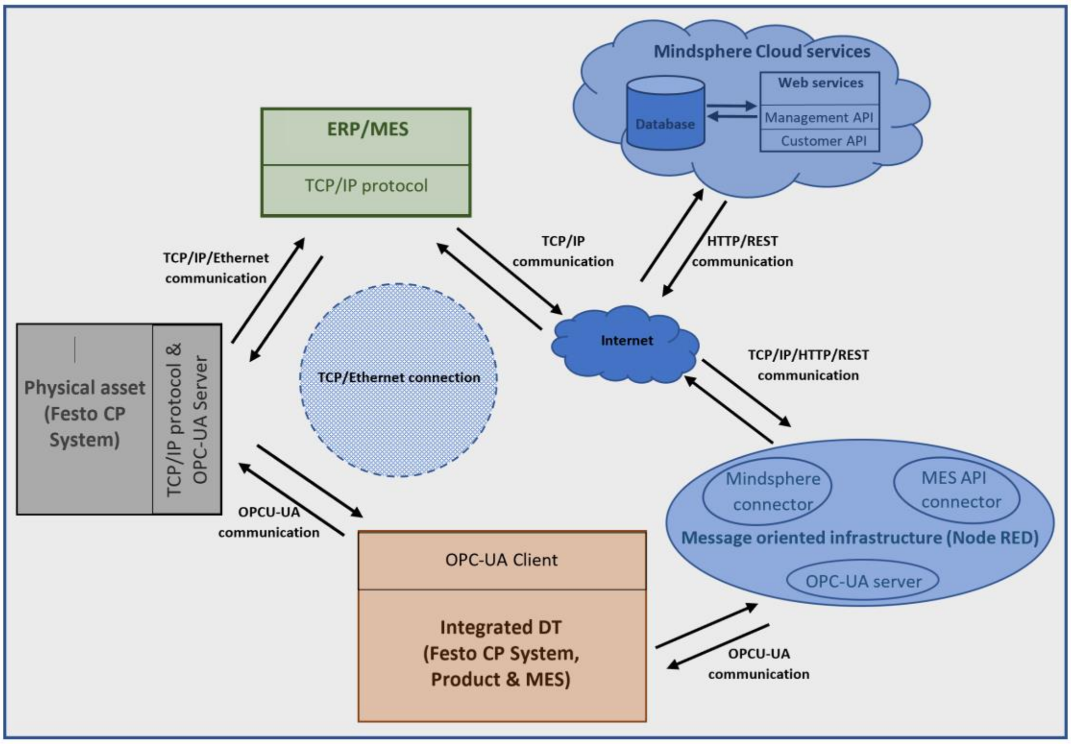


Figure 7.3: Developed Festo CP system DTDSS connecting all hierarchy levels of the rami4.0 architecture

Figure 7.3 presents a functional flowchart of the DT and its connection with the Festo CP smart factory, MES computer and Siemens Mindsphere cloud services. The OPC_UA protocol, HTTP connection, Node-RED MOM and TCP connection were the adopted Industry 4.0 technologies.

7.4.4 Components of the proposed CPPS_DTDSS infrastructure

(a) CPPS-Smart physical asset and smart product

The Festo CP smart factor was used. Details can be accessed in Chapter 3. It is a smart system that senses its environment, generates, stores and can share its operational data. The workpiece is transported on a smart carrier equipped with RFID technology. This CPPS has a TCP/IP/Ethernet communication network with an OPC_UA protocol.

(b) Integrated product-process digital twin

The DT is an integrated product-process DT with an established OPC_UA closed-loop bidirectional communication with its asset. Figure 7.4 shows an upgraded functional flowchart of the DT showing connection to the asset and Mindsphere cloud service. The DT uses an OPC_UA-HTTP connection to access the cloud services. This is made possible using the Node-RED application as a MOM.

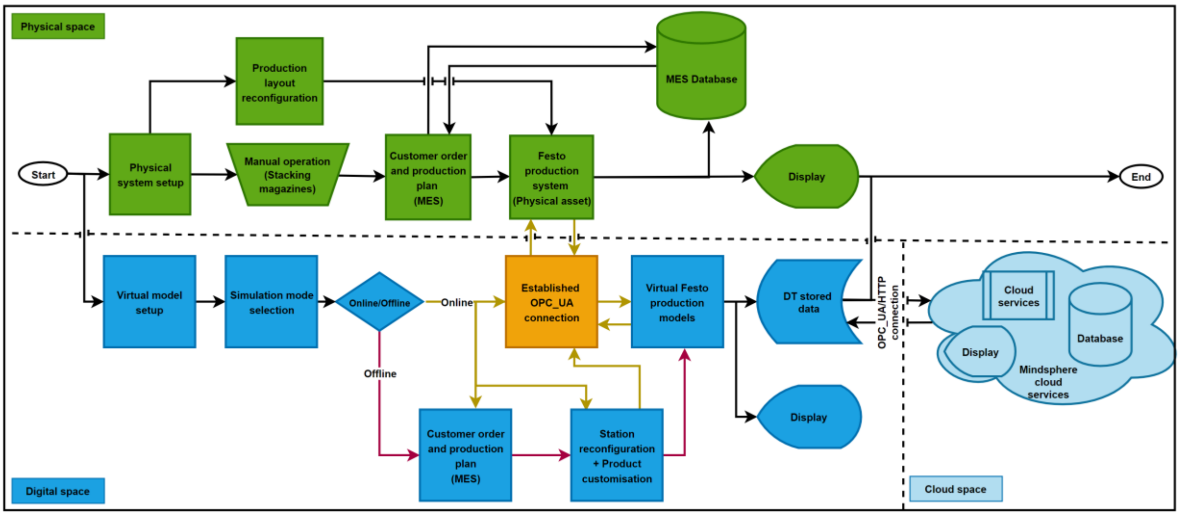


Figure 7.4: Functional flowchart showing a closed-loop DT set-up and digital connection across RAMI4.0 automation Hierarchy levels

(c) Message-oriented middleware (MOM): Node-red development

The Node-RED middleware was the MOM application used in this case study, it was used to establish the communication channels needed to interconnect the IoT components of the DTDSS framework through the internet. As shown in Figure 7.5, the digital twin (OPC_UA client) is connected to the ERP/MES (HTTP interface) using the Node-RED OPC_UA server node and TCP request node. It also supported the DT connection to the Mindsphere cloud service platform (Mindsphere API) using its OPC_UA server node and Mindsphere MindConnect node.

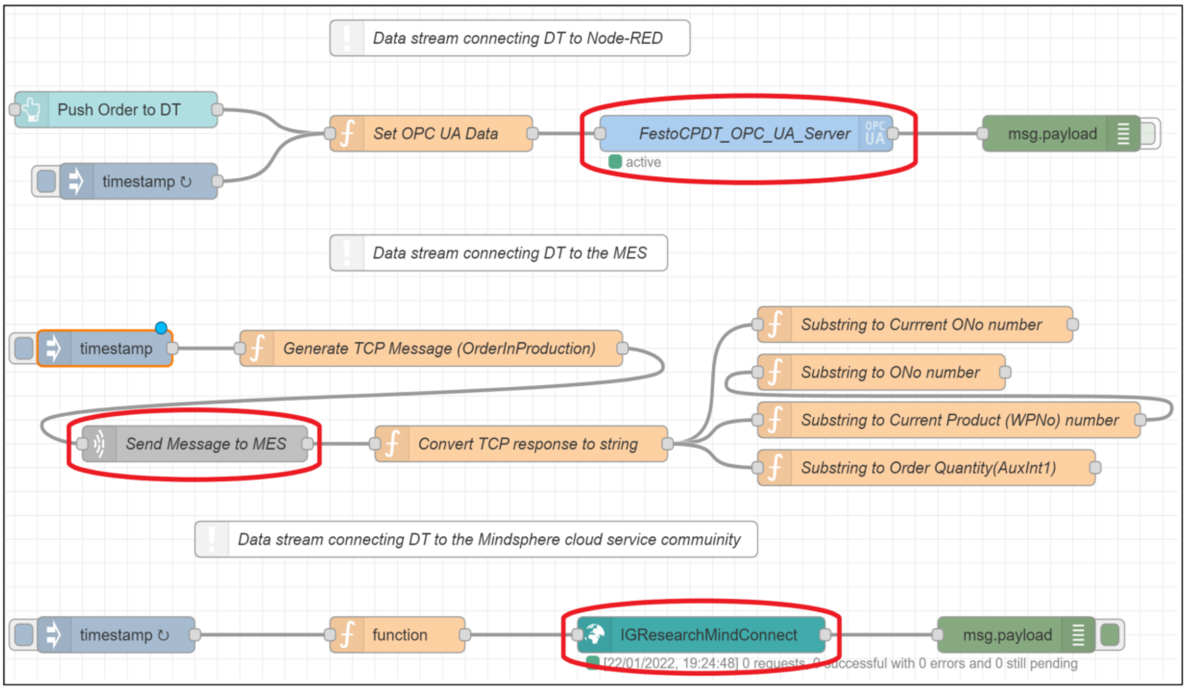


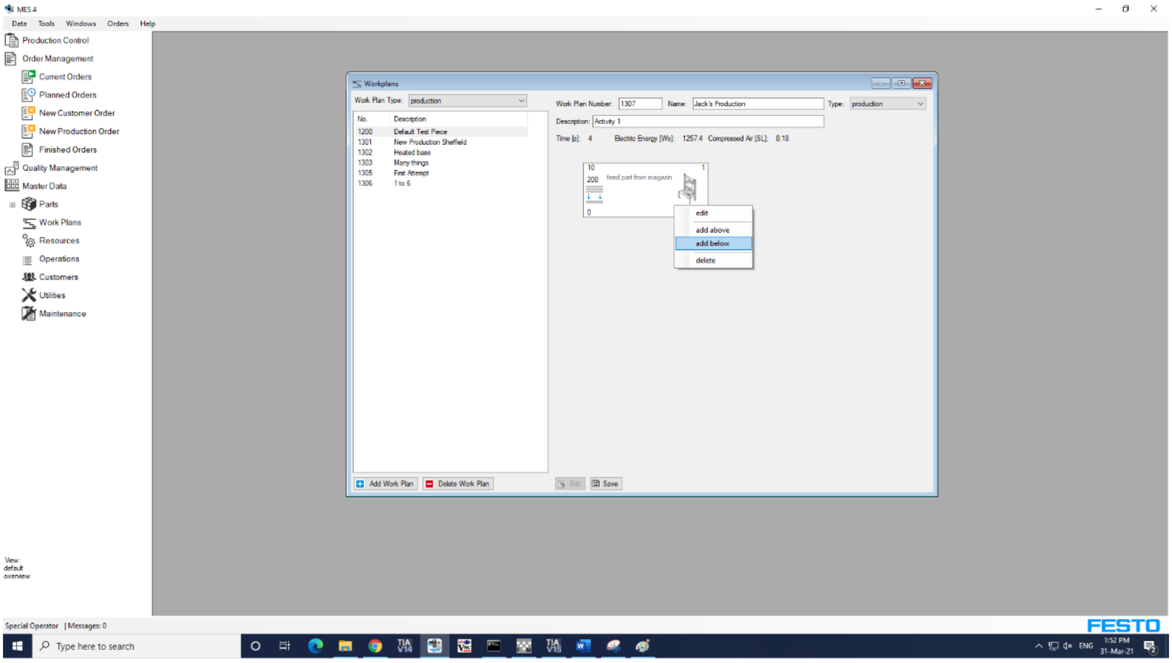
Figure 7.5: Developed Node-RED data stream infrastructure connecting DTDSS components

(d) The Festo CP Manufacturing execution system (MES)

The ERP/MES computer for the Festo CP smart factory is connected to the physical production system using the TCP/IP/Ethernet connection. It is designed to execute the following functions:

1. Production Control: Monitors the current status of the production.
2. Order Management: Manages the orders: creating orders, monitoring already created or current orders.
3. Quality Management: Manages the efficiency report of the different stations and the executed orders.
4. Messages: Manages the messages sent/received during production. These include production and communication status and error messages (production, communication).
5. Master Data: Handles the adding, configuring or deleting parts, work processes and stations.

Figure 7.6 presents the main menu of the MES application.



Work Plan Type: production

No.	Description
1200	Default Test Piece
1301	New Production Sheffield
1302	Heated base
1303	Many things
1305	First Attempt
1306	1 to 6

Work Plan Number: 1307 Name: Jack's Production Type: production

Description: Activity 1

Time [s]: 4 Electric Energy [Ws]: 1257.4 Compressed Air [SL]: 0.18

10 200 feed part from magazin 1 0

Figure 7.6: Festo CP smart factory MES application showing main menu interface

(e) Siemens Mindsphere cloud services

This is a cloud-based platform designed as an open Platform-as-a-service (PaaS) operating system. Developed by Siemens for connecting IoT devices in the industry, it has a cloud server-based infrastructure with a database and other digital applications that allow for data analytics and front-end interaction with the connected world (Customers and supply chain). In an industrial environment, it is used to collect and provide access to operational data and analytical tools through several front-end digital APIs like the Mendix and Node-RED. Customers and other connected users can extract factual information used for daily decisions. Figure 7.7 presents the main menu of the Siemens Mindsphere cloud service.

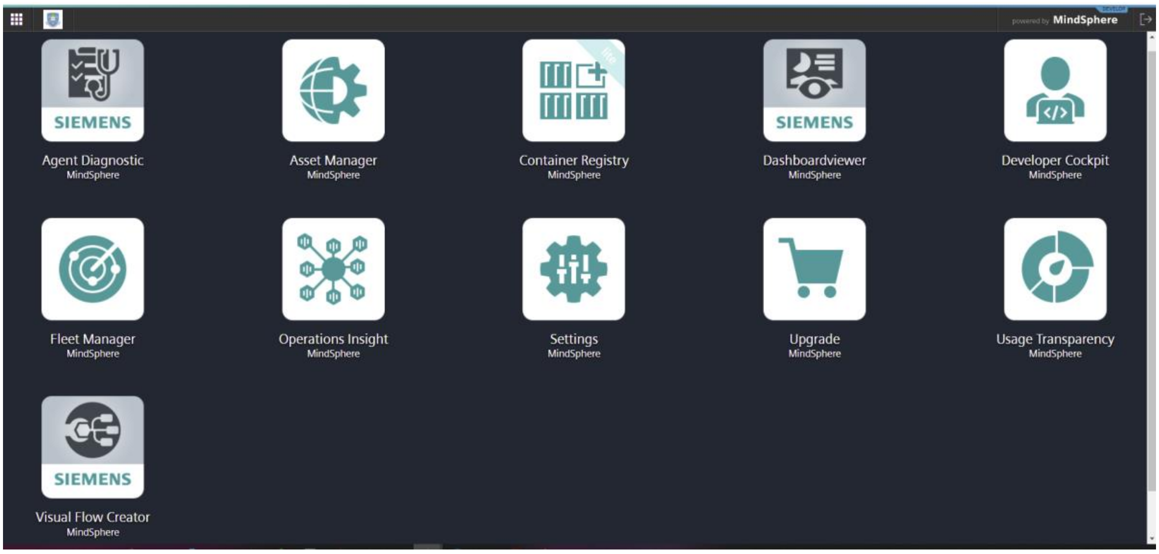


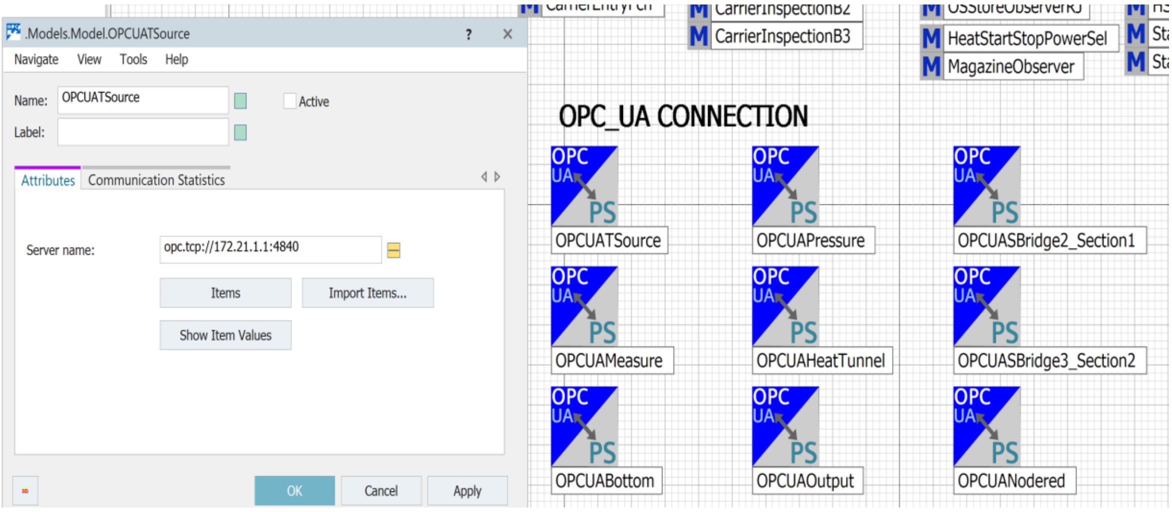
Figure 7.7: Siemens Mindsphere cloud service-Main menu showing different applications and service providers

7.4.5 Interaction loops between the digital twin and associated architecture

The concept of MOM via the internet was used to establish interconnectivity between the Festo CP DT, Customer API and Siemens Mindsphere cloud services. This project used the Node-RED application as the MOM channel. This was chosen because it is cost-free.

(a) Connecting the digital twin to CPPS-Festo CP smart factory

This was achieved using the OPC_UA protocol. The physical asset is the OPC_UA server and the DT is the OPC_UA client (Figure 7.8). Based on this infrastructure, data and control integration was achieved. More details of this have been discussed in detail in Chapters 5 & 6.



Name: OPCUATSource ☐ Active

Label:

Server name: opc.tcp://172.21.1.1:4840

Figure 7.8: OPC_UA server-client connection between the asset-twin. DT as an OPC_UA client connected to the asset an OPC_UA server.

(b) Connecting the digital twin to MES

To connect the MES/ERP layer of the Festo CP smart factory to the DT located in a separate computer, the OPC_UA protocol in conjunction with the Node-RED application was used (Figure 7.9). The MES application has a TCP API interface which is sufficient to establish secured DT access to the MES and its database. The DT as an OPC_UA client is connected to an OPC_UA server node of the Node-RED application. The Node-RED then establishes a connection with the MES application using a TCP request node. The DT can push the production order through to the MES to execute and receive MES data detailing which order the MES is currently executing.

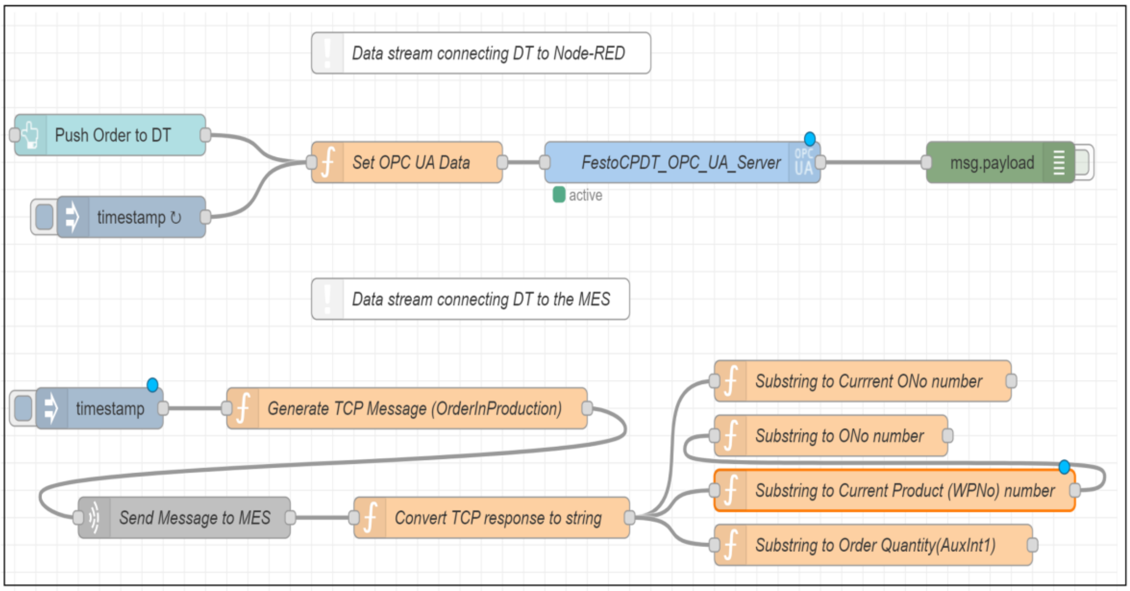
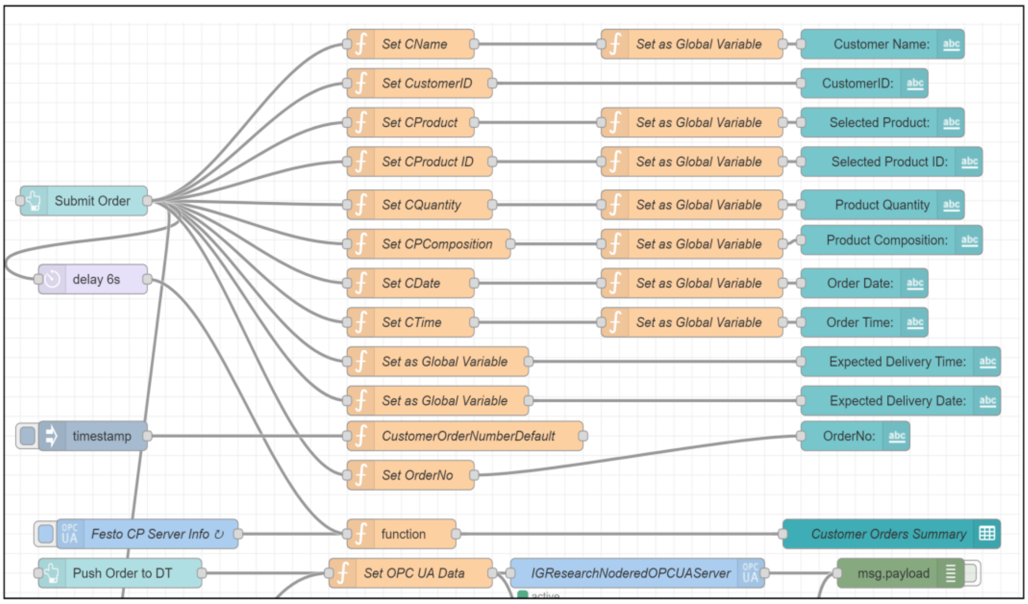


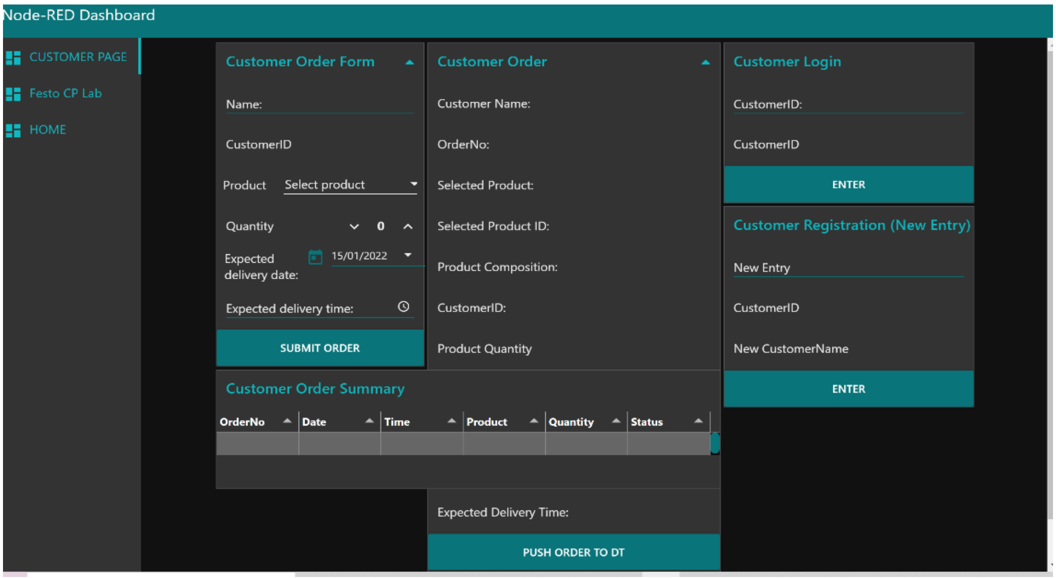
Figure 7.9: Communication thread between the DT and the Fest CP smart factory's MES. (OPC_UA Client-Node-RED OPC_UA server node – Node-RED TCP request node)

(c) Connecting the digital twin to Customer API

The Node-RED application was used to develop the customer front-end API (Figure 7.10). As such the connection was based on the OPC_UA protocol. The DT was the OPC_UA client and the Node-RED has its OPC_US server node. The Node-RED was used to create API GUI for customer interaction (Figure 7.10b). Generated data is sent to the Siemens Mindsphere cloud service using a Node-RED MindConnect node. The DT uses these data streams to collect stored customer orders and at the same time update customer on their orders. Also, other information like the production resource availability can be provided for customer consumption.



(a) Communication established between DT and customer API

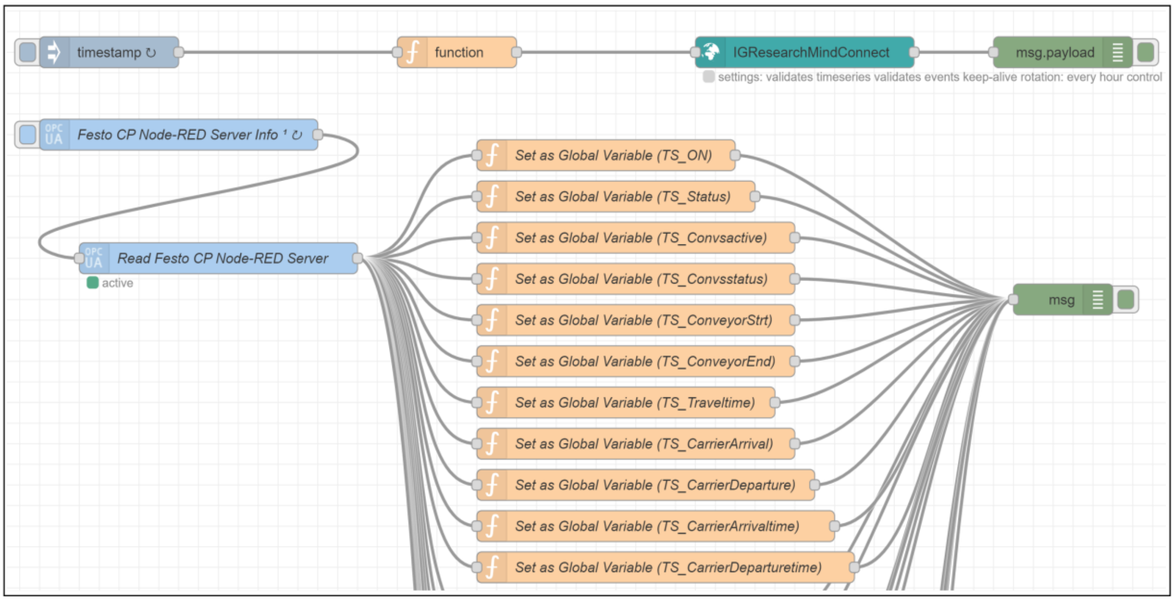


(b) Node-RED customer API (OPC_UA communication)

Figure 7.10: (a) Communication established between DT and (b) Node-RED customer API GUI (OPC_UA communication)

(b) Connecting the digital twin to Siemens Mindsphere cloud services:

The Siemens Mindsphere cloud service is made up of a database and several front-end APIs and analytical tools. It has a dedicated communication agent (MindConnect). This is connected to the Node-RED Mindconnect node and allows HTTP communication. The DT is connected to the Node-RED using the OPC_UA protocol. Figure 7.11 shows the connection between the DT and the Siemens Mindsphere cloud service. In this research, the operational data is processed by the DT. Dt data was pushed to the Siemens Mindsphere cloud database where ERP-level APIs and analytical tools can be used to extract information for managerial decisions. This stage of the research was hindered by the COVID 19 pandemic. As such could not be done.



settings: validates timeseries validates events keep-alive rotation: every hour control

Figure 7.11: Communication between the DT and Siemens Mindsphere cloud services. (OPC_UA, Node-RED and Mindconnect agent)

7.5 Discussion

The Node-RED application (MOM approach) enhanced heterogeneous interconnectivity and communication. The DT platform, MES/ERP platform, the Mindsphere cloud services and the customer API are all interconnected enabling communication and data accessibility. The DTDSS enabled the incorporation of customer data into the generated DT data which is reliably and securely stored in the cloud. Generated data on production, system performance, health monitoring/maintenance and DT experimental data can be uploaded in real-time to the

Mindsphere cloud service. This data is accessible to all connected Front-end APIs with permission. Specific based analytical functions, data distribution and visualisation can be done without adding any further computing pressure or operational risk to the physical asset or DT computer.

Operationally, the DT's MES connected to the customer API and the MES platform presents some benefits like dexterity. The operator can make production orders from the DT and the DT pulls information on production orders made directly on the MES application. Customer orders from the customer API are managed from the DT. This prevents unwanted disruptions of the MES operation from the internet. Customer orders can be confirmed, prioritised and organised into production orders before being forwarded to the MES application.

The implementation of the DTDSS was not without challenges. This has highlighted the interconnectivity/transmission issues conversant with the internet. Sometimes, a production order cannot be made from the DT's MES because the connection between the DT and the MES/ERP application was lost. Another observable issue is the cyber insecurity conversant with the cyber world. Industrial activities should be categorised such that critical or high-risk operations are handled remotely. Control across the internet still poses to be a challenge because of the instability of the internet service. To tackle this, the DT was remotely connected to the Festo CP smart factory. Constraints to communication due to the heterogeneity of the industrial environment are still a concern. Standard communication protocols should continue to be embraced across the industry and collaborations between extensively used data and communication protocols should be encouraged because such collaborations are extended to industrial facilities using them. An example is an OPC_UA-MTConnect collaboration (Onaji et al., 2022). The case study has been used to provide evidence of the viability of the proposed DT decision-making support framework.

7.6 Summary

The DT proposed in this research is a digital interactive and multifunctional platform. Posed with data integration and real-time analytics, it is an effective decision-support system. The proposed CPPS_DTSS extends the functionalities of the product-process DTs to the levels of the MES, ERP and the connected world. This makes other associated production management data and higher-level analytical resources accessible to the DT. This extends and positions the DT as a decision-support system across the RAMI4.0 automation Hierarchy levels to facilitate informed business strategic decisions. Interestingly, the DT data becomes lifecycle data accessible to all connected associates. This promotes collaboration across teams and units all through the lifecycle of the product/services.

The DT data becomes a bigger and better picture of the business as it is a build-up of data from all the RAMI4.0 Hierarchy levels. Business insights are more informed with daily operational information and analyses. The customer is aptly informed and allowed to contribute to the continuous improvement and production of his/her product/services. This creates inclusiveness of the customer and other supply chains in the production and management of the product/services all through its lifecycle.

CHAPTER VIII: RESEARCH CONTRIBUTION, CONCLUSION AND FUTURE WORK

This chapter presents a summary of the thesis report as it highlights the key contributions made in the research work. It also presents a summary of the validation processes and results, highlights the identified limitations of the research, provides some recommendations for future research and finally, concludes the research.

8.1 Research contributions

Dynamic production systems and smart products are part of the expectations of the fourth industrial revolution. The DT concept has been explored and applied in the digitisation and control of manufacturing processes to achieve real-time cyber-physical interaction and integration, involving both product and process digital twins. The novelties and contributions made by this research are summarised below.

Chapter 4 presented answers to the research question *"How can the product and process digital twins be integrated to harness the dependencies between the product and its manufacturing processes?".* This question is aligned with the research objective: "*Design a digital twin architecture for smart factories that supports the integration of both the product and the process digital twins".* A proposed DT architectural framework (Figure 4.4) for smart factories that supports the integration of both the product and the process DTs was presented. The integration of the product and process DTs was based on the dynamic interaction between the product and its production processes. This chapter also informs the reader on the proposed structure, techniques for implementing the various layers and the benefits they present due to usage. In summary, this architecture supports:

- The integration of both product and process DTs to utilise the product-process interaction in real-time simulation
- A closed-loop bidirectional communication between the asset-twin to achieve real-time interactive synchronisation
- Bidirectional control strategy that supports virtual control of the physical system in real-time

The application and benefits of the proposed framework are presented in the case study.

Chapter 5 presented answers to the research question *"What infrastructures are needed to support real-time synchronised interaction between the integrated product-process digital twin and its physical asset?"* This question is aligned with the research objective: "*Develop techniques to integrate product DT, process DT and the physical asset to support real-time synchronised interactive simulation"*. Proposed techniques to integrate and support real-time synchronised simulation between the product DT, process DT and the physical assets included:

- A dependency rule (Eqn. 5.9 & Figure 5.2) that is based on the dynamic interaction between the product and its production processes. This enabled a bidirectional dependency between the product DT and its production process DT
- A Real-time synchronisation mechanism (Figure 5.6 & 5.7) that supports real-time collaborative interaction and simulation between the asset-twin. With this, the product DT is simulated/updated in real-time based on the production data of its physical replica

These two techniques support the framework needed for collaborative interaction between the product-process DT and its physical asset to establish a synchronised real-time interactive environment (Figure 5.6). The CPPS supports its DT simulations, analyses and visualisation with operational data and control. In return, these analytical results are used to manage/control production operations and support operational/managerial decisions. A case study was presented as evidence of the feasibility and effectiveness of the propositions made in this chapter.

Chapter 6 presented answers to the research question *"How can bidirectional control be achieved between the physical system and the DT to enable a two-way interaction?"*. In extension, it also answered the question *"How can this control infrastructure support production flexibility, and product customisation as a decision support mechanism?"* These questions are is aligned with the research objective: "*Establish a cyber-physical control structure using closed control loops at multiple granularities that support real-time synchronized bidirectional control between the asset-twin: collaborative control".* The research contribution in this chapter included:

- A proposed cyber-physical control structure
- Virtual control strategies for manufacturing
- Real-time analyses for production performance improvement, data-driven control and product customisation using the product-centric control method

The proposed cyber-physical control structure (Figure 6.4) for the integrated product-process DT of a CPPS is a bidirectional control strategy that supports virtual control of the physical system in real-time. This utilised the closed-loop bidirectional communication between the asset-twin to integrate the DT virtual control structure with the physical asset's control system, achieve real-time control synchronisation and implemented control strategies. Equipped with the logical connection for virtual control of the physical asset, the integrated DT can execute real-time control, production management and product customisation. A case study was presented as applicative evidence of the usefulness of the cyber-physical control structure in production management and product customisation.

Chapter 7 presented answers to the research question *“How can the digital twin concept support decision-making across the RAMI4.0 automation Hierarchy level?”*. The question is aligned with the research objective: “*Develop a framework that positions the digital twin concept as a decision-support system across the RAMI4.0 architecture Hierarchy levels”.* A framework (Figure 7.1) that positions the CPPS integrated product-process DT as a decision-support system (CPPS_DTDSS) was proposed. It supports:

- The integration and storage of all associated data across the Hierarchy levels of the RAMI4.0 automation architecture
- The accessibility of DT data to cloud-based analytical tools and front-end APIs
- The accessibility of DT analytical results to support production management, business strategic decisions, and inform customers and supply chain associates.

A case study was used to test the proposed structure and used Industry 4.0 technologies.

The concept of integration across the Hierarchy levels of the RAMI4.0 architecture primarily avails data, knowledge and cloud resources to the DT and all interconnected associates of the business chain. The emergence of IoT and digital twinning in manufacturing provides the availability of customer information/opinion and supply chain data for operational decisions. This accessibility transcends through the lifecycle of the product/systems.

8.2 Validation

This section presents a summary of the validation process used and results obtained to validate the digital twin propositions made in this research. Each research proposition was tested on the case study (Section 3.7) and the outcomes were discussed in the Case study and Discussion Sections of Chapters 4 to 7. The validation process was done to determine the level of applicability, reliability and effectiveness of these propositions in various sectors of the manufacturing industry. More details can be found in Appendix G. Two approaches to validation were adopted, and they include:

1) Modelling of an integrated DT for a case study: An Industry 4.0 assembling facility (Section 3.7)
2) Testing and validation using a range of scenarios in the case study

The methodological framework for validation included modelling objectives, model development, experimentation, verification and validation, and recommendations. This methodological sequence was repeated all through the various phases of the practical work outlined in Appendix B.

8.2.1 Validation approach 1: Modelling of an integrated DT for an Industry 4.0 assembling facility.

The proposed DT framework was implemented in the development of a digital twin for the case study: Festo CP smart factory (Section 3.7). Its integrated product-process DT was first developed in its simplest form as supervisory DT (Section 4.6) and was upgraded to a decision-support system that supports the MES, ERP and connected world of the RAMI4.0 architecture Hierarchy levels (Section 7.4). The proposed digital twin frameworks and implementation methods were validated using planned performance metrics for each research proposition. These are summarised in Table 8.1.

Table 8.1: Summary of the outcomes of the validation approach 1

S/no	Propositions	Performance metrics	Outcome
1	Integrating the product DT and the process DT using the proposed framework and the dependency rule approach.	Simultaneous creation of the product DT using production data from the process DT.	This was achieved as presented in Section 4.6.
2	Integrating the product DT, process DT and the physical asset to support real-time synchronised asset-twin interaction.	Real-time update of the virtual assets' behaviour with operational data from physical assets.	This was achieved in near real-time as presented in Section 5.6.
3	A cyber-physical control structure that supports real-time synchronised bidirectional control between the asset-twin.	Controlling the physical assets from virtual assets.	This was achieved for a DCS using PLC controllers with OPC_UA protocols (Section 6.5). Simple control and automated operations were tested.
4	The digital twin data was created by integrating both the operational and virtual data.	Unique identification and association of each product and product DT with its production data. Comparison of DT recorded data of the product in production with MES description for each processed product.	The unique IDs assigned by the MES to the ordered products were used to identify each product and enabled the mapping of production data generated from the various stations also having unique identifiers. The integrated operational and all related virtual data evolved along with its asset-twin with provision to preserve built historical data from instances.
5	Positioning the digital twin as a support decision mechanism across the RAMI4.0 automation Hierarchy level in manufacturing.	Accessing data from the MES/ERP and the connected world levels of the RAMI4.0 automation architecture to build DT data.	Production order and customer data were added to the DT data. DT data can be stored in the cloud and processed information was decimated on need bases. This was achieved as presented in Section 7.4

8.2.2 *Validation approach 2: Testing and validation using a range of scenarios in the case study.*

The second approach investigates the integrated process-product DT for a CPPS as a decision-support system using a range of dynamic scenarios. This approach is aligned with the fifth research objective *"Validate the integrated product-process digital twins as a decision support system for a cyber-physical production system (CPPS) using a range of dynamic scenarios"* and takes into consideration the variability of the manufacturing processes in the industry. The scenarios represent processes common in most manufacturing set-ups like the automobile, assembling, fabrication, production and packaging industry. They were successfully tested as shown in Sections 5.6 and 6.5, thus confirming the viability of the propositions made here to position the integrated product-process DT as a decision-support system for CPPS. A summary of the outcome of this approach is presented in Table 8.2.

Table 8.2: Summary of the outcomes of the validation approach 2

S/no	Propositions	Performance metrics	Outcome
1	Part tracking and real-time product DT representation using the RFID technique.	Comparison of DT recorded data of the product in production with MES description for each processed product.	The unique ID assigned by the MES to a product ordered was used to identify each product DT and enable the mapping of its production data. This data supported the near real-time synchronous creation of the product DT.
2	Virtual control strategies for manufacturing.	Improved production performance, resource management and energy saving.	The Eco production strategies (Section 6.5) reduced waste due to idle stations. automated processes reduced human intervention and reduction in energy losses.
3	Real-time data-driven control.	DT production management actions and control are triggered by generated data.	Applied strategies enabled the DT to monitor these stations and informed the operator preventing downtime due to stalled processes and waiting time.
4	Real-time product customisation using the product-centric control method.	Variation in finished product attributes.	The applied strategy enabled DT to implement customisation in real-time. The Press and Heat stations were reconfigured in real-time by the DT based on specific product specifications that define variability in products.

Based on the nature (assembly line) and size (8 modules assembly line) of the case study, and the modelling approach (DES approach), the outcome of the validation showed reasonable designed performance. The integrated DT platform for the case study with analytical capabilities and real-time synchronisation presented a suitable platform for data integration, analyses and information management that supported data-driven control, production optimisation and informed business decisions. Observably, occasional failure in communication resulted in the termination of virtual control, data transmission and loss of data. This is expected to improve with more robust communication infrastructures like the 5G network. More proof of concept can be done on other manufacturing systems to evaluate the impact of the asset size and complexity, and modelling approach on the DT performance. Nonetheless, the gathered modelling and experimental results were supporting evidence that proved the viability of these research findings and conclusions.

8.3 Research Limitations

This research is limited in several ways. It is believed the integration of the product and process DTs can be done across different simulation platforms; a situation where the product DT is built and simulated on a platform different from the process DT. This scenario was not tested to evaluate the impact of communication constraints across heterogeneous simulation platforms on the DT performance in real-time.

The physical asset is limited to the CPPS with distributed control structure (DCS). Systems that do not support cyber-physical interaction were not included. The propositions here were tested on a miniature Industry 4.0 smart factory: a mimic phone assembly line. There is the need to test these propositions in real manufacturing installations/businesses to evaluate and understand the impact of the complexities and uncertainties inherent in real industrial environments. Also, the application of the cyber-physical control structure was tested on DCS built with PLC controllers. Other controllers like the Microcontrollers, Intelligent Electronic Devices (IEDs) and Programmable Automation Controllers (PACs) were not tested.

The operational speed of the physical processes/systems, the data transmission speed of the communication network infrastructure and the DT modelling platform impact the real-time virtual representation/simulation of the physical asset activity. The case study used in this research has a moderate operational speed across its activities, as such the DT platform with a data transmission speed of approximately 30ms could represent the production data in near real-time: i.e. the digital representation lags the operational instances. Production processes/systems with higher operational speed or DT modelling platforms with lower data transmission speeds were not tested to validate the viability of the propositions made in such operational conditions.

The communication link that connects the physical asset with the DT to support real-time interaction is based on the premise that it operates on a communication protocol that supports a unified data structure and standardised communication mechanism. Also, communication between the asset-twin over the internet has not been tested. This includes managing cloud-based integrated DTs. The impact of the internet traffic, transmission band and cyber security have not been checked over the performance, reliability and feasibility of the propositions made in this research.

Lastly, the DT development and simulation were restricted to the DES approach. Other simulation approaches like the Monte Carlo/Risk analysis, Systems dynamic, Agent-based modelling or a hybrid of these methods have not been tested.

8.4 Recommendations for future work

Results in this research also highlight areas that should be given more research attention. More research on DT modelling framework, DT modelling tools and applicative demonstrations from different fields would prove its diversified usefulness, highlight more business benefits, and encourage more investment and further adoption in existing industrial infrastructures. Much has been done within the simulation and modelling area. Simulation platforms are been upgraded to DT standards, while this is ongoing, digital platforms that support DES simulation of production flow, support CAD representation and analysis of the product should be considered. There is still the need to encourage the standardisation of communication and data semantics. It would increase interconnectivity across the heterogeneous communication network.

The integration of the product and process DTs was proposed based on the logical relationship existing between the product and its production process. Here, it is presented as a tool for improving the performances of the production system, the quality of the product, implementing product customisation and creating a holistic informatic picture of the product and its associated production/business. Future research should provide more applicative evidence across the manufacturing industry to establish the concept of integrating the product and process DTs as a potential digital platform that harnesses the logical relationship between the product and its production processes.

The DT stands to be the futuristic decision-support system equipped with data integration capacity and business analytics. With the influx of data from all levels of the system, it will continue to assist in providing more fact-based information and suggestions to the operator, line manager or any other interest group. More research in the digitisation of manufacturing processes should include an investigation of the DT management of information flow, the robustness of DT data management and the reliability of DT data creation. With the influx of data from all levels of the system, it will continue to assist in providing more fact-based information and suggestions to the operator, line manager or any other interest group. One of the observable challenges here is the management of information flow. More has to be researched on the robustness of data management with such an expanding complex network of data, digital tools and users. Information confidentiality, availability and security are major concerns when traversing the internet. Another issue of concern is the reliability of digital twin data creation. The evolution of DT data involves the creation of instances, historical data and analytical results. The reliability of their connections/mapping principles needs more research.

Innovations in IoT and cloud computing does increase the connectivity of the industrial shop floor with its associate enterprise network. This makes it possible for analytical tools to be launched from different platforms with access to DT data, and create information that can be centralised and made available to all associated parties. The integrated DT can be researched as a mechanism positioned as a data generator, integrator and needed platform for robust implementation of analytical-based production and business strategic decisions at the shop floor and enterprise level.

Another factor to be considered in digital twinning is scalability in manufacturing infrastructure/businesses. Implemented DTs for such systems should be scalable to create room for changes in size/application/performance/business/strategic demands. Implementing DT in manufacturing calls for the consideration of an implementation strategy. This takes into cognisance its creation, lifecycle usage and maintenance, data (sources, formats, analytics, visualisation, security and ownership), connectivity, cyber-security and ownership (Dittmann et al., 2021). Some identified scalability challenges include the DT lifecycle management, resource (including data) ownership, available data fragmentation (format, quality), traditional culture of data usage and insight and the cost of DT (creation, asset sensoring and data streaming, maintenance, scaling, data management and ecosystems integration) (Eckhart and Eckhart, 2019; Dittmann et al., 2021).

In response to some of these identified DT scalability issues, a framework for determining and developing the digital twin for your business was proposed (Appendix E). This is intended to enable businesses to methodically define their digital needs, identify resources, and create and implement a scalable framework that enables a systematic continuous improvement or adjustment to strategic business decisions. The sixth step creates room for DT upgrade (up/down scaling in response to business needs). As a recommendation, companies should consider

1) Identifying major processes which can be modelled as off-the-shelf DTs

2) Introduce IoT level DTs where IoT ontologies and the IoT “Plug and Play” strategy improves efficiency in the DT lifecycle maintenance using off-the-shelf DT resources
3) Introduce Cloud based DTs at ecosystem levels where DT resources can be extensively shared
4) Use standardised ontologies as guidance on describing device information models/data semantics. For instance, the Wide Web Consortium for sensor ontologies, OPC_UA companion specifications and ISO 13399. This would support supply chain integration and collaborations.

The existence and continued use of legacy systems in manufacturing pose some challenges to implementing DT/digital transformation in manufacturing. This is because they were not designed for the current digital services and applications in demand. If used, the DT representation would be flawed. These constraints are seen in limited infrastructural connectivity (communication infrastructures, protocols and speed), limited data access and incompatible technologies with limited virtual access, integration and high cyber-security risk (Eckhart and Eckhart, 2019).

To be able to integrate the proposed CPPS integrated DT framework with legacy systems, the following recommendations are presented to transform the asset into a CPPS:

1) These systems can be replaced with cyber-physical systems if affordable
2) They can be modified to improve the computing capacity and virtual connectivity by introducing more computing devices, IoTs, sensoring connections and interfaces.
3) The existing processes can be redesigned to improve the virtual description of devices/services using standardised information model ontologies and data semantics

4) Communication infrastructures can be upgraded to improve communication speed, capacity and cyber-security.
5) In the case of human operations, such activities can be modelled into machine procedures and human operation capturing devices (AR/VR) incorporated

Future research should look at the development of DTs in manufacturing using other simulation approaches like the Monte Carlo/Risk analysis, Systems dynamic, Agent-based modelling or a hybrid approach. This checks the viability of each approach and creates room for compatibility within the diversified industry. Finally, the idea of integrating DTs from the different Hierarchy levels of the RAMI4.0 automation architecture needs to be tested. In this wise, how can they be interconnected?, how can the DT data be built? and how can technologies like Virtual reality (VR), Augmented reality (AR), the Cloud and Edge computing improve the applicability of the DT concept across the business supply chain?

8.5 Conclusion

The journey so far in the restructuring of the manufacturing industry aligned with the fourth industrial revolution has made a great impact on the transition to a digital era. Anchored on innovations in sectors like ICT, AI, and sensor data fusion, the digitisation of manufacturing has resulted in strategies like Industry 4.0 and Made in China (Onaji et al.,2020). These strategies have given birth to concepts like cyber-physical systems, IIoT, digital twin, DMU, and digital avatars. The integration of OP and ICT has been the game changer resulting in what is now known as smart industrial environments (Smart shopfloors, smart factories, smart products, smart supply chains etc.).

The concept of digital twinning is embraced as the futuristic tool needed to advance digitisation in the industry to the next level of integration across the Hierarchy levels of the RAMI4.0

automation architecture and the entire business supply chain. This research has presented applicative pieces of evidence on the dexterity of the concept in generating, integrating and distributing data, and extracting information that improves the performances and decisions made across the business infrastructure.

The benefits of the DT concept in the industry are enormous as presented in most chapters of this report. Companies need to define their digital needs to identify what functions of the DT can be tapped to improve their chances of surviving in the forthcoming digital era. The business chain is continuously been interconnected, thus traversing the influence of the supply chain and the customer across the business and the lifecycle of the product/service. Also, the COVID 19 pandemic has sped up the transition process of our working environment into a highly virtual sphere. Companies especially SMEs need to strategize to ensure they are not sunk by this inconsiderate wave of changes in economics.

In summary, this research has highlighted how dexterous the virtual space is and what potentials are made available to industry by the integration of the physical and virtual space. The bidirectional communication established between a coupled CPPS and its integrated product-process DT provides the infrastructure for a real-time synchronised closed-loop interaction. The interdependence between the asset-twin is geared towards improving the production performance based on factual data, integration, collaboration and flexibility of the CPPS. While the digital twin collects operational data for real-time monitoring, simulation and analytics, it should be able to function as a decision-support system as it executes real-time control, production management and product customisation.

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APPENDICES

Appendix A: Highlights of Industry 4.0 objectives in the manufacturing

The fourth industrial revolution advocates for more inclusion of intelligence in the networking of the manufacturing industry (machines and processes) using artificial intelligence (AI) and information and communication technology (ICT). This brings the following possibilities (Platform Industrie 4.0, 2021):

1. *Flexible production:* A digitally integrated business chain of supply enhances better coordination of all involved processes/activities directly or indirectly geared towards the creation of the product(s), which would result in efficient utilisation of all associated scarce resources.
2. *Reconfigurable factory:* The introduction of modular infrastructure helps the reconfiguration of factory resources to achieve specific tasks. This creates an opportunity for increased variety in product types as individualised products can be manufactured at affordable prices and turnaround
3. *Customer-centred solutions:* Customers' inputs to product design can be considered. Smart products can provide customer usage data to the producer. This can be used to improve the product and offer other customers innovative services.
4. *Optimised logistics:* Smart logistic networks enable optimisation using AI algorithms to establish effective delivery routes and promote the push-pull techniques for resource distribution along the supply chain and production line.
5. *Use of data:* Isolated information silos can be linked to harnessing both design data, and operational and product usage data. Data analysis generates information that can improve the efficiency of the manufacturing process. This also provides new business

models and services as new techniques and technologies bring about new needs. Also, it promotes predictive maintenance as machines and equipment generate operational and environmental data enabling early prediction and detection of faults to reduce or prevent failures and downtimes.

6. *Resource-saving circular economy:* This supports the integration of product data all through their lifecycle. The concept of scarce resource management is suited with more tools as products are managed using data all through their lifecycle. Natural resources can be tracked and reused. Resources hazardous to the environment can be effectively managed to reduce their impact on the natural environment.

Technical requirements for this evolution is been addressed by the integration of generic concepts like decentralized control, advanced connectivity (IoT functionalities), digital twin, cyber-physical system (CPS), Industrial Internet of Things (IoT), Big data analytics (Cloud computing), sensory fusion with operational technologies (OT) like modular structures. In summary, the fourth industrial revolution introduces smart automated cyber-physical production systems making it easier to identify, locate, track, monitor and optimise production (Rojko, 2017). The combination of other technologies like AI, IoT, Cloud and Edge computing with the digital twin concept is a technical step taken in charting the prospects of digitisation across the supply chain.

Appendix B: Practical work methodology

The research plan for practical work was designed considering existing industrial infrastructures-communication, digital accessibility and functionalities. This was focused on identifying feasible techniques/methods to implement the proposed integrated product-process DT architecture in building an interactive and immersive predictive DT for existing Industry 4.0 CPPS. This strategy allowed for a systematic transformation of the case study's DT from a basic supervisory DT to an interactive and immersive predictive DT. This entails defining and modelling a digital framework of the physical system and then adding all necessary details/complexities in layers. This should reflect the complexities and uncertainties experienced in real manufacturing environments.

To implement this approach, the first step involved the development of a supervisory DT of a Festo CP production system. This in its simplest form is a monitoring virtual model fed real-time streams of data from sensory devices enabling an interactive simulation and monitoring of the physical system during production. After verification and validation of this DT, it was then used as the framework for the DT of higher threshold (interactive and immersive predictive DTs with control and decision-making capabilities). This is a closed-loop interactive DT designed to be a decision-support system with access to data and resources across the RAMI4.0 Hierarchy levels.

Established methodology for the practical work

The following steps were used to establish a methodology for the practical work. This took into consideration the steps proposed in Tao et al., (2018) for the development of the DT. This approach facilitated the building of the DT model using a structured layout.

Step (1): Model development of the physical product/process

- DES simulation model: System elements, behaviour, production layout and flow
- Implementation of the developed digital twin architecture- *IT* ontology for system integration, communication and data integration and management.

Step (2): Data processing to facilitate design decision-making

Step (3): Simulation of product/process behaviours in the virtual environment

Step (4): Verification of model behaviour

- Compare with physical asset performance of recommended behaviours
- Make necessary modelling modifications to achieve simulation objectives

Step (5): Establish real-time, two-way and secure connections between the physical and virtual product

- Digital link and data acquisition using the *RFID* technique and OPC_UA protocol

Step (6): Collect all kinds of product-related data from different sources

- Supervision and monitoring of physical assets via the virtual model

Step (7): Implement identified control techniques to achieve bidirectional control

Step (8): Inclusion of cloud computing techniques in data analytics and machine learning

    - Verification and validation

Step (9): Validation (Simulation/testing)

The following scenarios were validated:

v. Updating virtual assets from physical assets (Figure 3.2, index a)

vi. Linking virtual products with virtual processes (Figure 3.2, index b)

vii. Controlling physical assets from virtual assets (Figure 6.4)

viii. DT accessibility across the RAMI4.0 hierarchy levels (MES/ERP and Connected world) (Figure 7.1)

Simulations included:

- Offline simulations and experimentation
- Online/real-time simulations
- Data acquisition and distribution across RAMI4.0 Hierarchy levels.

Appendix C: Research methods/techniques

This section critically describes the key concepts, techniques and methods used in achieving the research objectives.

3.1 Reference Industry 4.0 architecture

The RAMI4.0 (Figure C1) is the automation reference architecture for Industry 4.0. This model in pursuit of a uniform structure and standards makes it possible for gradual migration from Industry 3.0 to Industry 4.0 (DIN & DKE, 2018). It minimises the number of different standards required despite the integration of information, automation and operational technologies in manufacturing. Production objects have records of their data and function through their lifecycle (left horizontal axis) in six layers (vertical axis). In response to recent technological advancements, the traditional automation pyramid has been modified to define a new set of hierarchy levels (right horizontal axis) to include product, field device and the connected world (Figure C1).

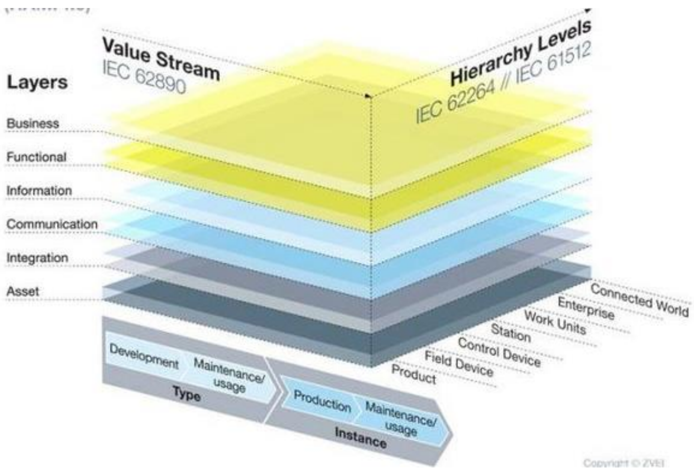


Figure C1: Reference Industry 4.0 architecture (RAMI 4.0) Source (Rojko, 2017)

Key to this concept is the integration of the physical asset with its digital image enabling a continuous accumulation of relevant data (layers) right from the design phase all through its lifecycle. The RAMI 4.0 was chosen as a reference framework for building the DT architecture. It considers existing operational standards, thus providing unification in standards and structure for the next generation of industrial infrastructures intended to use Industry 4.0 technology and techniques. Also, it is wildly adapted and has thoroughly been worked with as a standard road map by the industrial and academic community (Rojko, 2017). For most companies, adopting the Industry 4.0 initiative would mean building a smart business structure/refined structure on already existing equipment, technologies and standards (Zezulka et al., 2016; Rojko, 2017). The digital twin is a mirror of its physical twin as such, it would be strategic to make use of a standardised building framework composed of layers and domains.

(a) Integrating RAM14 layers using data

One prospective advantage of the digital twin in manufacturing is the possible connectivity and data integration of all layers of the RAMI4.0 automation architecture. Data from the managerial, customer and supply chain is integrated with the DT data of the CPPS DT (Coronado, et al., 2018). This DT data is made available to all Hierarchy levels. Production-associated information becomes more accessible to operations and data from operations becomes accessible to support daily business decisions and policies.

3.2 Cyber-physical production systems (CPPS)

Industry 4.0 smart production lines are built using cyber-physical systems (CPS). These are operational machine networks integrated with ICT components and sensors. These autonomous systems are meant to make their own decisions based on machine learning algorithms, real-time operational data and environmental conditions data, data analytics and successful past behaviours (Rojko, 2017; Ward et al., 2021). Systems being able to monitor their state through their lifecycle enhances proactive maintenance strategies.

Employing artificial intelligence in manufacturing systems transforms traditional production systems into CPPS. This is a progressive step towards flexibility, and increased productivity with the more efficient use of resources and energy (Avventuroso, et al., 2017). Having an aggregate model that allows different physical systems to interact with the DT still poses to be a major challenge in the actualisation of the integrated process-product DT framework (Schroeder et al., 2016). Scalable and modular structures are being introduced to shorten engineering time in production processes and the cost of mass customisation. This approach enables last-minute changes to production and flexibly responds to disruptions and failures caused by suppliers. Furthermore, the introduction of the CPPS paradigm into the production system comes with more enhancements. It expedites a new era of production as it introduces autonomous integrated, adaptable production systems (Vachalek et al., 2017).

3.3 System identification and modelling

System identification is the first step taken in defining the physical system to be modelled. This identifies the structural and functional composition of the production system and associated products. This also covers the identification of the digital accessibility of the system. The DES modelling theory is used to define the graphical and algebraic specifications used to represent the composition, structure and operation of the CPPS and its product(s). The symbol " $<>$ " is used to represent the logical composition and characteristics of the logical model and the symbol " $\times$ " is used to represent the logical interaction between its elements.

(a) Production system configuration (elements and relationships)

A manufacturing/production system can be described by its components, operation and the logical relationship between them. The 4MIE method outlines these components as resources (R) namely man, machine, material, method and its operating environment. Under the production organisation, these elements are configured to form subsystems/units based on a hierarchical production structure and material logistics network (Jiang et al. 2021). The logistics network (L_{net}) exist within the subsystem/unit and among the subsystem/units. This defines and handles the material flow that occurs between the logistic, processing and storage facilities.

(b) Physical system representation

Production cell model: The production cell (P_c) of a production system is considered the largest independent unit constructed based on the class of services and control. Its composition is also defined using the 4MIE method. The logical and logistic configuration of these resources is dependent on the production design. The services provided are either adding value (assembling/processing) to the flow entity or simply providing some logistics (packaging/transport/buffer/storage).

Product: A manufactured product is that unique/refined entity that is a result of a set of predefined manufacturing processes. These manufacturing processes provide services that add value/attributes to the product by refining raw materials and/or assembling parts to create a finished product. The product attributes includes tangible properties like the geometric structure, material composition, weight, size and colour and intangible characteristics like quality, value, reliability, performance and behaviour.

During production, the work in progress (WIP) is known as the flow entity. It is described by its attributes (A) and a measure of the quality of those attributes (Q). In smart production, the flow entity is a smart active workpiece pushed through the system for processing. It has a memory that contains its unique identification number and production information. During production, the state of the product is important, and they include work in progress (WIP)/approved/rejected/faulty/finished states. Logically, this can be viewed as an encapsulation of the basic details of its state, attributes and other information.

3.4 Product-process dependencies

There exist dependencies between the product and the processes from which they have been created. The product defines the production processes and the process configurations. Furthermore, product quality attributes are highly dependent on the effectiveness of the value-added processes that transform the raw materials to finished products. To promote flexibility in production, production line reconfigurations can be driven by the virtual product via the virtual process. Smart production systems can be reconfigured using virtual configurations.

(a) The physical product-process and interaction model

In the production phase, the product is logically dependent $(\bowtie)$ on its production processes (Figure C2). During production, this logical dynamic interaction(x) in the physical space is in one direction (Eqn. C1).

$$Processes \overset{\bowtie}{\rightarrow} Product \qquad \text{(Eqn. C1)}$$

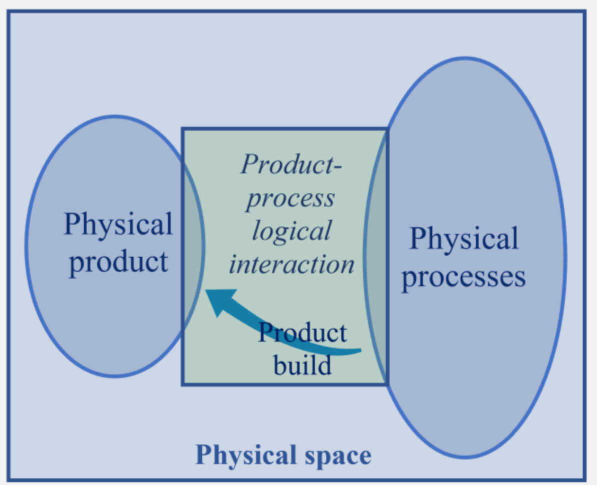


Figure C2: Product-process interaction in the production phase

This dynamic interaction builds the finished product thus defining its actual attributes and quality. This is illustrated in Figure C3.

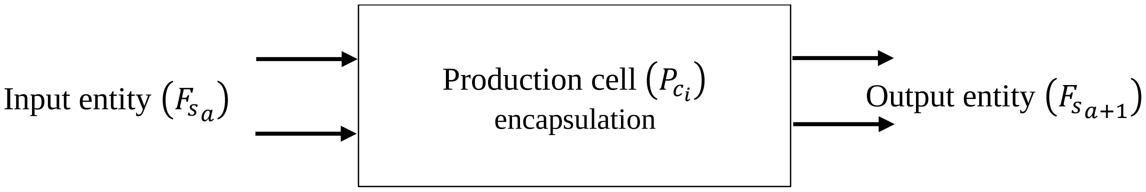


Figure C3: Product-process interaction

During production, the logical interaction between the value-added services(S_i) and the flow entity (F) yields an improved version of the flow entity $(F_{s_{a+1}})$. If the services are just logistic services then Eqn. C2 holds:

$$F_{s_{a+1}} = F_{s_a} \qquad \text{(Eqn. C2)}$$

Else:

$$F_{s_a} \times S_i \rightarrow F_{s_{a+1}} \qquad \text{(Eqn. C3)}$$

$$S_i = \left\{S_{i,j} \,|i = 0, \dots, n, j = 0, .. b\right\} \qquad \text{(Eqn. C4)}$$

where

S_i: Service set of P_{c_i}

i: ith production cell

j: jth service

F_{s_a}: Attribute composition of the flow entity before entering P_{c_i}

$F_{s_{a+1}}$: Attribute composition of the flow entity after interaction with ith production cell (P_{c_i})

The logical interaction ($\times$) between the services and the flow entity(F_{s_a}) transforms the flow entity (Eqn. C3). The composition of the production cell services(S_i) as shown in Eqn. C4 outlines its functionality. The impact of these services (S_i) can be weighed (W_i). This defines the value of the services and could be measured relative to a predefined benchmark. Logically, the contribution of the production cell to the flow entity transformation can be algebraically presented in Eqn. C5 and illustrated in Figure C4.

$$(S_i, W_i) = \{(S_{i,j}, W_{i,j}) | i = 1, \dots, n, j = 1, \dots, q\} \qquad \text{(Eqn. C5)}$$

Where

i: Production cell index

j: Service and corresponding weight index

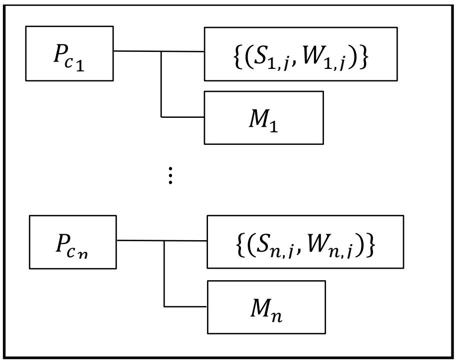


Figure C4: Production cell services (S_i) and service weight (W_i) and the state of the production cell (M_n)

The impact of the transformation on the flow entity is observed in its attributes and can be weighed (Q_Z). It defines the quality of the product against a predefined benchmark. Logically, the result of the interaction on the flow entity can be algebraically presented in Eqn. C6 and illustrated in Figure C5.

$$F_{s_{a+1}} = \{(A_z, Q_z) | z = 1, \dots, b\} \qquad \text{(Eqn. C6)}$$

Where

$a + 1$: Flow entity index after interacting with production cell services

z: Attribute and corresponding weight index

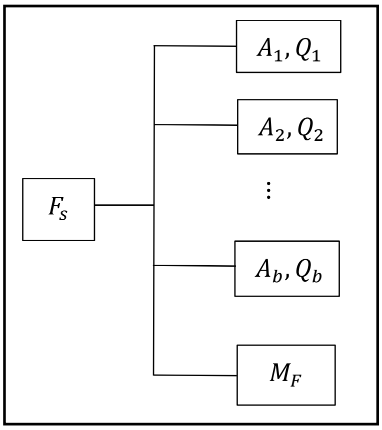


Figure C5: Flow entity attributes (A_b) and attribute weight (Q_b) and the state of the production cell (M_n)

3.5 The digital twin for manufacturing

The digital twin concept is viewed beyond engineering. It is considered an instrument for integrating business strategies along the business supply chain (Microsoft 2017). At its basic level, the DT (Figure 2.3) is a virtual replica of its physical asset built mainly of structural and behavioural models mainly for basic control, monitoring and evaluation of its performance (Onaji et al., 2022). Key to the concept is the integration of the physical and virtual space all through the lifecycle of the subject-product/process. This establishes a cyber-physical space for effective data generation and uses not just for analyses but for real-time smart operations. In production, it is used for monitoring and dynamic management, enhanced flexibility and controllability of the physical asset (Ding et al., 2019).

(a) The digital product

The virtual product is a representation of the product properties. These reflect the characteristics unique to the product (Haag, & Anderl, 2018). This twin is active during production/assembling. The product in 3D visualisation/animation is a composition of two parts assembled. During production, the virtual product is updated with data on its assembling and processing using the RFID technique.

(b) Process digital twin

The process DT is a digital representation of the production line. Seen at the systems level, it is an integrated data-oriented composition of all unit-level process elements. This includes manufacturing equipment, material flow, operating systems, human resources, and other value stream elements (Onaji et al., 2022). Models considered include Production capability models for production capability and characterisation, Process models to link process-related parameters to product design attributes and mirror the interaction between a product and the model of its corresponding production process model (Cheng et al., 2018).

(c) DT simulation

The built Festo CP smart factory DT is in 3D visualisation. The virtual models are considered DTs because of the established real-time connectivity between the asset-twin using the OPC_UA protocol. In online mode, the DT twin simulation is managed by the physical asset behaviours (process time, travel time, waiting time, process flow etc) in near real-time. In offline mode, the DT reflect a recorded instance of its physical asset. Experiments are carried out using the DT to provide metrics to support the analysis of production, scheduling or business decisions.

The strategy adopted in the development of the proposed product-process DT involved a gradual evolution of a supervisory fixed process-product DT to an immersive variable process-product DT. Variability in this case reflects the reconfiguration of the workstations and product attributes to suit predefined products or product customisation.

(d) Digital twin data

Data in this research was considered to include system design data, operational data (static and real-time), process sequence and parameter relationships and all production-associated data. All data collected/generated or used by the DT is assumed to be called the DT data. This is an integration of all associated production data.

i. *Data generation:* DT algorithms extract operational data, generate virtual data that represents the physical system behaviour and generate virtual data that reflects the model's behaviour in terms of actions/response/analyses/visualisation. These data can be in different formats-timestamps, quantities/states.

ii. *Operational data from the real system:* Two approaches have been adopted to extract operational data. Operational data from the controllers like PLCs and sensors/transducers can be extracted and stored, also control triggers can be used to generate virtual data. The DT model variables/elements were mapped to OPC_UA tags. These tags are triggers that prompt the virtual element to generate the required data or/and asset behaviour.

    a. *Extraction by physical system:* Here, the data is generated by the physical system and stored in the controller. This is then pooled from the OPC_UA table and stored in the model.

    b. *Virtual data generation using physical system triggers:* Data describing operational activities is generated in the model using triggers from the physical system.

iii. *Virtual data generation from virtual operations and sensors:* Virtual data not triggered by the physical system includes virtual activities needed to generate desired digital information. It also includes activities that cannot be directly extracted from the physical system but are modelled. For instance virtual model id, part movements in areas without sensors.

iv. *Other production-related data:* Other production data relating to production order/customer/supply chain can be pulled from the MES/ERP platforms and/or extracted from the physical system manuals/documents and incorporated into the model platform.

v. *Data integration:* The digital twin data integration was achieved using the concept of data mapping. This involved:

- The integration of all operational data,
- The integration of all associated virtual data and lastly,
- The cyber-physical data integration.

The logical relationship between all associated elements of the CPPS and all associated production processes/flow/logistics/resources formed the basis for this approach. Figure C6 highlights the sequence of creating the DT data.

vi. *Data storage:* All data pulled into the virtual platform correspond to single data semantics. Based on the collaborative dependencies between the physical system and virtual twin, All relational data on the product and processes are linked and stored.

vii. *Data evolution:* A set of data is said to evolve if it can establish the current status or reflect changes in its source. These could include changes in information content and structure. A good data management system should be able to retain historical data with a well-established connection to its current state and evidence of evolution. This could be a record of the changes/modifications and the time of implemented changes. Data management systems can map relational data to their sources. Updates or modifications are properly managed to reflect the current status of the data source and all interconnected data instances/bases are kept up to date. Keeping track of these changes is very useful in health monitoring.

This research supports the evolution of the DT data, therefore it should be a composition of the physical asset’s lifecycle storyline/picture. To achieve evolution, its needs a database(s), algorithms and data management mechanisms to keep historical and instance data, track changes leading to data evolution and keep all related databases/instances updated. Constrained by the finite nature of computer processors and storage devices, cloud services/storage is looked at as a prospective solution.

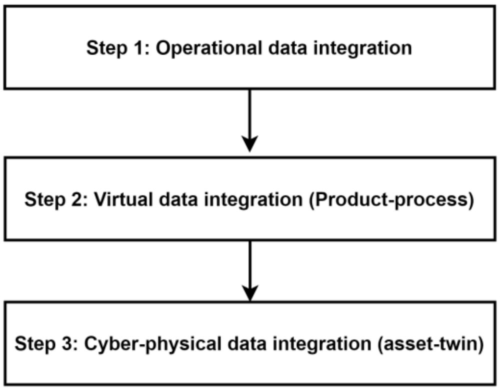


Figure C6: Methodology for establishing data integration

3.6 The Concept of integration

Integration in this research is considered a concept that allows for the interconnectivity, interaction and interdependency of related/associated components/functionalities to form a unified platform. This could include physical components like subsystems, data, control structures or even layers within an architecture. Integration in production systems was considered under the following categories: physical asset integration, virtual space integration (product and process digital twin) and cyber-physical integration.

(a) Physical asset integration (Cyber-physical systems)

The integration of modern information technologies with operational technologies has given rise to cyber-physical systems that have sensing and communication capabilities. Some of these systems have some level of intelligence. Techniques like modular structures in production systems, sensor fusion, artificial intelligence and better communication protocols like the profiNet, TCP/IP/Ethernet protocol have redefined modern production systems to support physical asset integration. These capabilities enable them to sense their environment, react/respond to sensed information, collaborate with connected systems and very importantly provide operational data for analytical purposes.

(b) Virtual space integration

In literature, the product and the process DTs have been discussed independently. This research attempts to integrate them and as such needs to carry out virtual space integration. This idea is based on the fact that products and their production processes are interdependent. These dependencies could be harnessed to improve product quality, production efficiency, reduce waste and shorten the time-to-market. Model standardization/specifications stand out to be a way forward to eliminate heterogeneity in generated data. Data and resource integration within the virtual space would allow for both DTs to share resources and collaborate to improve each other’s performance.

Simulation software that can accommodate dynamic CAD visuals, simulation speed, data processing, analytical tools, physical-virtual connectivity like OPC_UA and simulation speed would support an integrated product-process DT. OPC_UA compliant components of the production network make use of unified data semantics. They can generate and transmit/receive data within the network. This can be collated into a single database, processed, analysed and made available to all interest groups. In recent times, object-oriented simulation software like Plan simulation Tecnomatix from Siemens has been improved for digital twinning.

(c) Cyber-physical integration

With a focus on the production phase of the product, the integration of both the physical and virtual space would enable the physical system to benefit from the functionalities obtainable in the virtual space. From the information perspective, operational data is made available to virtual analytical tools. These additional data reduce engineering estimations and errors due to uncertainties. It ultimately improves the precision of operational analyses and decisions made. Furthermore, with the OPC_UA protocol, operational data and data-driven control can be achieved in real-time.

From a control and automation perspective, the virtual space expands the system control capacity by adding more interfaces for human engagement, establishing interconnectivity between independent control structures, expanding control configuration/collaborations and providing real-time data-driven control (Onaji et al., 2022).

3.7 Cyber-physical connections and interactions

To achieve cyber-physical integration using data and control, there has to be an established bidirectional communication link between all associated elements of the cyber-physical system. This enables the desired interaction and accessibility of resources. These communications exist between the asset-twin.

(a) Connecting the product twin to the product

Research interest is in the production phase of the product. For a smart production system, the physical product/workpiece in production is contained in a smart container equipped with communication facilities like radio frequency identification (RFID) technology. This container stores all related production data and can transmit such information to the virtual platform. For this research, the physical product is connected to its DT using the RFID technique in conjunction with the OPC_UA connection. The RFID technique enables real-time product/part tracking, data storage and transportation along the production line. This made it possible to track the production process and update the virtual twin with reliable real-time information. As the physical product was assembled, its virtual counterpart was updated as it passed through the production line.

(b) Connecting the process twin to the physical system

The process DT comprises simulation models whose granularities were defined by the functionalities and modular structure identified within the physical system. It was built based on the identified processes to be digitised, accessible operational data, and process behaviour/functionalities to be modelled/visualised. Communication between the physical system and the digital twin is highly dependent on the digital accessibility of the existing system architecture. The communication system of the physical system is built on TCP/IP/Ethernet protocol. Upon this communication structure, the OPC_UA protocol provides a standardised and robust channel to establish a bidirectional communication link, generate and transmit data in a unified format irrespective of the source/vendor.

Based on a server-client structure, the physical system is configured to be a server and the digital twin a client. Both communicate via the OPC_UA table. These tables are a list of dynamic tags of the physical system mapped to virtual alias called in the virtual space. A change in the values or states of these tags is used to trigger virtual activities. Also, virtual activities can be used to update the values/states of these tags which in turn trigger activities within the physical systems.

(c) Connecting the product DT to the process DT

The product information model is mapped to the relevant process information models. These data models are updated with production data as the flow entity/workpiece passes through the process DT. A product type determines its production work plan. The work plan is a description of the product attributes and the configuration of its production flow. it also gives details of the resources to be used (workstations, processes and respective process attributes). For example, heating temperature setpoint, drilling depth and processing time. In the virtual space, the product DT's properties are mapped to the related processes that are responsible for adding them to the product. This plays a key role in the data structure created within the DT database.

Product data mapped to the relevant process data is used to manage the workpiece path through the process DT model. From the control perspective, using the product-centric control method, control functionalities/loops can be interconnected to this product-process relationship. This connection enables the product DT to manage its production and introduce product customisation using predefined specifications.

3.8 Real-time, two-way and secure connections between physical and virtual spaces

Most industrial communication networks are built using the ProfiNet/TCP/IP Ethernet protocols. This provides better-improved communication, cyber security and utilises unique IP addressing for each active device (controller, computers and communication devices) in the network (Nazarenko et al., 2020). Figure C7 shows a zoomed-in view of the RAMI4.0 model communication layer showing the TCP/IP framework.

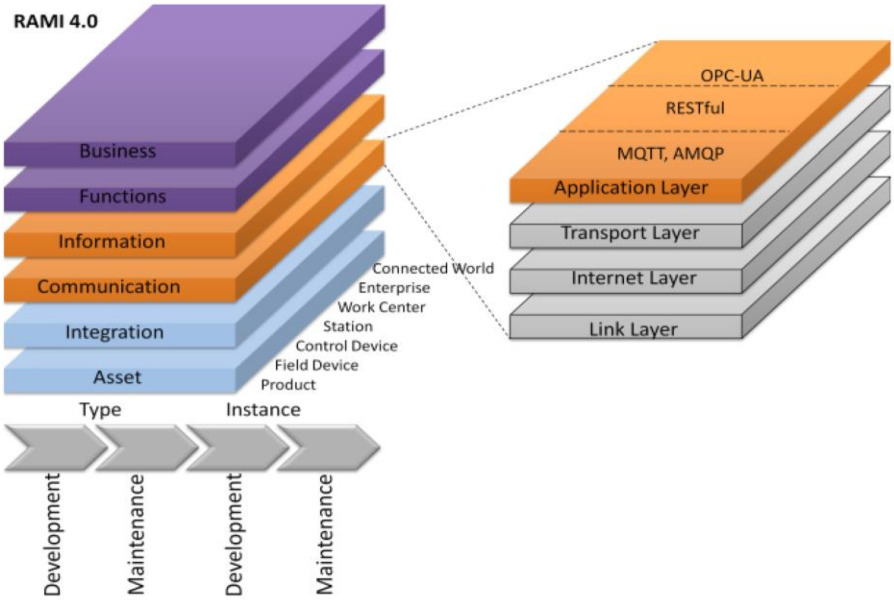


Figure C7: RAMI4.0 model communication layer using the TCP/IP framework Source (Nazarenko et al., 2020)

(a) Open platform communications universal architecture (OPC_UA)

A fundamental challenge for implementing Industry 4.0 objectives is the establishment of manufacturer-independent data exchange interfaces. The Open platform communications universal architecture (OPC_UA) specified in IEC 62541 existed long before the Industry 4.0 initiative (OPC Router, 2021). This protocol has increasingly improved to provide such a uniform interface for machines and production networks. It stands out to be an industrial communication protocol suitable for Industry 4.0 because it provides standardised and secured access to industrial systems, machines and other related devices enabling manufacturer-independent control and data exchange (Pethig et al., 2017). As shown in Figure C8, it integrates the information and communication levels of the Lifecycle value stream and the layers of the Hierarchy levels of the RAMI4.0 automation architecture.

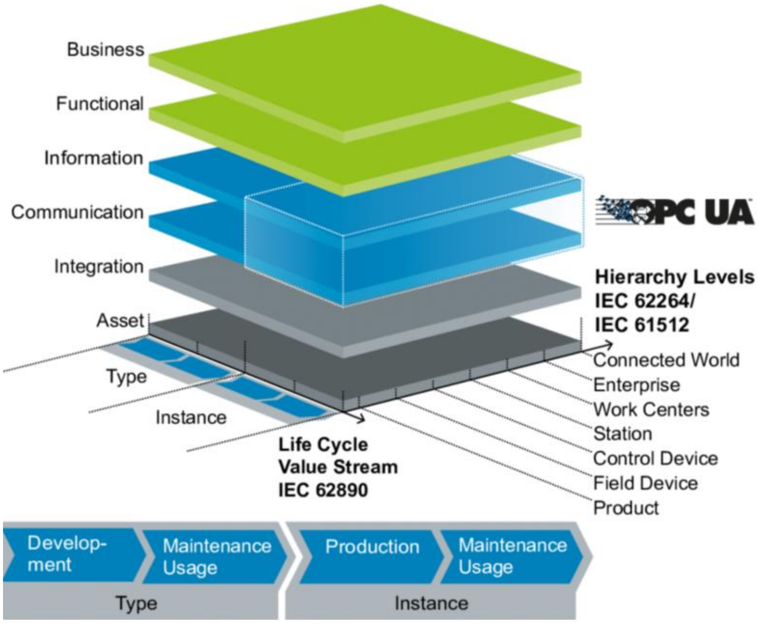


Figure C8: Integrating the hierarchy levels of the RAMI4.0 automation architecture using OPC_UA. Source (Pethig et al., 2017)

(b) OPC_UA Structure

OPC_UA was built on the basic web TCP/IP, and HTTP/SOAP technologies. It uses a server/client structure with the OPC_UA server as the basis for implementing the OPC standard (OPC Router, 2021).

OPC_UA Server: This provides an OPC standardised interface with propriety communication protocol enabling the access and control of manufacturers' hardware by other applications configured as OPC_UA clients (Pethig et al., 2017).

OPC_UA Client: The logical counterpart of the OPC_UA server is the OPC_UA client. It is an application-specific interface used for data exchange with OPC_UA servers. The manufacturer of the hardware provides an OPC_UA server for the system with predefined standardised access enabling OPC_UA clients to access and exchange data in the same way (OPC Router, 2021).

OPC_UA is selected for this research because

a) This makes it ‘firewall friendly’
b) This also has the basic concept of data exchange
c) It allows industrial devices operating different industrial Ethernet protocols (EtherNet, EtherCAT, ProfiBus, ProfiNet) and operational platforms (Windows, Linux) to communicate with each other
d) This connectivity extends across the RAMI4.0 architecture Hierarchy levels
e) It can be managed using standard network techniques like TCP/IP for fast applications and cross-platforms like SOAP platforms using HTTP

Appendix D: Industry 4.0 technologies

Industry 4.0 concepts and technologies to least a few include the DT, IoT, IIoT, Cloud computing, Edge computing, virtual reality, augmented reality, technologies like ambient light, cameras and image processing, sound and wearable devices, Radiofrequency (RF) and mmWave radar (Cheng et al., 2018). This section takes a look at key Industry 4.0 technologies adopted in this work and looks at the critical functions they provide that can be harnessed to position the DT as a prospective decision-support system. There have been several notable innovations in ICT, AI, machine learning, sensor data fusion and OT to highlight a few.

1) Internet of Things (IoT)

The Internet of Things represents a communication infrastructure that enables the processing, operation, storage, exchange, and connectivity of data between connected devices and systems over the internet (Stark, Kind & Neumeyer, 2017). Data can be collected from several remote sources like industrial sites, stored at local databases or in the cloud and connected to several front-end service platforms (Lu & Xu, (2018). Innovations in fields like computing, machine learning, AI, communications, instrumentation and other embedded systems have provided technologies that support the IoT infrastructure. Short-range wireless technologies like near-field communication (NFC), Bluetooth mesh networking (BLE), light-fidelity (Li-Fi), Wi-Fi, Radio-frequency identification (RFID), ZigBee, and Z-wave are in common use (Sørensen et al., 2008; Nagabushanam, George, & Radha, 2020; Cheng et al., 2018,).

Interestingly, the advancement in IoT technology has increased the possibility of establishing communication between infrastructures of dissimilar architecture and data semantics. Protocols like OPC_UA allow communication and data sharing within a heterogeneous network. Also, with the concept of collaboration, communication semantics continue to be standardised allowing communication between systems that initially cannot work together because of the variance in their architecture.

2) *Cloud computing services*

This simply refers to the on-demand availability of computing resources and services like data storage, computing power, front-end applications, and analytical or job-specific tools to the user with no direct or active management of these resources. These resources are usually distributed across the internet and data centres (Yang et al., 2017). Major industrial players include Amazon Web Services, Microsoft Azure, Google Cloud, Oracle Cloud Infrastructure, IBM Cloud and Cloud Linux.

3) *Communication infrastructure*

The core of the modern manufacturing ecosystem is the information technology and communication (ICT) infrastructure. This is the framework that hosts the interconnectivity and integration of the various components of the business chain. For demographically distanced industrial sites/services/data sources/bases to be connected and managed, the communication infrastructure needs to be robust and reliable to ensure smooth transmissions and cyber security. The following ICT infrastructure has been identified and implemented in this proposed network. This has been considered based on their availability and acceptance across heterogeneous platforms. They include TCP/IP/Ethernet communication, OPC_UA communication, TCP/IP communication and REST/HTTP API communication (Nazarenko et al., 2020).

4) *Message-oriented middleware (MOM)*

This is a middleware layer in the communication level that enables heterogeneous devices/platforms/applications to communicate irrespective of their differences (network platforms, communication interfaces, data semantics etc) (Curry, 2005). It is sender-oriented communication middleware that enables the asynchronous transmission of data/information across distributed applications as sent and received messages. Comprised basically of the MOM provider (API and administrative tools), its clients and messages, a MOM can use different server architectures or a combination to route and deliver messages (Curry, 2005; Oracle Corporation, 2010).

5) Data analytics

This includes the processes of data extraction, processing, integration/mapping, storage, information extraction/modelling/distribution and management (Onaji et al., 2022). Advancements in AI, machine learning and data management have resulted in more efficient and affordable data management infrastructures with algorithms/applications for structuring/storing data. Also, methods/applications to process and visualise information from useful perspectives.

Appendix E: Proposed framework for determining and developing the digital twin for your business

1) Background

Justifying the added cost of running a business by introducing digitisation concepts like the digital twin, especially in SMEs is a difficult issue. The question most often asked is *"why should they invest heavily in digitisation when the current status quo of the business is profitable."* While major players are strategising and restructuring to reposition their businesses to thrive in the digital age, it is pertinent for SMEs like servicing companies to envision to remain relevant by implementing digitalisation strategies that will transform their service provision to services of the new age. The focus here is on how companies can determine the kind of digital twin needed.

2) Proposed framework for determining and developing the digital twin for your business

This research through analysis presents a methodology (Figure E1) that can be used to determine the DT needs of a company based on its identified digital needs. This is a guide on how to:

a) Define the digital needs of the business,
b) Map those needs to the functionalities of a DT
c) Use the mapped business-digital twin needs for the selection of the business level application (s) (product/service, unit/systems and system of a system (SoS)/shop-floor levels)
d) Select the type of the digital twin (product/service DT, process DT, integrated product-process DT)

e) Select the level of its functionalities (supervisory, immersive interactive, CPPS_DTDSS)

f) Develop and utilise the digital twin

This sequence of activities has been grouped into 6 phases of the proposed framework (Figure E1). They include (i) Description of strategic digital needs, (ii) DT conceptual design, (iii) DT framework selection (iv) DT development strategy (v) Experimentation/Analysis and (vi) DT upgrade.

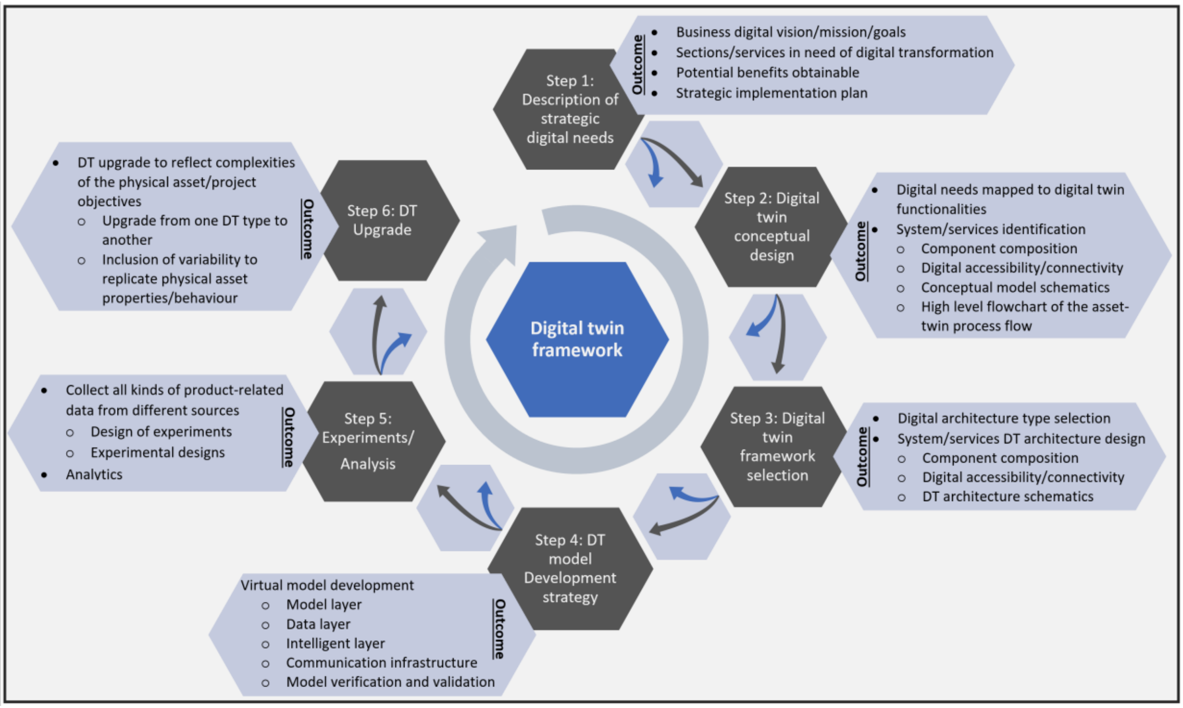


Figure E1: Proposed framework for determining and developing the DT for your business

(a) Step 1: Description of strategic digital needs

This stage involves defining the business's digital vision/mission/goals. It enables the company to determine its digital transformation needs. Things to consider at this stage include:

- Identifying the digital needs of the business relative to the company's objective/mission/vision (long/short term)

- Transforming those needs to digital goals/visions relevant to the digital era (4th industrial evolution)
- Proposing strategic plans toward achieving those digital goals/objectives/vision
- Identifying areas of the business that would need digital repositioning/transformation in line with its set goals
- Defining the kind of digital transformation that is needed
- Identifying the kind of digital resources that are needed- Front-end APIs, Computing facilities, ICT, modelling, data management and analytics

Business enterprise digital representation includes decision making, service enablement, event/rule handling, business models, knowledge management, resource management and maintenance and asset intelligence. Business systems digital representation includes monitoring (supervisory and reports), interaction (remote access), diagnostic(trend analysis), predictive analysis, product/process/service design, training, maintenance (condition-based, predictive based), inspection (product, process, service) (Catapult 2019).

(d) Step 2: DT conceptual design

This phase handles the development of a DT conceptual design. It defines the framework for implementation and involves mapping the identified digital needs in the first phase to the existing DT functionalities (simulation, resource integration/collaboration, optimisation, control, data integration, analytics, data insight, knowledge management and smart scheduling). Also, within this step, the identification and justification of what components constitute the DT is done. Components like the physical asset, unique physical asset, data set (offline, live), model representation (graphic 2D, 3D CAD or data-based), simulation (real-time, offline) and analysis (diagnostic, descriptive, prognostic) are considered (Catapult, 2018).

What should be considered includes:

- The needed DT services
- The DT functionalities that would effectively provide these services
- The digital accessibility of the business assets (product/services, processes, management, connected world-customers & supply chain)
- The digital platform and tools needed (CAD-based for products, DES for process and high-level management)
- Data management (generation, structure, storage, insight, accessibility)

The effective use of data in business has become crucial in today's economy. The involvement of data analytics (data generation, integration, distribution and information extraction/transformation/distribution) both vertically and horizontally across the company organogram points to the need for an effective DT. A conceptual model can be designed following the strategy implemented in this research (Section 3.1, 3.3 & 4.6). This conceptual composition entails both structural and behavioural features like process behaviour/functionalities that can be modelled and visualised and the digital tools are needed for implementation. The ASME symbols can be adapted to represent the process/product activities. Material/process flow analysis provides sufficient information for developing the conceptual model process chart and the high-level flowchart of the asset-twin process flow.

(e) Step 3: DT framework selection

There are several areas the DT concept can be applied. Selecting the DT framework to implement requires categorisation based on the use case. The concern here includes:

- The selection of different kinds of DTs applicable to the business

- Which levels of the RAMI4.0 architecture need the DT support
- When and what would be the digital objectives
- What are the performance metrics (KPI) for the DT in the business

The DT architectures outlined here are of four types namely: supervisory DT, interactive DT, interactive DT with offline analytical functions and the CPPS_DTDSS. This categorisation is based on the use case functionalities.

1. *Type 1: Supervisory DT:* The first DT type is composed of the basic requirements-physical and digital assets for supervisory purposes. As shown in Figure E2, operational captured data is used to define the simulation behaviour of the DT. The virtual data is integrated with the captured operational and environmental data to create the DT data.

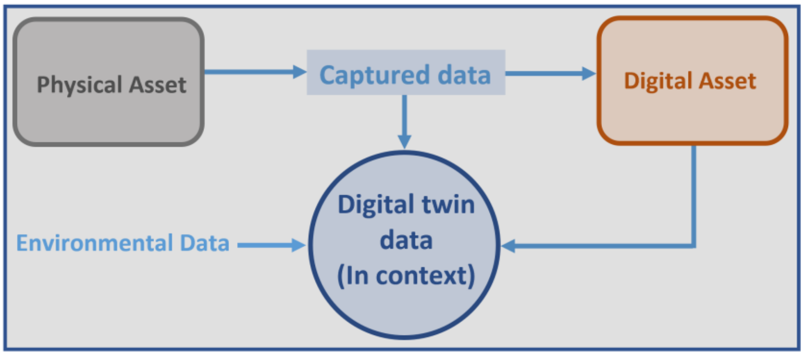


Figure E2: Type 1: Supervisory DT architecture for monitoring purposes

2. *Type 2: Interactive DT:* This is built upon the Type 1 DT. It takes advantage of the bidirectional communication link to establish a real-time interactive simulation between the asset-twin. Integration is achieved using data and control. As shown in Figure E3, the virtual control of the asset is implemented enabling the DT to influence the behaviour of the asset.

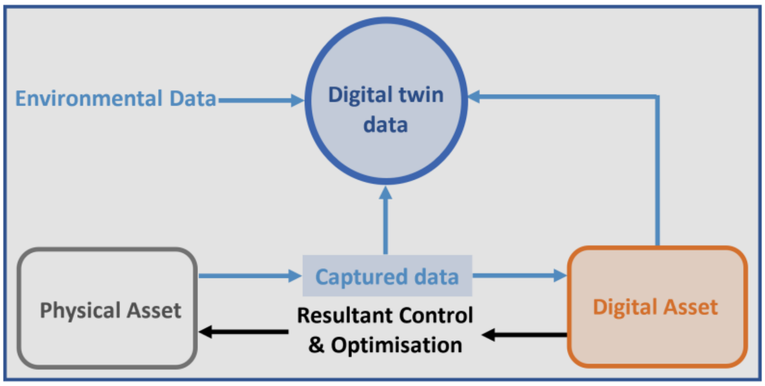


Figure E3: Type 2: Interactive DT

3. *Type 3: Interactive DT with offline analytical functions:* This as presented in Figure E4 is an upgrade of the Type 2 DT. Offline analytics is introduced to have direct access to the DT data. Analytical results are not used directly to manage the physical asset. This is suitable for delicate operations that do not need disruptions.

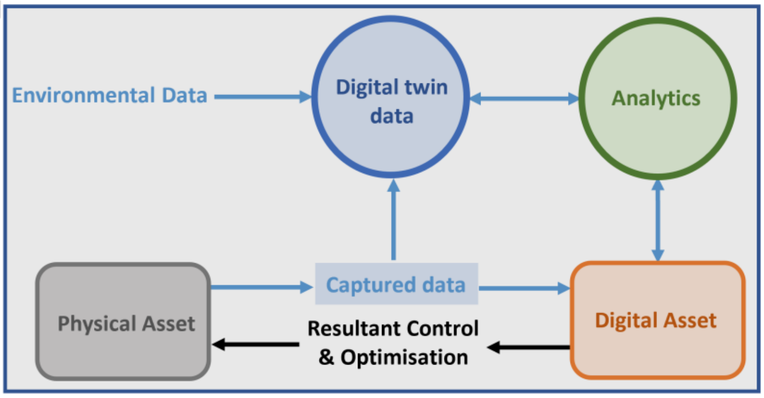


Figure E4: Type 3: Interactive DT with offline analytical functions

4. Type 4: CPPS_DTDSS: A synchronised immersive interactive DT with real-time influences on the asset-twin interaction using analytics. As shown in Figure E5 this level of DT is developed with decision-making mechanisms (machine learning algorithms) positioned to implement data-driven control, optimisation operations and health monitoring.

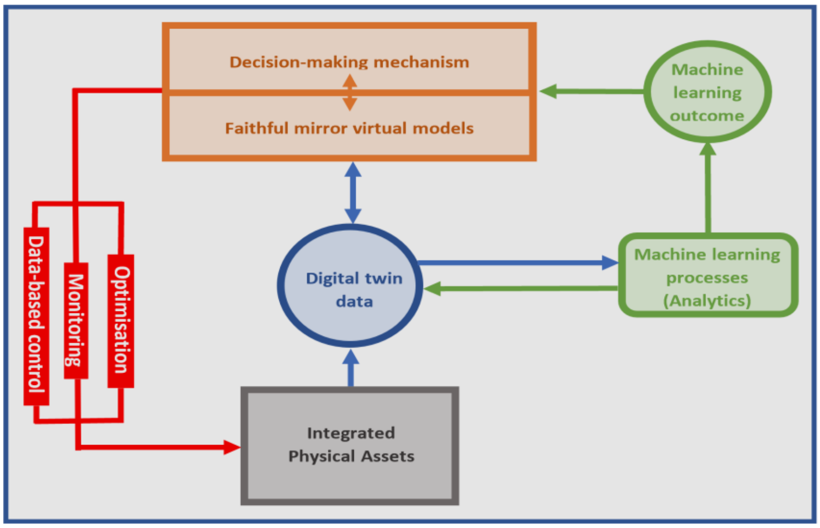


Figure E5:Type 4: CPPS_DTDSS

Technical requirements can include contextual models (CAN, plan, rule, schematics, text field), connectivity (sensors, actuators, data feeds, ICT infrastructure), storage (database, tables, files, management), frame of reference (spatial and temporal) and simulation.

(f) Step 4: DT development strategy

This phase allows for the methodological development of the DT. The method used in this research (Section 3.3) is positioned to enable a systematic approach towards introducing the complexities of the real asset either as the DT is upgraded in types or the inclusion of variabilities unique to the resources/product/services. In a situation where the key element is not the product and the process, variability is introduced by keeping one variable fixed while the other is varied. This allows for proper implementation and observations of the impact of such design objectives.

The DT development methodology (Section 4.6) applied in this research in developing the DT of the case study is presented as an effective DT development strategy. It involved the following steps: conceptual model design, virtual model development, control panel development, data layer development, intelligent layer development and lastly, verification and validation process. This approach allows the gradual build-in of the complexity of the existing business/production/product to be modelled.

(g) Step 5: Experimentation/Analysis

This phase is used to design and carry out experiments and analyses. One of the primary objectives of a simulation environment is to enable experimentation/analyses of manufacturing system performance to gain insights into complex systems, identify developmental opportunities and test new concepts/solutions before implementation without obstructing the business objectives (Onaji et al., 2019). The DT is used to incorporate operational data into experimentation and analyses. This is expected to improve the results and overall system/business performance.

(h) Step 6: DT upgrade

It is a good engineering practice to give room for expansion/upgrade of design models/infrastructures. This phase allows the business to upgrade the existing DT infrastructure or capabilities to reflect predefined business digital strategies. This could include the upgrade of the DT from one type to another or the addition of functionalities like analytical tools at the intelligent layer, information visuals or data layer restructuring.

3) Case study

This shows the benefits of the proposed framework for determining and developing the DT for your business to industry and academics. The proposed framework was used in deciding and developing the DT to be developed for the Festo CP smart factory.

Step 1: Description of strategic digital needs: The case study is an Industry 4.0 teaching and training facility. The digital need was a robust digital platform that supports training, experimentation and analytics for the Festo CP smart factory.

Step 2: DT conceptual design: Section 3.2 outlines the structural abstract of the DT conceptual model. The ASME code was adopted to represent the asset production flow activities. Material flow analysis of the production processes generated sufficient information for developing the material flowchart and high-level asset-twin process flowchart (Figures 4.7, 4.8, 4.9, 4.10).

Step 3: DT framework selection: The integrated product-process DT was considered the right DT for a CPPS_DSS. The required digital tools were identified based on the criteria outlined in Section 3.1.6. This aligned with the project objective to investigate the viability of the DT as a potential integration, collaboration and flexibility support digital tool.

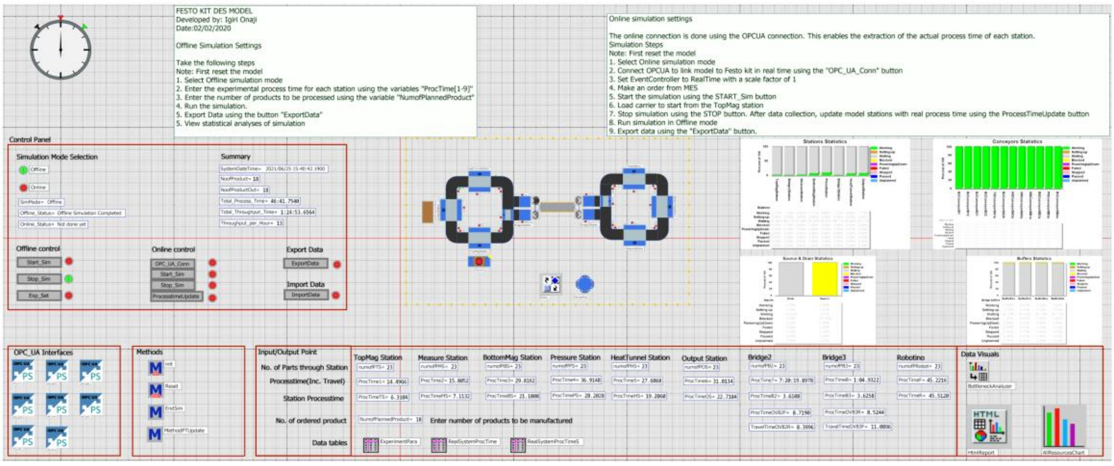
Step 4: DT development strategy: The methodology is reported in Sections 3.3 and 4.6. This saw the development of the DT from a simple supervisory DT to a CPPS DSS of the system across its automation hierarchy level.

Step 5: Experimentation/Analysis: Several online and offline experiments were carried out, the Design of the experiment (Onaji et al., 2019) and experimental designs as shown in Chapters 4, 5, 6 and 7.

Step 6:DT framework upgrade: Based on the design objectives, the first developed supervisory DT was upgraded from a single island to the two islands of the Festo CP smart factory. The development process was repeated continuously resulting in the final upgrade of the DT to a CPPS_DSS. This saw the interconnection of the MES/ERP and connected world levels of the RAMI4.0 automation architecture as an extension of the DT functionalities and data description.

Appendix F: Siemens connected curriculum

Siemens introduced the connected curriculum (Siemens, 2022) designated to support industry-tertiary institution collaboration. This research was called upon to technically support this group with the development of DES digital twins (Figure F1) for the Festo CP smart factory at the University of Sheffield and Exeter University, UK. In addition, it also supported the program in the development of a Siemens guideline document on how to develop a DT for the Festo CP smart factories spread across several tertiary institutions.



FESTO KIT DES MODEL
Developed by: Igiri Onaji
Date:02/02/2020

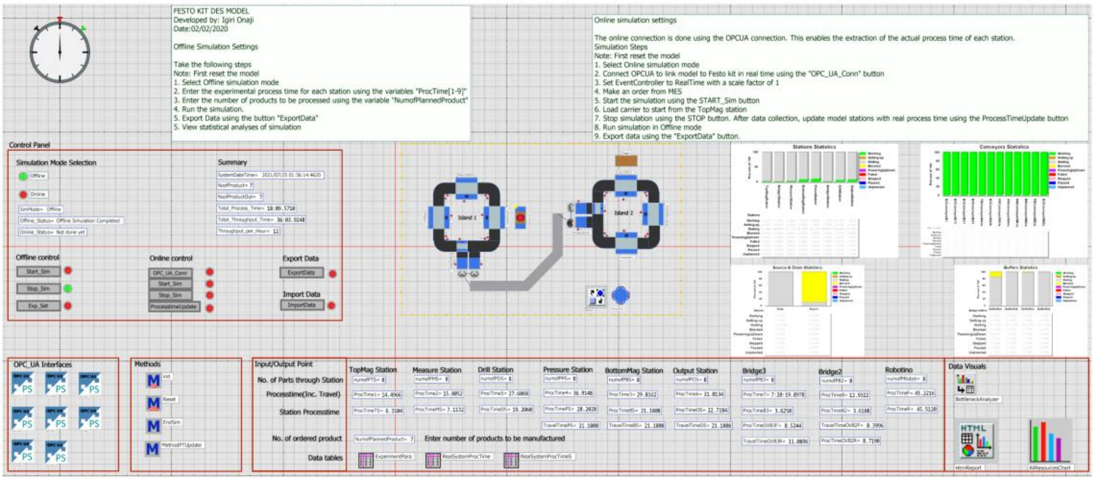
Offline Simulation Settings

Take the following steps
Note: First reset the model
1. Select Offline simulation mode
2. Enter the experimental process time for each station using the variables "ProcTime[1-9]"
3. Enter the number of products to be processed using the variable "NumofPlannedProduct"
4. Run the simulation.
5. Export Data using the button "ExportData"
5. View statistical analyses of simulation

Online simulation settings

The online connection is done using the OPCUA connection. This enables the extraction of the actual process time of each station.
Simulation Steps
Note: First reset the model
1. Select Online simulation mode
2. Connect OPCUA to link model to Festo kit in real time using the "OPC_UA_Conn" button
3. Set EventController to RealTime with a scale factor of 1
4. Make an order from MES
5. Start the simulation using the START_Sim button
6. Load carrier to start from the TopMag station
7. Stop simulation using the STOP button. After data collection, update model stations with real process time using the ProcessTimeUpdate button
8. Run simulation in Offline mode
9. Export data using the "ExportData" button.

(e) Siemens DT for the Festo CP smart factory in the University of Sheffield



FESTO KIT DES MODEL
Developed by: Igiri Onaji
Date:02/02/2020

Offline Simulation Settings

Take the following steps
Note: First reset the model
1. Select Offline simulation mode
2. Enter the experimental process time for each station using the variables "ProcTime[1-9]"
3. Enter the number of products to be processed using the variable "NumofPlannedProduct"
4. Run the simulation.
5. Export Data using the button "ExportData"
5. View statistical analyses of simulation

Online simulation settings

The online connection is done using the OPCUA connection. This enables the extraction of the actual process time of each station.
Simulation Steps
Note: First reset the model
1. Select Online simulation mode
2. Connect OPCUA to link model to Festo kit in real time using the "OPC_UA_Conn" button
3. Set EventController to RealTime with a scale factor of 1
4. Make an order from MES
5. Start the simulation using the START_Sim button
6. Load carrier to start from the TopMag station
7. Stop simulation using the STOP button. After data collection, update model stations with real process time using the ProcessTimeUpdate button
8. Run simulation in Offline mode
9. Export data using the "ExportData" button.

(b) Siemens DT for the Festo CP smart factory in the Exeter University

Figure F1: Festo DT models developed for Connected curriculum

Appendix G: Validation

This section presents the validation process, experimental set-up used and results obtained to validate the digital twin propositions made in this research. Each research proposition was tested on the case study (Section 3.7) and the outcomes were discussed in the Case study and Discussion Sections of Chapters 4 to 7. The validation process was done to determine the level of applicability, reliability and effectiveness of these propositions in various sectors of the manufacturing industry. Two approaches to validation were adopted, and they include:

1) Modelling of an Integrated DT for a case study: An Industry 4.0 assembling facility (Section 3.7)
2) Testing and validation using a range of scenarios in the case study

The methodological framework for validation included modelling objectives, model development, experimentation, verification and validation, and recommendations. This methodological sequence was repeated all through the various phases of the practical work outlined in Appendix B.

1) Validation approach 1: Modelling of an integrated DT for an Industry 4.0 facility:

The proposed DT framework was implemented in the development of a digital twin for the case study: Festo CP smart factory (Section 3.7). Its integrated product-process DT was first developed in its simplest form as supervisory DT (Section 4.6) and was upgraded to a decision-support system that supports the MES, ERP and connected world of the RAMI4.0 architecture Hierarchy levels (Section 7.4). The proposed digital twin frameworks and implementation methods were validated using planned performance metrics for each research proposition.

2) Validation approach 2: Testing and validation using a range of scenarios in the case study.

The second approach investigates the integrated process-product DT for a CPPS as a decision-support system using a range of dynamic scenarios. This approach is aligned with the fifth research objective *"Validate the integrated product-process digital twins as a decision support system for a cyber-physical production system (CPPS) using a range of dynamic scenarios"* and takes into consideration the variability of the manufacturing processes in the industry. The scenarios represent processes common in most manufacturing set-ups like the automobile, assembling, fabrication, production and packaging industry. They were successfully tested as shown in Sections 5.6 and 6.5, thus confirming the viability of the propositions made here to position the integrated product-process DT as a decision-support system for CPPS.

3) Experimental set-up

The modelling and experimental set-up consisted of the following:

i. Integrated physical system: Festo CP smart factory
ii. Modelling platform: Siemens Tecnomatix for DES digital twinning
iii. Bidirectional communication: ProfiNet/TCP/IP/Ethernet communication infrastructure, OPC_UA communication protocol and MOM (Node-Red) for connection across the internet
iv. Data management: Digital twin platform and Cloud services (Siemens Mindsphere)

v. The cyber-physical control structure for virtual control and implementation of control strategies

vi. Siemens Mindsphere Cloud service: Provide Cloud services like storage and front-end APIs for the connected world level (Cloud service community and customer).

4) Validation outcomes

The outcomes of the validation processes are outlined below:

A. *Integrating the product twin, process digital twin and the physical asset to support real-time synchronised interactive simulation*

   i. *Linking virtual products with virtual processes (Figure 3.2, connection b):* The two DTs exist on the same platform. The product characteristics (information model) mapped to the process configurations (information model) enabled a two-way update channel. For offline simulations, before production, the selected product reconfigures the virtual production line with the resources it needs and recalibrates the workstations. During production, the process updates the product information model with the value (attributes) added to the physical product. Flexibility in station calibration due to the digital twin allows for product customisation during production. Process reconfiguration or workstation recalibration can be automated depending on the flexibility of the production line.

   ii. *Updating virtual assets from physical assets (Figure 3.2, connection a):* During asset-twin real-time interaction, the DT is driven in response to the behaviour of the physical asset. This way, the digital twin behaviour is synchronised to its physical twin thus presenting near real-time status of the physical system behaviour for monitoring purposes. The case study DT platform allows data transmission up to 30ms. This was suitable for the processes being modelled. RFID captured product-related data is used to build the product DT model in near real-time as the real product (WIP) flows through the production line. Data transmitted in near real-time to the DT supported:

- Real-time synchronised interaction: DT behaviour is data-driven in response to the physical systems' actions/triggers
- Update the digital twin database
- Real-time system monitoring: Using data from the sensors/actuators manage the DT model behaviour to reflect its physical twin status in real-time.
- System configuration for any instance can be recorded and used to calibrate the digital twin for offline simulation experiments and analyses.

B. *A cyber-physical control structure using closed control loops at multiple granularities that supports real-time synchronized bidirectional control between the digital twin and the physical asset*

i. *Updating the virtual model with control responses:* The bidirectional communication allowed for a synchronised connection between the physical control system and its virtual replicated interface. The feedback channel allowed the virtual model to be updated with control operation status. If control is initiated from the physical system or the digital twin, the virtual model is updated with the outcome thus reflecting the current state of the initiated control and system.

ii. *Controlling physical assets from the virtual asset:* Using the same digital link (OPC_UA), the virtual platform has control capabilities using its virtual control interfaces. Control scenarios on virtual control were developed and used to optimise production. They included:

- Virtual control strategies to improve production performance
- Real-time data-driven control
- Real-time product customisation using the product-centric control method

Several control scenarios have been built. Simple ones included:

- Store monitoring to avoid downtime due to station blockage as a result of stores being full.
- Magazine observation to prevent downtime due to empty part magazines

More inclusive control scenarios include

- Setup sequence to get an empty carrier to the front station awaiting production order
- Eco production to reduce loss of energy due to running conveyors when stations are idle.
- Eco production to reduce throughput time by heating the Heat tunnel to its setpoint before the workpiece arrives at the station
- Path coordination using RFID data to clear path for workpiece through a station that is not its next destination
- Product customisation: This is having the same product but with variations based on customer specifications. This is demonstrated by varying the process time/pressure of the press or/and process time/heating temperature of the heat tunnel stations at runtime

C. *Positioning the digital twin as a support decision mechanism across the RAMI4.0 automation hierarchy level in manufacturing.*

i. The developed DT architecture was based on its existing infrastructure/technologies

ii. The integrated DT was built using a DES digital twin platform (Siemens Tecnomatix) which supported bidirectional communication between the physical system and its DT was achieved using the ProfiNet/TCP/IP/Ethernet communication, OPCUA protocol and IoT integration platform.

  - The communication link between the physical system and DT: OPC_UA protocol
  - The communication link between DT, MES, customer and cloud database (Mindsphere): OPC_UC- MOM (Node-red)

iii. Integration of all generated data: All production-associated data is mapped and made available for analysis. Generated results are readily available for production management and business decisions

  - Past data – historical performance data of individual workstations, overall processes, and production configurations.
  - Present/instance data – real-time data from active sensors, actuators, order details, product details, WIP and system performance.
  - Future data: descriptive and predictive analysis

Production management: The DT control capability in conjunction with its analytical capability enabled the autonomous management of the production process. Production using the DT when compared with the CPSS without the DT shows an improvement in production performance. Data-based control scenarios were developed into the cyber-physical control structure. This enabled the collaboration between the virtual-asset controllers to manage the production processes. For instance, throughput was improved by eliminating the wasted time identified in the heat station process time, the conveyors are stopped to save energy when stations are idle, and the operator is informed of potential bottleneck situations (output station and magazine stations) to be prevented from occurring. This resulted in proactive actions like timely reloading of the magazine stations to prevent downtime due to empty magazines during production or timely offloading of the storage unit to prevent downtime due to filled-up Output station storage units.

Decision-support system: The integrated product-process digital twin has been presented as a decision support system for its asset. This approach is in an attempt to harness the functionalities of the digital twin as a data integrator, data analytics and information extractor. As seen in Chapter 7, using Cloud computing services and MOM communication techniques, this service of the digital twin can be extended across the Hierarchy level of the RAMI4.0 automation architecture. As the other levels provide other production-associated data/analytical tools, they are supported with digital twin data and information that improves their services and increases evident-based decisions.

In conclusion, the validation has shown the following results:

i. The product DT and the process DT can be integrated on the same platform, and they performed as designed
ii. Real-time synchronised interaction between the asset-twin is achievable with the techniques proposed in Chapter 4.
iii. The Cyber-physical control structure proposed to achieve virtual control using real-time implemented control strategies and data-driven control is achievable for smart assets using PLC controllers

iv. Digital twin data is created by the integration of both operational and virtual data. Using the concept of logical mapping, this data evolves along with its asset-twin

v. Part tracking using the RFID technique enables the transmission of product data as the workpiece travels from one station to another. This supports the synchronous creation of the product DT

vi. Experiments showed DT usage improves asset performance and supports virtual training of users (staff and students) before they are exposed to the real working environment

vii. Analysed operational data supports operational and business decisions. For example, the station performance and production strategy performances when the number of carriers used in production was varied helped the operator to design optimal production schedules to suit daily production demand.

Based on the nature (assembly line) and size (8 modules assembly line) of the case study, and the modelling approach (DES approach), the outcome of the validation showed reasonable designed performance. The integrated DT platform for the case study with analytical capabilities and real-time synchronisation presented a suitable platform for data integration, analyses and information management that supported data-driven control, production optimisation and informed business decisions. Observably, occasional failure in communication resulted in the termination of virtual control, data transmission and loss of data. This is expected to improve with more robust communication infrastructures like the 5G network. More proof of concept can be done on other manufacturing systems to evaluate the impact of the asset size and complexity, and modelling approach on the DT performance. Nonetheless, the gathered modelling and experimental results were supporting evidence that proved the viability of these research findings and conclusions.