Digital Continuity in the Manufacturing Process

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Abstract

The manufacturing industry is currently in an era of exploration in an attempt to realise the benefits of Industry 4.0, connectivity and the use of data. In particular, shop floor tools and assets should be connected to their application and environment, and shop floor data generated during manufacturing and assembly operations should be taken advantage of in real time in order to make decisions and remove non-value added steps. Digital continuity in the respect of a wireless torque tool use case is discussed in this research, where the data required to configure the settings of the tool for a specific structural assembly operation is transferred from a design specification and subsequent work instruction generation process through to the manufacturing execution stage in order to activate the tool and dynamically enable the settings required for the fasteners within the chosen assembly operation. This approach thereby maintains a connection from the design origin and removes unnecessary manipulation or duplication of the data. This capability is enabled by the vertical integration and application of several proposed digital architecture components, which when combined follow the ISA-95 standard for the integration of enterprise and control systems. The digital architecture demonstrated in this research features the Dassault Systèmes' 3DExperience and DELMIA Apriso software products which are tested together with a connectivity platform and the torque tool system. The connectivity between hardware and software components is explored further in order to drive subsequent events such as data capture, visualisation for the Operator and automatic non-conformance detection. The implementation presented in this research demonstrates that the proposed digital architecture can be used in a shop floor production environment to leverage the benefits of connecting business processes through connected systems, plus the benefits of capturing and using near real time process data.

Key words: Digital continuity, Digitalisation, Industry 4.0, Vertical integration, Smart Factory, Connectivity

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List of Abbreviations

CPS	Cyber-Physical System
ERP	Enterprise Resource Planning
FOD	Foreign Object Damage/Debris
(I)IoT	(Industrial) Internet of Things
ISA	International Society of Automation
IT	Information Technology
M2M	Machine to Machine Communication
MES	Manufacturing Execution System
MID	Message ID
MOM	Manufacturing Operations Management
MQTT	Message Queuing Telemetry Transport
MRP	Material Requirements Planning
OPC UA	Open Platform Communications United Architecture
PLC	Programmable Logic Controller
PPR	Product, Process & Resource
REST	Representational State Transfer
RFID	Radio-frequency identification
TCP/IP	Transmission Control Protocol/Internet Protocol
WI	Work Instruction
WO	Work Order

Declaration:

I, the author, confirm that this Thesis is my own work. I am aware of the University's Guidance on the Use of Unfair Means (www.sheffield.ac.uk/ssid/unfair-means). This work has not been previously been presented for an award at this, or any other, university.

Chapter 1

Introduction

1.1 Background

Today, the developments and industrialisation of smart factories where manufacturing facilities and their processes are connected and sharing real-time information through networks and the internet are on the rise; a particular area of focus is the integration of hand held tools with information systems for manufacturing are on the rise. Traditional tools, still used widely in the manufacturing industry today are disconnected, require frequent calibration whether they are used or not, and do not provide process data from shop floor operations. This unfortunately means that many manufacturers are not able to take advantage of the benefits offered by automation and connectivity, which may result in loss of traceability, inefficient use of inventory, loss of asset performance, excessive set up times, and a lack of data to support problem solving and diagnosis.

Tools used in the factory environment need to be connected to the enterprise IT and software systems in the context of the manufacturing process they are performing in order for meaningful key performance indicators and operational data from the production process to be captured and utilised. The capability to vertically integrate a production system (sensor-control-MES-ERP) represents the ability to realise customised production (Park, 2016); by integrating connected tools with a manufacturing execution system (MES) and other software tools, data captured from the manufacturing operation could be used instantaneously for certification, to provide information about tool and process performance, to provide functionality based on Operator competency and tool location, as well as other factors. These benefits contribute to a lean manufacturing system where companies can make best use of their workers' time and their assets' performance.

The term *digital continuity* refers to the ability to integrate, validate, execute and report from "concept to delivery" (Computer Express, 2018), and will be used in this report to explain the continuous and ongoing transfer of core data throughout a digital/software architecture and/or manufacturing process. In many companies today there is a distinct lack of digital continuity due to the wide variety of software and information systems operating in silos. This research will explore and demonstrate a method for enhancing digital continuity which is important for creating a single source of truth (or a digital thread) throughout various software systems, linking the design of certain components that make up a product within a software platform to the shop floor process used to assemble those parts. Manufacturers need to extend the digital thread beyond the start of production (Green, 2019); the integration of feedback from the shop floor would be experienced in different but relevant ways by multiple stakeholders, especially the Operator.

An example of where there is an opportunity to research and improve digital continuity in a manufacturing setting would be a fastening tool being automatically set to a certain torque setting depending on the fastening operation they are due to perform; such connectable battery tools are available today and offer improved traceability and flexibility (Secheret & Valentin, 2013). Today's lack of process feedback from the tools means that manual inspection of each product is responsible for ensuring that the manufacturing process is carried out correctly, with no data to consult. In addition, there is currently a lack of ways of automatically integrating operational data to influence continuous improvement; data captured by connected tooling will enable trends to be made which may ultimately affect the changes in manufacturing processes.

The term "Smart Tools" is commonly used as a way to describe hand held power tools that can collect and communicate data in real-time (Umer, et al., 2018); they possess intelligent features such as wireless connectivity, dynamic program selection and in-process verification. These tools are contributing to the increasing digitalisation of the manufacturing sector, helping lead us towards better levels of traceability and control. Smart fastening tools which are connected over an industrial network could be used to evaluate the benefits of automatically configuring tools for the wing assembly process based on manufacturing work instructions, and subsequently for capturing process data which can be used to automatically certify tasks and generate a feedback loop with engineering for continuous improvement of manufacturing processes. A "Smart Tool" is shown in Figure 1.

Figure 1 - Desoutter EABS "The one handed nutrunner" smart torque tool (Desoutter Tools, 2019)

1.2 Motivation

This research in to the digital continuity in the manufacturing process covers a complete vertical integration of the digital architecture, taking data from a design model through to shop floor execution using the core software systems and market leading aerospace tools. In order to demonstrate and prove the benefit of innovative digital solutions during this research programme, the methods and limitations of digital continuity (system integration and data transfer) need to be understood. Having a detailed understanding of how a digital architecture is formed and how systems can interact with it is key to having a long term view of how the Smart Factory will function and operate; this is particularly important at the shop floor end where there may be a variety of different hardware vendors with their preferred methods of connectivity. The outcome of this research will be used in the selection and development of other digitalisation use cases and their requirements for compatibility.

1.3 Aim & Objectives

1.3.1 Aim

The introduction of Industry 4.0 has uncovered problems and opportunities in manufacturing like never before by opening the eyes of manufacturers to the power of leveraging data and connectivity within the factory and supply chain. The thought of receiving a notification requesting a maintenance engineer address a robotic system before it breaks down or the thought of remotely monitoring the sensors within a system to ensure quality is controlled mid-process is too good for manufacturing companies to miss; the new opportunities promote lean manufacturing, can increase product quality and throughput, and ultimately save recurring costs. The problem lies within the complexity of deploying such solutions, it generally requires a knowledge of network architecture and software integration to be done correctly and not to create further silos within enterprise set ups. The area of connectivity and integration needs to be explored in order for these benefits to be experienced.

The opportunity is that tool manufacturers and software vendors recognise the benefits that digital connectivity can bring to the manufacturing industry as a whole and tools with "smart" capabilities are becoming widely available, often packaged with their own software. This in turn presents us another problem, whereby manufacturing companies want to maintain their digital architecture and software strategy and therefore need to integrate these tools with existing systems in order to capture the data and visualise it; after all, the data is only valuable if it brings benefit from its context. These benefits may be quality or safety related, to ensure that what was supposed to happen did happen and the relevant data is available as evidence.

Many manufacturing organisations are embracing the digital transformation and have a requirement for manual manufacturing processes to capture data for traceability and process validation, with the aim to generate offline tasks for support functions and enable continuous wing production.

There is value to establishing digital continuity for all manufacturing processes; using data from design models and manufacturing planning activities to automatically send settings to shop floor tools before gathering key parameters of process data to prove whether or not the process has been carried out to design tolerances. This digital continuity will enable the production of "As Built" reports based on the data captured from automated processes and manual processes, such as fastening. There are many advantages to be gained by the capture of data from manual manufacturing operations, one of which is data validation and certification at the time of the operation which may remove unnecessary inspection processes. There may be an opportunity to monitor and improve process capability, tool performance, and the capture and rectification of issues.

The aim of this research is to demonstrate digital continuity in the manufacturing process by assembling a digital architecture and demonstrating how data is transferred through various systems, from a design model through to shop floor execution. This thesis focuses on hand held (smart) torque tools as a use case where an Operator will use a tool (that has been automatically configured) during an assembly operation on a small scale wing structure. The data from each fastening cycle will be captured and validated as part of the solution.

1.3.2 Objectives

The following objectives have been defined for this research:

- To identify the architecture and integration required to demonstrate digital continuity from a design model through to shop floor execution
- To develop a case study focused on a torque tool fastening process and identify the range of parameters that need to be considered for the case study (e.g. target torque, angle)
- To develop methods for automated configuration of hand held (smart) torque tools for specific tasks

    - Based on manufacturing work instructions, how can the automated configuration of smart torque tools be carried out?
- To develop methods for enabling dynamic configuration of tools during the manufacturing process
- To raise a non-conformance if the target torque value is not achieved for fastening operations
- To develop a set of scenarios to test and identify the limitations of the vertical integration of the architecture components and methods developed

1.4 Research Methodology

When planning a research project one has to acknowledge the various approaches to research and the type that is most applicable to the work and this may depend of the discipline and field. This section looks at some common approaches and different types of research in order to explain the justification for this research project.

The inductive approach is generally associated with qualitative research, where a theory is developed and a general conclusion is drawn from individual instances or observations (Hammond, 2016).

It is common to use the inductive approach when there is a lack of existing literature on the research topic and therefore little to no theories to test. This approach follows an observation of data, the studying for patterns within the data, and the development of a theory. A limitation of this approach is that the theory can never be proven but it can be invalidated (Streefkerk, 2019).

In contrast, the deductive approach usually begins with a hypothesis and the aim is to test an existing theory (the conclusion of inductive research). There are four stages to this approach starting with an existing theory, the formulation of a hypothesis based on the existing theory, the collection of data to test the hypothesis, and the analysis of the results (is the hypothesis supported by the data?). A limitation of this approach is that the conclusion relies on the premises set in the inductive study being true (Streefkerk, 2019).

Based on the above definitions, this research will be conducted with the inductive approach because it is based on a case study to prove the aim that has been set. The case study related to the vertical integration of architecture components to support digital manufacturing will provide scenarios which will be tested in order for conclusions to be drawn from the multiple findings and solutions.

This research project will follow the action research process where a problem statement defines a starting point for the research. From this point, the problem is turned in to a researchable question where actions and strategies are tested in a cyclical process in order to achieve results. The findings of other researchers within this field will be drawn upon in order to develop the actions and understand the limitations and consequences of potential solutions. The final step is to analyse and generate the theory that supports the testing (Altrichter, et al., 1993).

This research project will follow the following steps in order for a conclusion to be drawn:

- A problem statement (starting point)
- Research existing literature
- Clarify the steps needed to develop methods and strategies
- Test solutions in practice and record results
- Analyse results and carry out further tests
- Analyse the overall results of this reach and generate the conclusion

The research objectives are reiterated below and the research process is shown in Figure 2.

- *To identify the architecture and integration required to demonstrate digital continuity from a design model through to shop floor execution.*

This objective is to identify the components and methods of integration required to transfer data from a design model dataset, through to a manufacturing process and work instruction, through to a shop floor execution use case. The scope of this objective also includes the transfer of data from the shop floor execution use case back to the manufacturing execution system for validation and traceability.

- *To develop a case study focused on a torque tool fastening process and identify the range of parameters that need to be considered for the case study (e.g. target torque, angle)*

This objective is required in order to understand the reasons and value behind capturing certain parameters of data from a torque tool fastening process. Meaningful data needs to be captured in order to enhance the manufacturing process; this data may be beneficial for the Operator, Manufacturing Engineer, Quality Engineer, Maintenance Engineer and/or other stakeholders.

- *To develop methods for automated configuration of hand held (smart) torque tools for specific tasks.*
    - *Based on manufacturing work instructions, how can the automated configuration of smart torque tools be carried out?*

This objective is to develop a method for automatically setting the torque requirement of the smart torque tool without an Operator having to manually select a program or setting before starting a task. Instead, using the software systems and wireless connectivity to the tool, the setting required for the upcoming fasteners should be sent to the tool just before the task is executed. Data capture from the torque tool should be achieved using the communication channel.

- *To develop methods for enabling dynamic configuration of tools during the manufacturing process*

This objective is to develop a method that allows torque tool settings to be changed rapidly between fastener positions if it is required by the design specification. This is to enable the solution to be flexible rather than one setting being sent to the tool before the start of the process and lasting until the end of the process.

- *To raise a non-conformance if the target torque value is not achieved for fastening operations*

This objective is to develop a method for capturing details about fastener positions that do not meet the required torque values. In order for non-conforming fasteners to be highlighted, the torque tool needs to be disabled and the Operator interface needs to be used to capture details before continuing with the task

- *To develop a set of scenarios to test and identify the limitations of the vertical integration of the architecture components and methods developed*

This objective is to develop a sequence of tests to identify the strengths, limitations, and opportunities to improve the methods developed to demonstrate digital continuity through the various components of the digital architecture. This set of scenarios is to test the individual interactions between single components before the end-to-end system is demonstrated.

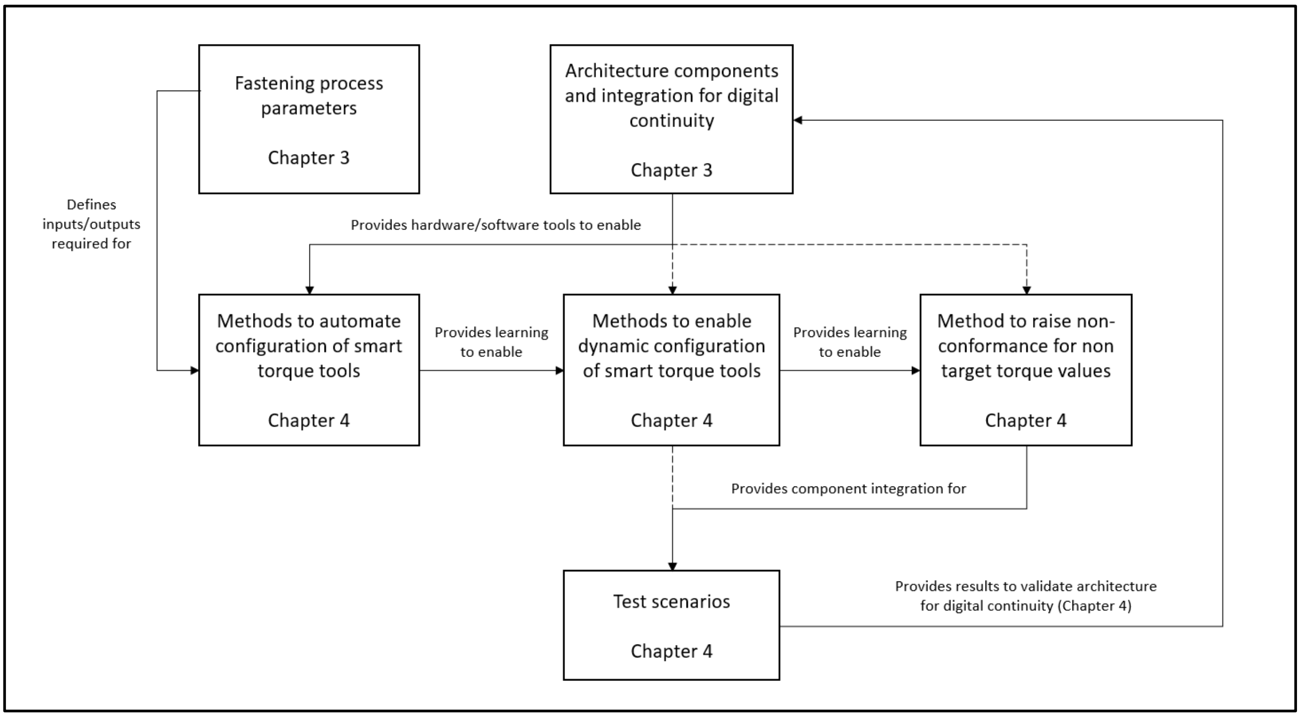


Figure 2 - A diagram to show the process for this research

1.5 Structure of Thesis

The following research thesis will introduce the problem and opportunities currently faced my manufacturers, particularly in the area of smart torque tools and digital continuity in manufacturing processes. This will lead to a review of literature to identify the research and learning in the area of digital architecture for manufacturing and factory operations, data capture, smart tool utilisation and end-to-end digitalisation in Chapter 2. These topics are directly related to this research and a review provided a view of the landscape for what is known today and where further work is required. By identifying the gaps in the literature, aims and objectives for this research were defined before the structure and key components of software and toolsets are described in a general sense and in the context of the application of this research in Chapter 3. Chapter 4 of this thesis describes the method that was followed to test the digital architecture and practices that were implemented, and this is followed by a review of the results and a discussion of the findings and limitations in Chapter 5. The thesis ends in Chapter 6 with a conclusion and recommendations for further work and research.

1.6 Summary

This opening chapter has presented the introduction, motivation and the aims and objectives for this research in to digital continuity in the manufacturing process. The action research methodology with the problem statement have been identified as the starting point for this project, along with the steps that will be taken to achieve results and provide discussions which will lead to a conclusion. This chapter signposts the following chapters of this report in order to provide the reader with an overview of the thesis.

Chapter 2

Literature Review

Research contributions to digital manufacturing and Industry 4.0 mainly include conceptual insights and references to work involving network/enterprise architecture components, internet of things, digital or smart factory, communication methods and examples of where connected assets have been used to improve manufacturing in various ways. This chapter of the thesis will evaluate literature concerning these topics in order to understand the advances and lessons learned by prior work.

2.1 Digital Thread

A description of a digital continuity in manufacturing is offered by Green (2019), who summarises the concept of digital continuity begins with a digital thread which extends beyond the start of production and includes integrated feedback from the shop floor and supply chain, and has inputs from the distribution network and consumers. Digital continuity is created by the integration between product lifecycle management (PLM), enterprise resource management (ERP), shop floor applications and equipment to enable the exchange of information about the product and the process (Green, 2019).This concept of continuity is discussed further in Smith (2015) where the typical flow for products from design through to manufacture are presented. They are shown as five key stages; Design, Product Engineering, Manufacturing Engineering, Production Planning and Manufacturing Execution. In the context of wire harness manufacturing, Smith (2015) explains that there is a technology void which drives the necessity for integrated systems for data to 'flow upstream and downstream with no manual re-entry'. The emergence of standards and robust IT platforms have made the realisation of digital continuity and a continuous flow possible along with other key benefits (Smith, 2015).

A number of architecture approaches and concepts are discussed in literature, including the 'development and implementation of a reference architecture to enable a digital thread in manufacturing' which is presented in Helu, Hedberg Jr. and Feeney (2017). This literature summarises that using a 'four-tier architecture enables seamless vertical and horizontal integration across different product lifecycle stages' (Helu, et al., 2017). The four tiers used for a smart manufacturing systems test bed are shown in Figure 3 and are defined as services (Tier 1), aggregation (Tier 2), delivery (Tier 3) and client (Tier 4). A possible limitation of this implementation is the use of 'custom scripts to automate the data transfer'.

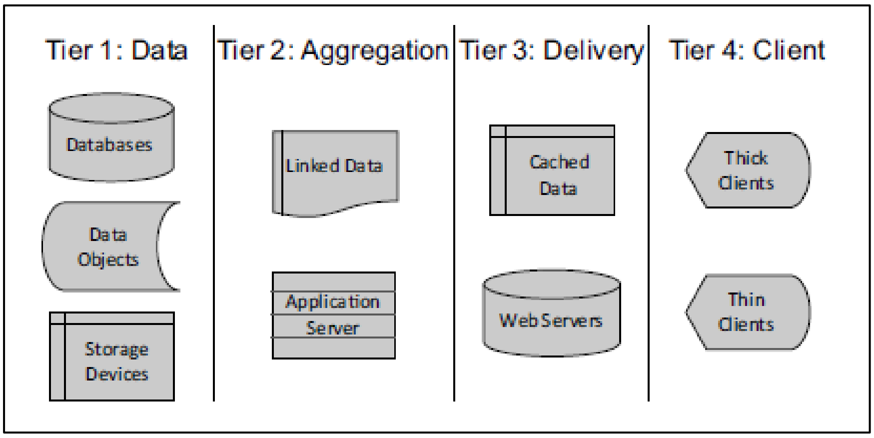


Figure 3 - A schematic example of a four-tier architecture (Helu, et al., 2017)

An ISA-95 based manufacturing intelligence system is investigated in Unver (2013) which produced an integrated architecture model to support continuous improvement in lean manufacturing by providing real-time visibility to shop floor operations (Unver, 2013). The main contribution of Unver's study was the ability to contextualize shop floor data with enterprise resource management (ERP) data to 'dynamically generate KPIs'; this shows an ability to associate data through various levels of the network architecture.

Further research in to architecture is presented in Farooqui et al. (2020) where an event-based data pipeline architecture is modelled. There is consideration for the requirements of data collection from manufacturing systems in the form of extendibility, vendor-agnostic, non-intrusive, plug and play, usability and security. This literature presents the components of a data pipeline such as endpoints, message bus, and message format before the proposed architecture is presented in the context of a manufacturing station with a robot (Figure 4).

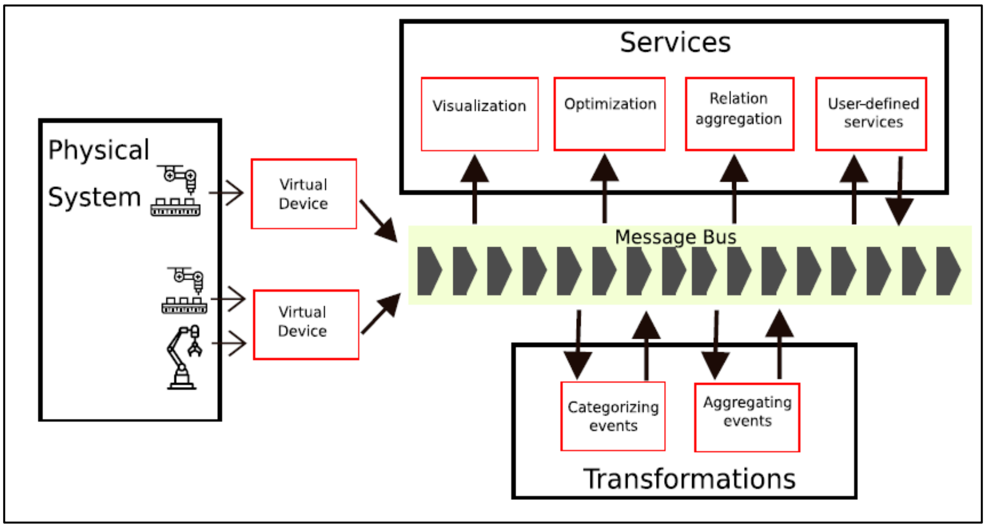


Figure 4 - A schematic of the data pipeline architecture presented by Farooqui, et al. (2020)

Further work lies in the integration of programmable logic controllers (PLCs) in to the data collection architecture (Farooqui, et al., 2020). The importance of architectures to manage complex information is discussed in Park (2016) where the success factors contributing to introduction of the hyper-connected smart factory are presented as part of the 'development of innovative strategies for the Korean manufacturing industry'. This literature evaluates the effects of the introduction of the connected smart factory along with the integration requirements of the factory value chain, before concluding with the success factors. These include:

- The standardisation of core technology
- Build architecture to manage a complex information system
- Build infrastructure for high-quality data exchange in the manufacturing industry
- Distribute methodology, instructions and guidelines for companies to evolve
- Establish comprehensive promotion policies

(Park, 2016)

2.2 Digital Architecture

2.2.1 Product Lifecycle Management

Product Lifecycle Management (PLM) and variations have been popular within the literature; collaborative process planning and manufacturing in PLM is the focus of Ming et al. (2007) where a framework is proposed in order to respond to new business requirements and a need for the integration of people, processes and technology. An implementation in this study showed the efficiency and effectiveness for product collaborative manufacturing which provides a foundation for the future development of collaboration throughout the entire product lifecycle (Ming, et al., 2008). In a different approach, Lee at al. (2011) firstly present the 'composition and position of PLM' (Figure 5) before presenting a 'real-time and integrated engineering environment using ubiquitous technology' with product lifecycle management, known as u-PLM. This literature defines the characteristics and components of PLM, the conceptual architecture of u-PLM (PLM, information systems, middleware and ubiquitous technology), and the proposed concept of u-PLM is applied to a die try-out process using RFID technology (Lee, et al., 2011).

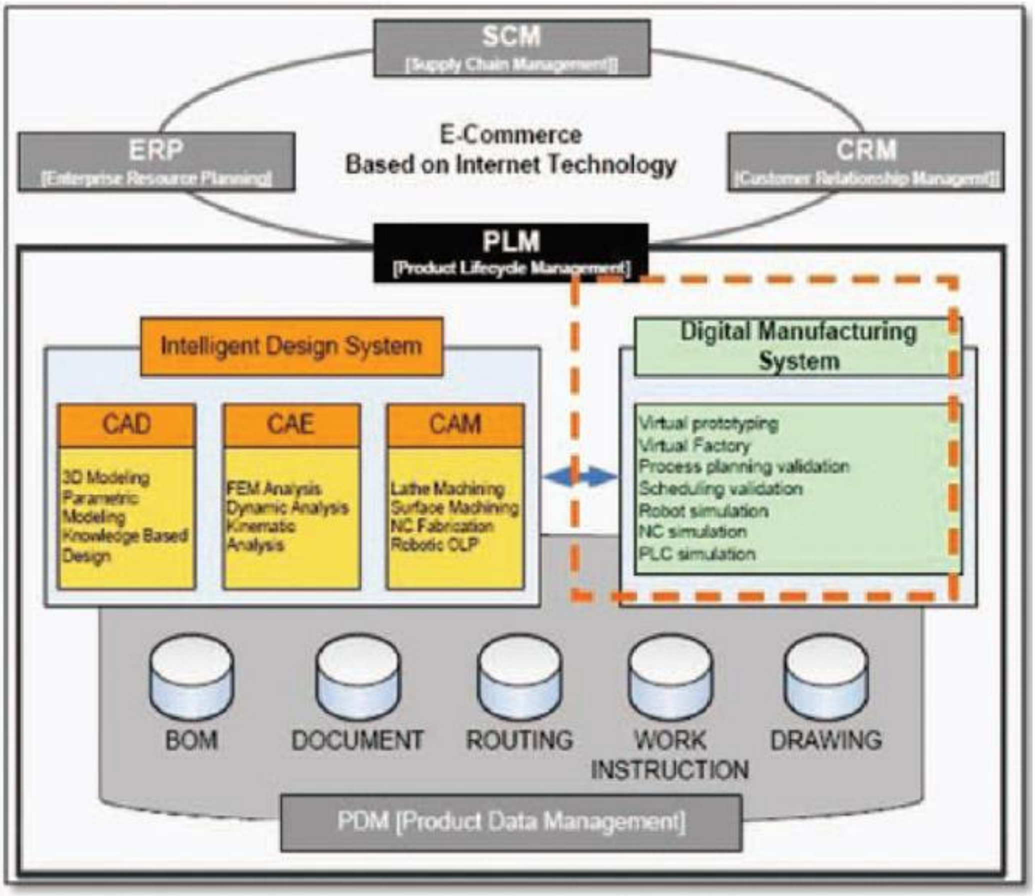


Figure 5 - The internal composition and position of PLM (Lee, et al., 2011)

Helu and Hedberg Jr. (2015) present a 'concept for a product lifecycle test bed built on a cyber-physical infrastructure that enables smart manufacturing research'. This concept consists of creating a 'digital thread of information across the product lifecycle' through computer-aided technologies that interface through the product model. The proposed structure and architecture of the test bed are presented and the requirements and challenges of implementing a cyber-physical infrastructure for manufacturing are highlighted, noting that tools such as a manufacturing execution system (MES) for the integration of heterogeneous solutions are enabled by the proposed concept (Helu & Hedberg Jr., 2015).

2.2.2 Manufacturing Execution

The implementation and applications of manufacturing execution systems (MES) is another key topic of the literature. Cottyn, Van Landeghem, Stockman and Derammelaere (2010) investigates a method to align a manufacturing execution system (MES) with lean objectives. This literature illustrates how a MES provides useful information that can 'trigger, feed or validate' the lean decision-making process, while it also enforces a standardized way of working (Cottyn, et al., 2011). In other work, the effective implementation of a manufacturing execution system (MES) is presented in Govindaraju and Putra (2016). This study focused on how the ISA-95 standard can be utilised to determine the MES requirement specification in order to develop a methodology for implementation. The proposed methodology follows the following steps:

- Initial Assessment: analysing system scope, manufacturing processes and MES requirements
- MES Design: developing the design of processes and integration of touch points
- Configure, Build and Test: detailed plan for change management, system integration and test
- Deployment: data migration, cut over planning and training
- Operation: continued use of the system as art of daily activities and run of operations

(Govindaraju & Putra, 2016)

The study highlighted the importance of defining the requirements and scope of the MES and the consideration of information exchange between the MES at Level 3 of the ISA-95 hierarchy and ERP system at level 4 (Govindaraju & Putra, 2016). Figure 6 shows the equipment hierarchy model presented in the literature.

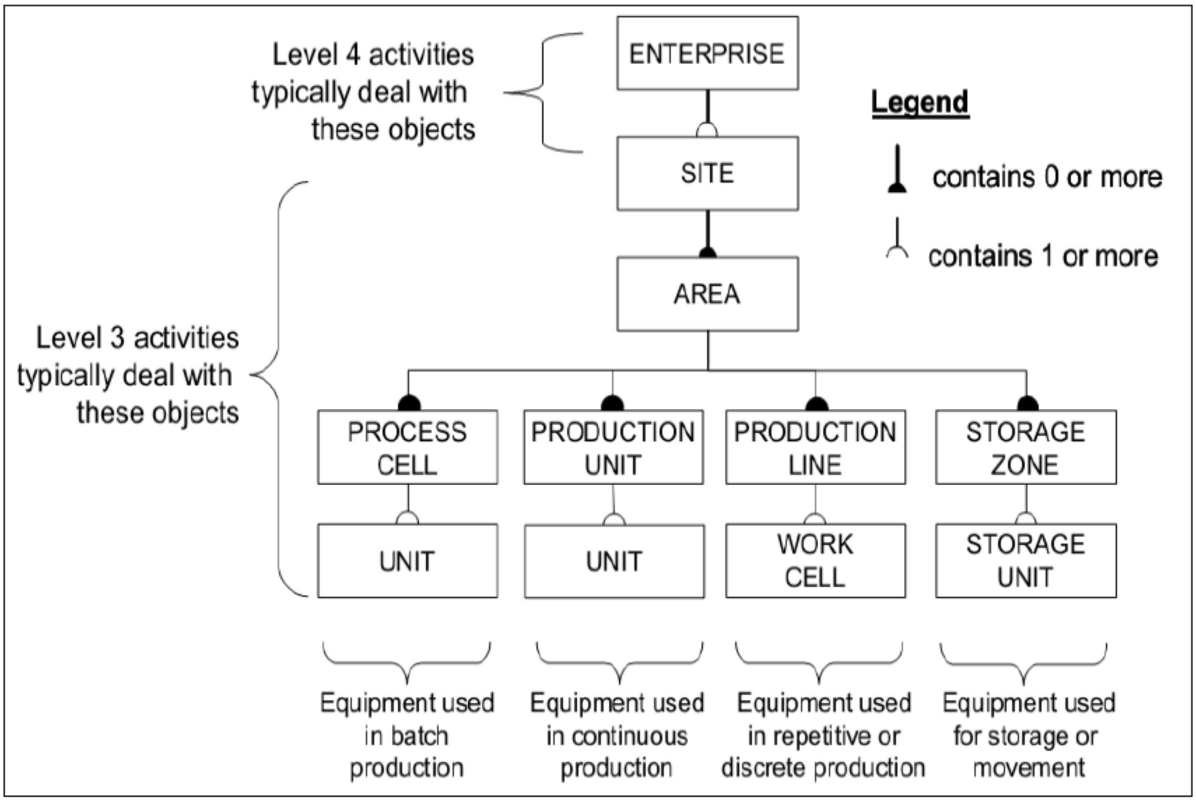


Figure 6 - Equipment hierarchy model with reference ISA-95 hierarchy levels (Govindaraju & Putra, 2016)

2.2.3 Industrial Connectivity

On the topic of industrial connectivity and data collection, guidelines and abstractions for data distribution service (DDS) in the connectivity or control layer of a factory architecture, also referring to a virtual software bus, are presented by Calvo et al. (2013). This study illustrated the use of DDS as a middleware component for 'connecting industrial controllers at the control layer of the automation pyramid' (Calvo, et al., 2013). This topic is explored further, with reference to the internet of things (IoT) in Chen et al (2018) where key technologies and challenges related to the smart factory of industry 4.0 are presented. The study covers the hierarchical architecture of a smart factory and challenges, focusing on the physical resource layers, network layer, cloud application layer and the terminal layer (Figure 7); this required reference to the internet of things (IoT), intelligent data acquisition, industrial wireless sensor networks and applications of big data in manufacturing.

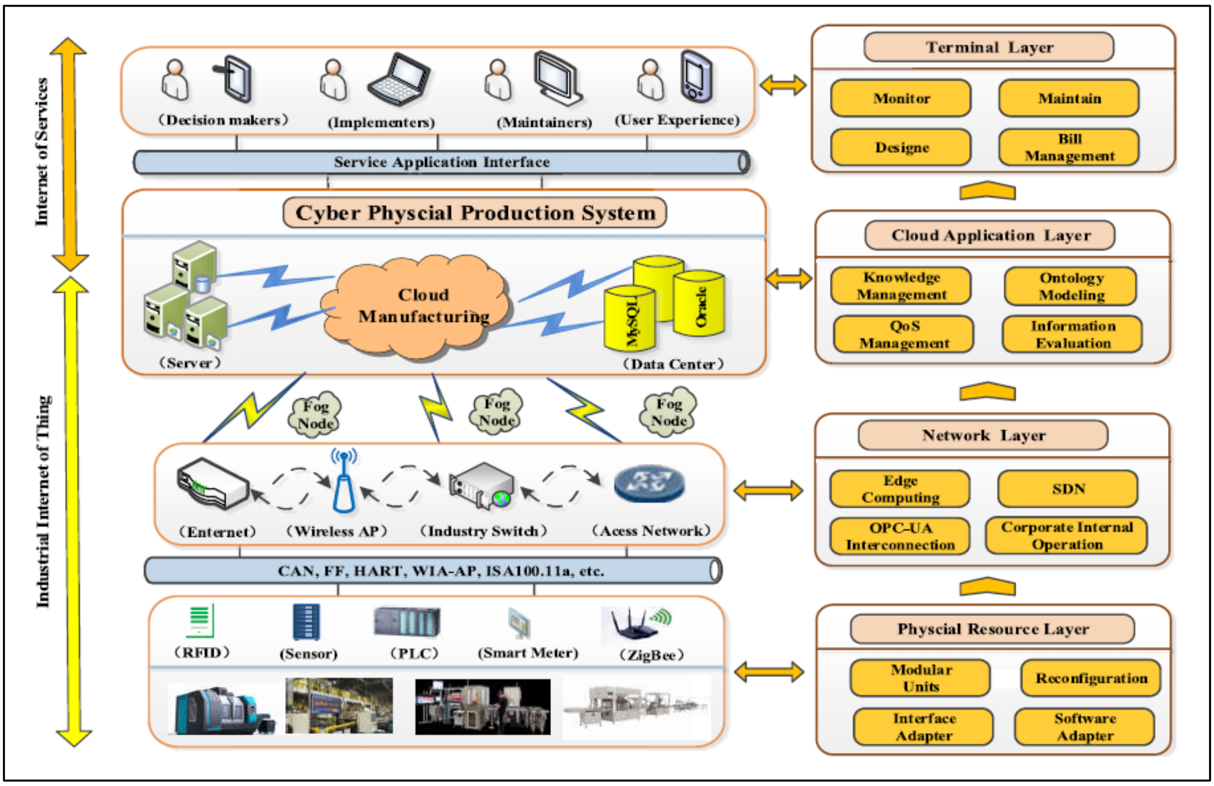


Figure 7 - The hierarchical architecture of a Smart Factory as presented in Chen, et al. (2018)

The data transmission protocol OPC-UA (open platform communications unified architecture) is noted as part of a related technology to enable the connection of multiple manufacturing agents and ensure real-time communication between devices in a standardised manner (Chen, et al., 2018). This literature applies the smart factory architecture to a laboratory prototype platform which represents a candy packing production line. In further reference to the use and application of the OPC-UA protocol, Cavalieri et al. (2019) proposes the definition of a web platform which offers access to OPC-UA servers through a REST architecture. This study provides an overview of OPC-UA, the available services, security information, and the proposed OPC-UA web platform architecture. The role of OPC-UA is to ‘standardise machine-to-machine communication using a uniform data format’, according to the reference architecture model for Industry 4.0

(RAMI) (Cavalieri, et al., 2019). Further evaluations of machine communication was conducted in Duerkop et al. (2015) where OPC-UA achieved the best test results in an evaluation of machine-to-machine (M2M) protocols over cellular networks. OPC-UA was tested alongside CoAP and MQTT in order to compare their transport mechanisms, evaluate transmission times and analyse the potential for optimisation. OPC-UA was summarised to have the most suitable protocol for cyclic data transfer although it has the largest protocol overhead of the three protocols that were tested (Duerkop, et al., 2015).

2.3 Data Capture

The concept of connecting objects and systems within a network to exchange data, known as the internet of things (IoT) was a popular topic in the literature. Boyes et al. (2018) improve on existing definitions of the industrial form of this concept, the industrial internet of things (IIoT) and propose a framework for analysing the use and deployment of IoT technologies in industrial settings. This literature explored the definitions of connectivity, devices, technology and the user in relation to IoT while explaining the various links to cyber security, IoT solutions architecture, the Purdue enterprise reference architecture model and legacy systems (Boyes, et al., 2018). This concept is taken further by the demonstration of an IoT use case for machine-tool monitoring system, which is presented in Mourtzis, Milas and Vlachou (2018) in order to demonstrate the actual status of resources using the internet of things and cyber-physical systems (CPS) paradigms. The use case in this literature covers data acquisition from wireless sensors, use of the OPC-UA communication standard, data processing and data extraction, and the use of cloud computing for aggregation and visualisation of the meaningful information (Mourtzis, et al., 2018). The IoT-based monitoring system proposed in this literature is shown in Figure 8.

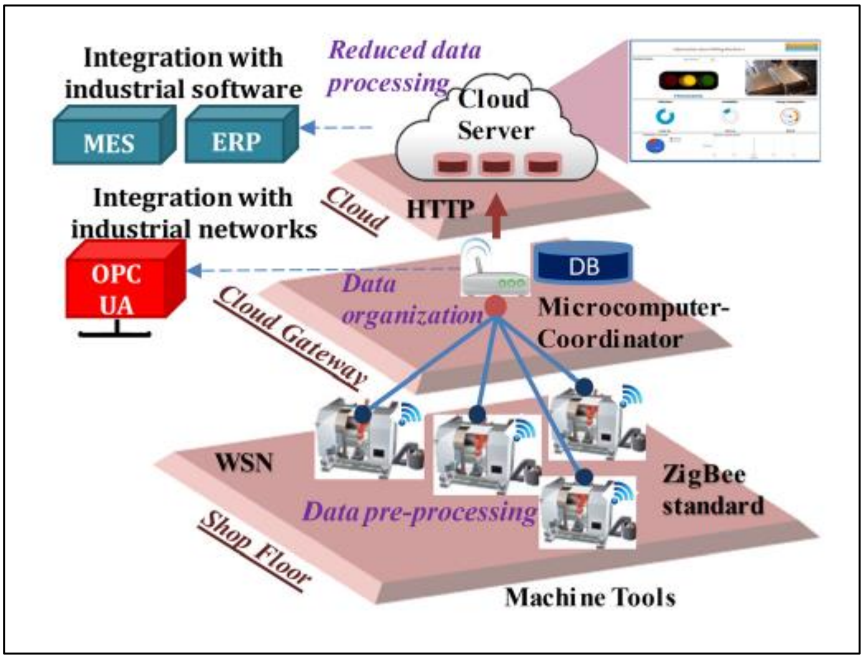


Figure 8 - The IoT-based monitoring system proposed in Mourtzis, et al. (2018)

A different use case is presented in Sunithkumar et al. (2017) where an IoT-based architecture for a shop floor data capture is presented for the assembly of a railway heating, ventilation and air conditioning (HVAC) unit. The components of an IoT architecture are presented along with detail around the application of IoT based software for a manufacturing shop floor, plus the literature also refers to torqueing and recording activities. The core use case is the implementation of barcode technology in an assembly workstation which ultimately resulted in an improvement of productivity due to the elimination of the complexity when getting data (Sunithkumar, et al., 2017).

Not directly linked to IoT, Tiwari et al. (2008) demonstrated the potential of data capture with the use of database technology to perform automated inspection activities in aircraft wing assembly, delivering significant benefits such as reduced inspection lead-times, improved machine utilisation and a method to detect errors that are difficult to detect manually (Tiwari, et al., 2008). This study shows the advantage of using data captured from shop floor assets to validate that manufacturing activities have been carried out correctly, and highlighting activities that require rework during the process. This methodology could be applied to the connected technologies that are emerging on manufacturing shop floors today.

2.4 Connected Assets

There are a number of use cases related to the connectivity of shop floor assets and wireless technology in the literature. A review of literature, recent developments and case studies related to wireless manufacturing is undertaken in Huang et al. (2009) where the benefits of wireless manufacturing and its reliance on key enabling technologies such as RFID (radio frequency identification) and communication networks such as Wi-Fi and Bluetooth are highlighted for the collection of real-time field data in manufacturing (Huang, et al., 2009). The theme is continued in in Huang et al. (2007) where wireless manufacturing, an emerging advanced manufacturing technology, is the focus of the study. This literature presents a simplified example to illustrate the deployment of wireless manufacturing technology, such as radio frequency identification (RFID), and wireless information networks for the collection and synchronisation of real-time shop floor manufacturing data. This study also discusses the smart objects to be tracked and traced on shop floors, and outlines the architecture for information communication (Figure 9) related to wireless technologies (Huang, et al., 2007).

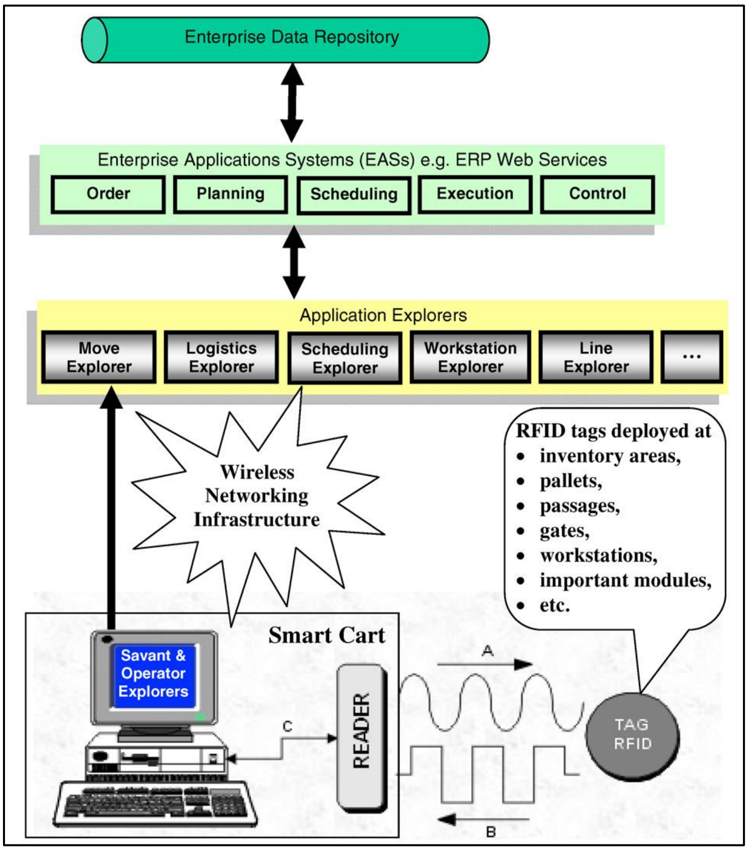


Figure 9 - The conceptual architecture of wireless manufacturing as presented by Huang, et al. (2007)

Huang et al. (2007) suggests that the real-time traceability and visibility offered by wireless manufacturing methods can support common shop floor problems such as 'tedious and error-prone manual data collection and entry'.

The advent of hand held wireless battery tools is introduced in Secheret & Valentin (2013) where the reasons for why this technology is chosen to assemble aircraft are presented. This literature states that the development of the Lithium-Ion battery was the first significant enabler of this technology as it answered some of the key problems with battery technology. Furthermore, the development of wireless technology such as Wi-Fi and ZigBee has improved the reliability of message transmission. The literature presents the quality requirements, tightening strategy (Figure 10) and reporting elements of the Desoutter hand power tools, concluding that the many advantages of the tools using wireless technology include:

- Reduced non-quality
- Full traceability
- A wide range of advanced tightening strategies
- Tightening range and accuracy
- Improved user ergonomics
- Energy and cost savings
- Improvements in FOD (foreign object debris) management

(Secheret & Valentin, 2013)

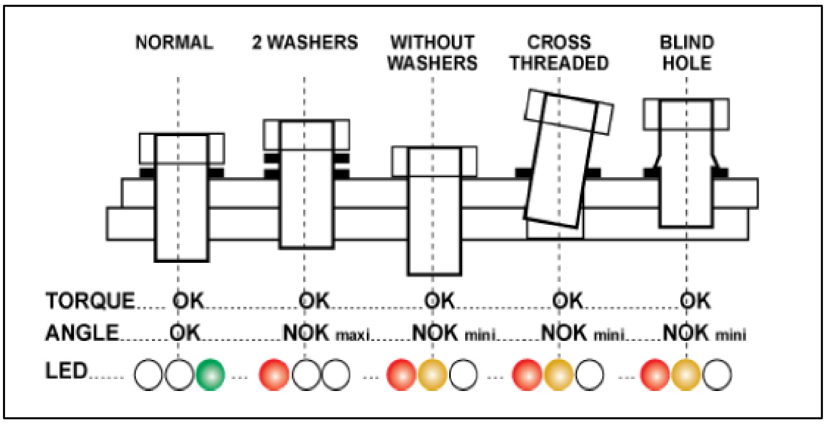


Figure 10 - Desoutter torque strategy set up with Angle monitoring as presented in Secheret & Valentin (2013)

A hand power tool use case is discussed in Umer et al. (2018) where the implementation of an event driven architecture including a plant service bus (PSB) is evaluated in order to make the shop floor equipment and smart tools capable of transmitting data. An event driven architecture where systems could communicate by subscribing and publishing data was used for this smart power tool use case rather than a point-to-point communication system (Figure 11). The architecture implemented in this study was capable of collecting data from the shop floor equipment which enabled a robust deployment of endpoints and services (Umer, et al., 2018).

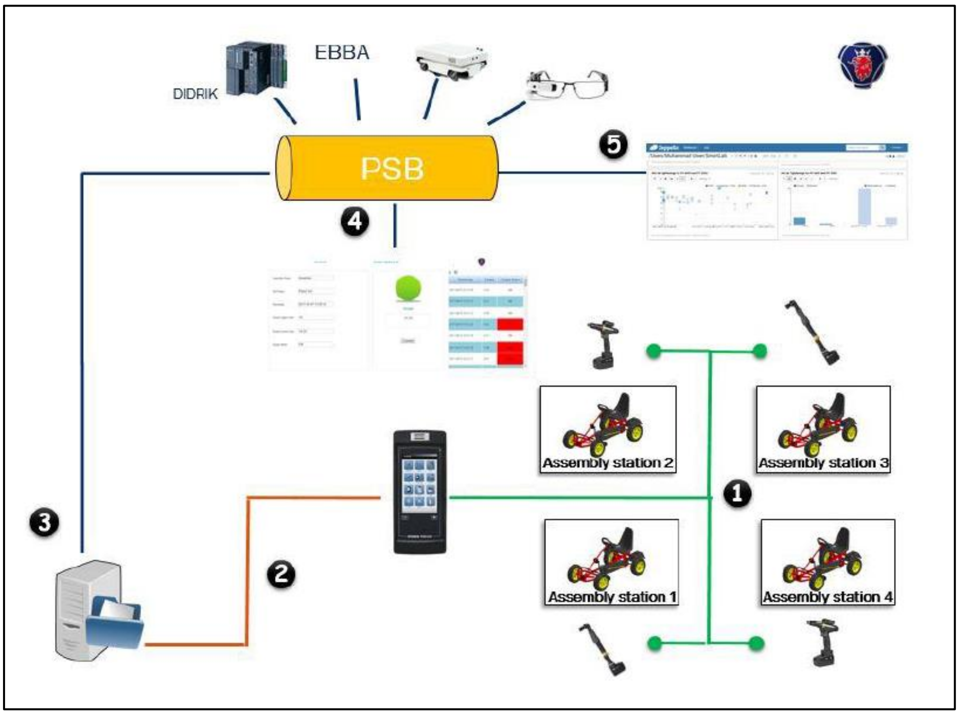


Figure 11 - Information flow for the smart power tool use case presented by Umer et al. (2018)

2.5 Research Gaps

The literature reviewed has not only highlighted key findings and progression of knowledge around network architecture, the application of software systems, connectivity of assets and real-time monitoring methods, but it has also highlighted a number of gaps in existing research, such as the development and expansion of digital continuity through vertical integration of the digital architecture; connecting design, manufacturing and execution phases with a single source of data. The following gaps in research are explained in this section.

2.5.1 Automatic Configuration of Assets & Tools

The ability to capture data from a connected asset, controller or tool in order to visualise process data from activities such as tightening in real-time is considered in Umer et al. (2018) by the event driven architecture and communication method presented. From the research reviewed, this area of work needs to be taken further to consider previous stages not only of the tightening activity and tool configuration, but of the product lifecycle in terms of the product design specifications and manufacturing process plans. Conducting further work in to enabling a two-way communication method between systems which contain process requirements and connected assets will promote digital continuity and stretch the digital thread throughout more stages of the manufacturing process. An area of opportunity would be exploiting the benefits of configuring shop floor assets and tools automatically based on the task they are about to carry out; this information is contained further upstream in the architecture within the PLM and MES toolsets.

2.5.2 Data Capture for Digital Continuity

In addition to establishing a two-way method of communication in order to send process requirements (or settings) to shop floor assets, there is a research gap associated to manipulating and utilising the data that has been captured in order to add business benefit and promote lean manufacturing. This could be in the form of using data, tolerances and rules engines to trigger subsequent events or send notifications, such as managing issues or sending logistics requests. The process of capturing real-time data from shop floor assets and processes is well established and is referred to in many cases within existing literature, as is the visualisation of data, but real-time and automated process activation is not well covered other than in references to data analytics which is generic. The opportunity associated to the next stages of data capture will enable a wider application and benefit of the digital thread, connecting various processes and factory events to one source of information and promoting a lean manufacturing methodology.

2.6 Summary

This review of literature has covered a number of relevant topics related to digital manufacturing, digital architecture and the use of connected assets. This review has shown that research has been carried out on the application and use of PLM, MES and shop floor use cases, mainly in isolation and in the context of various network architecture approaches. There appears to be a gap in end-to-end vertical integration and a demonstration of digital continuity from the product design phase through the shop floor execution, extending to data capture, visualisation and activating processes to support business requirements and lean manufacturing objectives. The literature reviewed presented a variety of different applications and highlighted challenges for concepts related to data capture and connectivity, such as internet of things.

Chapter 3

Architecture (Technologies & Systems)

3.1 Introduction

This chapter of the thesis will outline the technologies and systems that will be used for this research in order to meet the objectives. The key components of the architecture will be described to provide the context before a more detailed description is provided for how these architecture components will work together to provide a solution for the application of smart tooling, the focus of this research.

In order to automatically activate certain settings on a hand-held torque tool based on the content of the digital manufacturing routing for a given process (which will be referred to as “work instructions (WI)”), information relating to the requirements of the fasteners, such as target torque, must be exposed and available. In this research, a method for taking designed fastener requirements and using this data to configure a torque tool to the appropriate setting of product assembly will be developed. This will demonstrate that digital continuity can be transferred from the design model within a platform software suite to the shop floor. This will mean that the information must pass through several stages; the data set in the design model, through a planning process where work instructions are generated, through a manufacturing operations management (MOM) system where work instructions will be allocated to an Operator, and finally to a controller for wireless tools which requires connectivity to the industrial network.

3.2 Method

To successfully demonstrate a solution in a relative production environment, the first step was to define the value of gathering data from a shop floor torque tool; this is to increase product quality, improve the management of tooling, and manage defects in a proactive manner in order to save time. The data set that can be extracted from the connected torque tool system is large and not all aspects will provide value. The initial step of connectivity was to define the parameters and attributes required to automatically configure a torque tool that could be used for any fastening operation. The following attributes were defined:

- Torque Minimum
- Torque Maximum
- Torque Target
- Angle Minimum
- Angle Maximum
- Final Angle Target

The second step was to pin-point a specific assembly operation where the wireless torque tool could be used to demonstrate connectivity to a work instruction and the industrial network to meet the objectives of this research. The digital work instruction for this operation would include the torque tool ID in its list of tools and the torque parameters would be assigned to the fasteners being fastened; this would enable the digital continuity throughout the digital architecture.

The third step was to implement a digital architecture that enables the transfer of design data for the fasteners to a wireless torque tool on the shop floor. For this solution to demonstrate a benefit to the business, it was important to ensure that there was no duplication of work between the different stages of this process or levels of the architecture; for example, design specifications were manually assigned to the fasteners at the first stage and they should not alter from that point forward; the data should only be transferred.

The digital architecture to prove the data flow for the control of wireless torque tools was pre-defined based on the available tool set; this research and demonstration needed to test the connectivity capability of the various software platforms, the latency of data transfer, and the secureness and scalability of the solution.

The event-driven network architecture for this research was formed of a Product Lifecycle Management (PLM) platform, a Manufacturing Operations Management (MOM) system, a connectivity platform and a smart tool controller which connected to a wireless torque tool. This tool was used on the shop floor to carry out assembly operations.

3.3 Architecture Design and Key Components

The ISA-95 international standard from the International Society of Automation (ISA) has been developed for manufacturers for application across all industries in order to provide a consistent foundation for manufacturing information management and control systems. This section of the report will discuss the alignment of the ISA-95 architecture to this research with a description of each level. The ISA-95 functional hierarchy is shown in Figure 12.

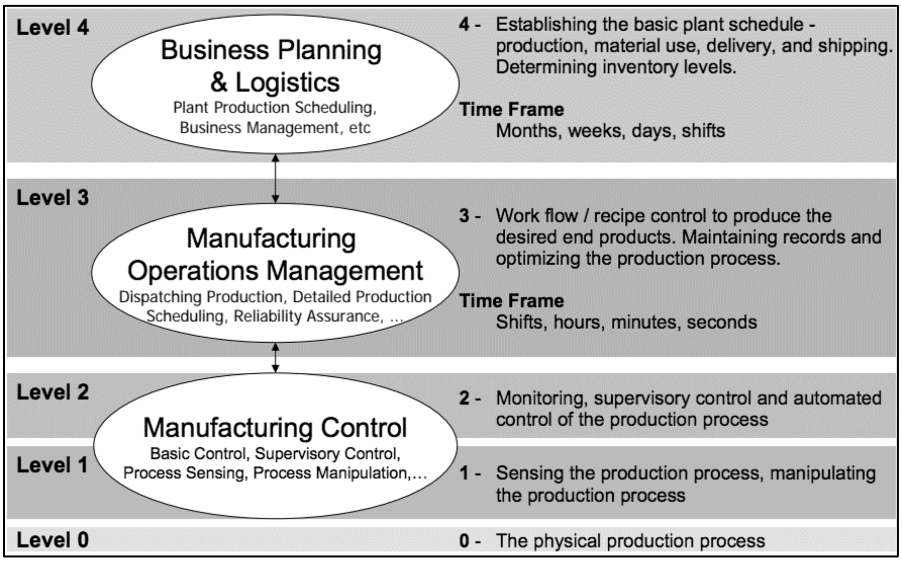


Figure 12 - Production functional hierarchy as defined in ISA-95 (American National Standard, 2010)

3.3.1 Product Lifecycle Management (PLM)

Product Lifecycle Management (PLM) is an information management system usually used by manufacturing companies to manage several stages of the product lifecycle, such as prototyping, design, manufacturing, servicing and through to disposal. PLM forms part of a company's software strategy and is a leap forward from using silo CAD/CAM software suites. PLM systems can integrate and leverage data from processes, assets, people and business systems in an extended enterprise.

3.3.2 Manufacturing Operations Management

The term "Manufacturing Operations Management" is used to describe the level of the ISA-95 architecture model that covers topics such as scheduling, manufacturing execution, asset tracking, document management, reporting and material requirements planning (MRP). In this research the functionality of a MES will be the focus; this is the system that oversees the transformation of parts, components and raw materials in to finished products and assemblies. These systems help manufacturers monitor and understand current conditions and production schedules and can also be responsible for managing the allocation of work orders and distribution of work instructions to shop floor workers.

3.3.3 Middleware / Connectivity Platform

In order to establish communication channels from the MOM systems (such as MES) to various controllers, assets or monitoring systems on a factory shop floor, a method of connectivity that can manage a series of protocols and industrial network requirements needs to be used. In this research an open platform communications (OPC) server is used to channel communication between the MES and the controller managing the tool on the shop floor.

3.3.4 Controllers and Devices

At the shop floor level where the manufacturing operations take place, connectivity reaches the controllers, sensors and/or actuators of the assets and devices that input or output the information received via the communication channels. For example, in this research a series of tool settings are sent to the torque tool controller and a series of fastening cycle outputs are sent back. Figure 13 shows the structure of the components of the architecture.

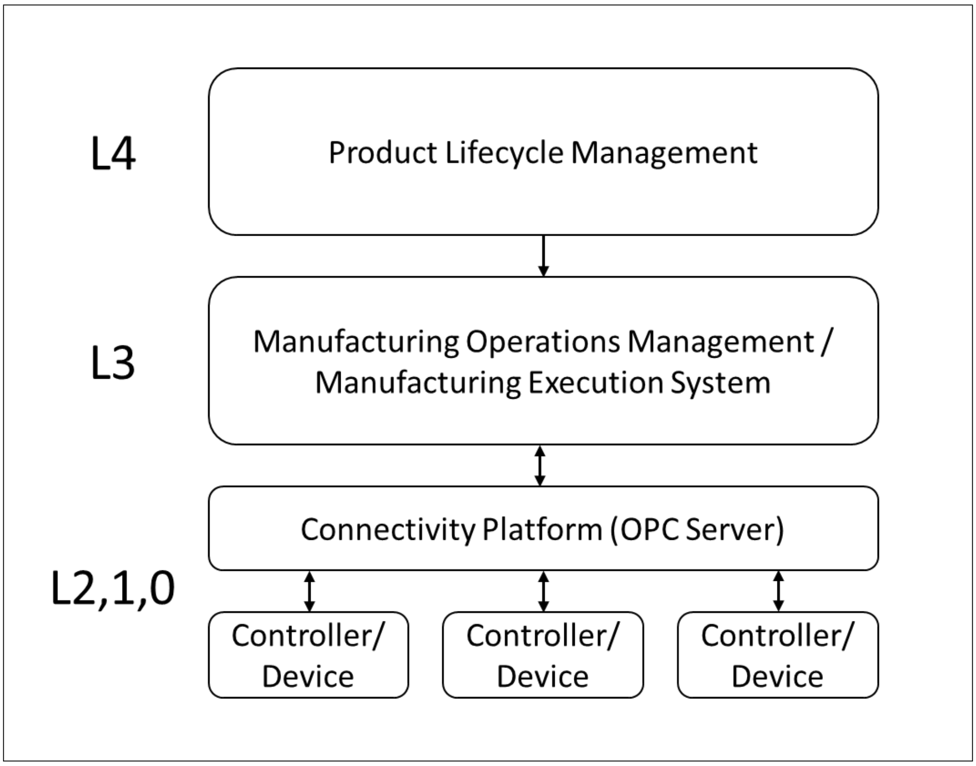


Figure 13 - Diagram to show the hierarchy of the key components used in this research

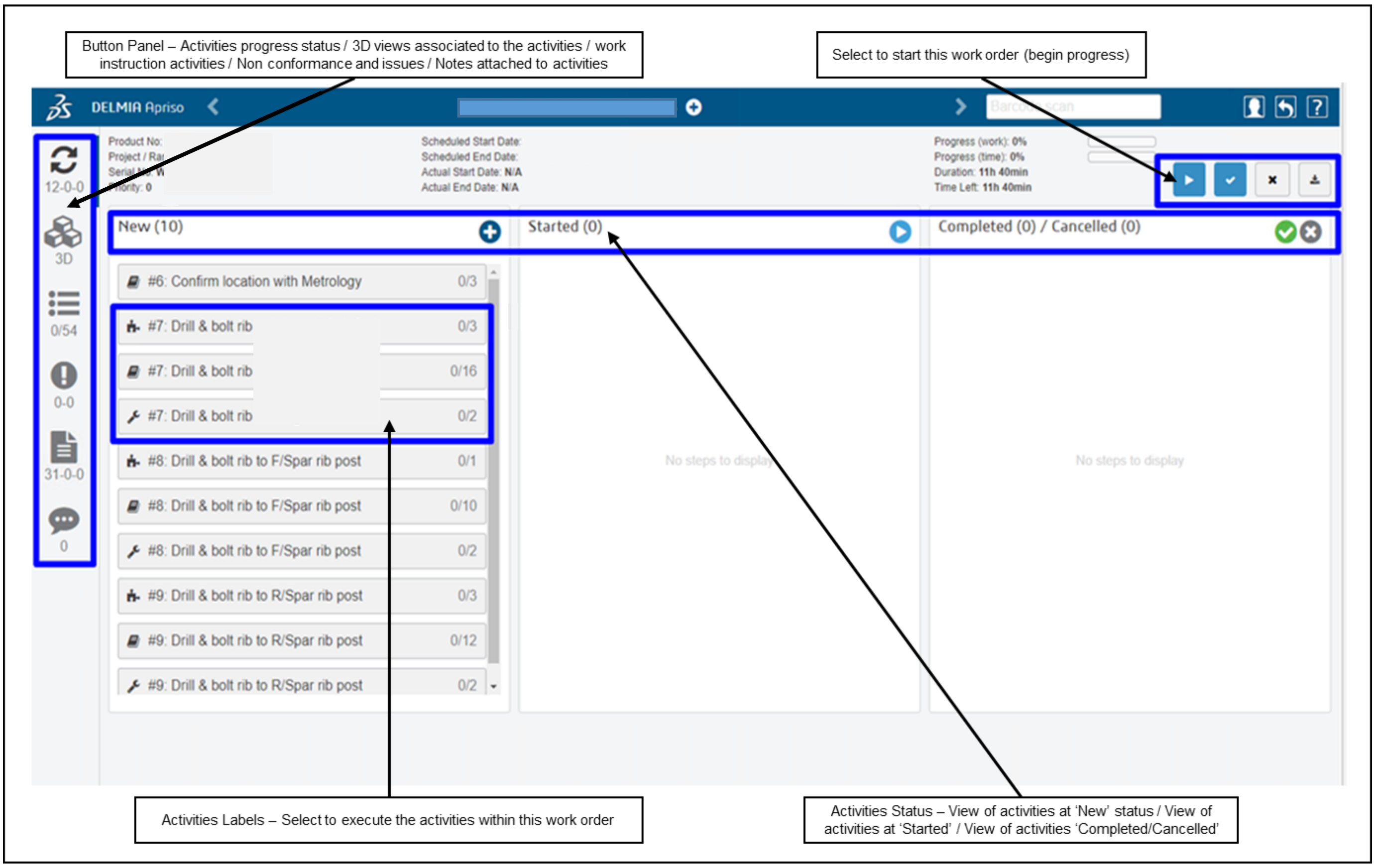
3.4 Architecture Setup for Smart Tooling

3.4.1 Product Lifecycle Management (PLM)

The PLM platform that was used to test this solution was Dassault Systèmes' 3DExperience. This platform was used to design the components and product assembly for the wing structure used in the demonstration of this research, inclusive of design models and data sets. The platform was then used to generate PPR (product-process-resource) structures which create the work instructions for the various assemblies of the wing structure. The use of this platform offered an opportunity because the content inputted in to the wing structure design model by the design function was directly transferred in to the digital work instruction. The work instruction for a given assembly operation contains the bill of materials (BOM) for the components that are to be assembled, the tools and equipment to be used, and the instructions for how the task is to be executed which are provided in text, 2D and 3D formats.

3.4.2 Manufacturing Operations Management (MOM)

The MOM platform used in this research was Dassault Systèmes's DELMIA Apriso. DELMIA Apriso works as a manufacturing execution system (MES) and the work instructions created in 3DExperience PLM are imported in to DELMIA Apriso where a work order is raised; this work order represents an instance of a work instruction. For example, Work Instruction "X" has been created in the PLM for a given wing assembly activity – when this "X" is required to build wing 1 a work order "A" is created as assigned to Wing 1. When the same work instruction for the same wing assembly activity is required again to build Wing 2, work order "B" is created and assigned to Wing 2; the same work instruction but a different instance. This is to ensure version control is traced against Wing production; "B" may be an updated and improved version of "A". Once a work order is created, the Production Supervisor assigns the work order, and therefore wing assembly activity, to an Operator using the MES. The Production Supervisor uses MES to allocate wing assembly activities to their team of Operators for the shift ahead. The Operators use a tablet device to view the digital work instructions where they can raise issues related to the task and work through the various steps that they certify to show that they are completed (Figure 14); this allows the Production Supervisor to monitor the progress of the shift using on their user interface. In this research, DELMIA Apriso is responsible for the management of the work instructions associated to assembly activities, monitoring progress, capturing issues, providing visibility of operational data and for distributing settings to a torque tool for a given work instruction.


Button Panel – Activities progress status / 3D views associated to the activities / work instruction activities / Non conformance and issues / Notes attached to activities

Select to start this work order (begin progress)

Activities Labels – Select to execute the activities within this work order

Activities Status – View of activities at 'New' status / View of activities at 'Started' / View of activities 'Completed/Cancelled'

Figure 14 - Example of DELMIA Apriso user interface for a Work Order

DELMIA Apriso has an in-built component called Machine Integrator which provides a link to manage automation, tools and equipment in the lower layers of the digital architecture. In this research Machine Integrator was used to dynamically select and send torque tool settings, known as 'Psets" from fasteners cited within a given work instruction and receive specified cycle parameters back in real-time after each fastening was completed. In order to demonstrate this capability, Machine Integrator (known functionally as an OPC client) was linked with a connectivity layer (OPC server) where points were configured to exchange data in both directions. This connectivity enabled tool control on the equipment side and visualisation and management of cycle results on the MES side.

3.4.3 Middleware / Connectivity Platform

The connectivity platform used to transfer information back and forth from DELMIA Apriso and the smart tool system was an open platform communications (OPC) server, KEPServerEX from Kepware. This software-based server solution enables ‘interoperability between client applications, industrial devices, and systems’ (PTC Inc., 2019). This server works by integrating drivers from client servers and enabling communication and transfer of data across a variety of communication protocols (Figure 15).

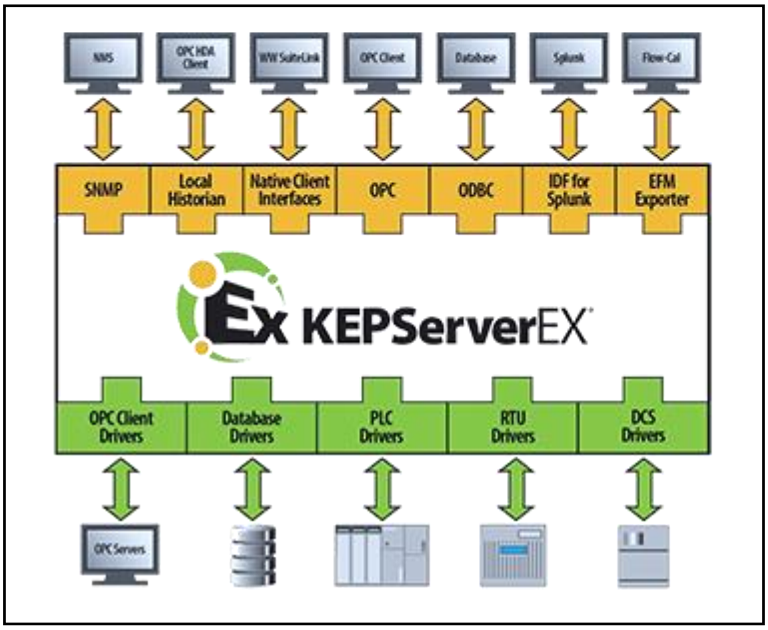


Figure 15 - Diagram to show the function and flexibility of KEPServerEX (Novotek, 2020)

Working in conjunction with Machine Integrator, for every fastener in the work instruction this OPC server was used to transfer the appropriate tool setting to the tool system and then transfer the cycle data gathered during the physical fastening operation back to DELMIA Apriso so that it could be managed and visualised.

3.4.4 Smart Tool System

The Smart Tool system used to demonstrate digital continuity in this research was a Desoutter CONNECT controller or hub for industrial tooling, and a Desoutter EABS17-800-10S wireless torque tool. On the shop floor the tool controller and torque tool communicated wirelessly using Open Protocol, a communication protocol created by Atlas Copco. It is a string-based TCP/IP messaging protocol, which allows real-time data and results to be communicated from the tool. The protocol is based on a series of communication Message IDs (MID) that define the command being sent, followed by the associated parameters. The primary functions of the tool controller in this research were to receive inputs from the KEPServerEX connectivity platform to control the activation/enablement of the specified torque tool and update the tool's setting for the next fastener cycle as per the work instruction in DELMIA Apriso.

3.4.5 Digital Architecture Structure

The aforementioned components of the digital architecture were implemented so that design requirements related to the fasteners in the work instruction could pass successfully to the manufacturing stage of the process and the results could be managed and visualised in the manufacturing execution system. This followed a number of steps through manufacturing planning up to the torque tool being used on the shop floor in a given wing assembly process. The integration of each component was achieved through manual configuration of systems and servers which was necessary to ensure functionality and security of the overall system.

The diagram of the digital architecture is shown in Figure 16.

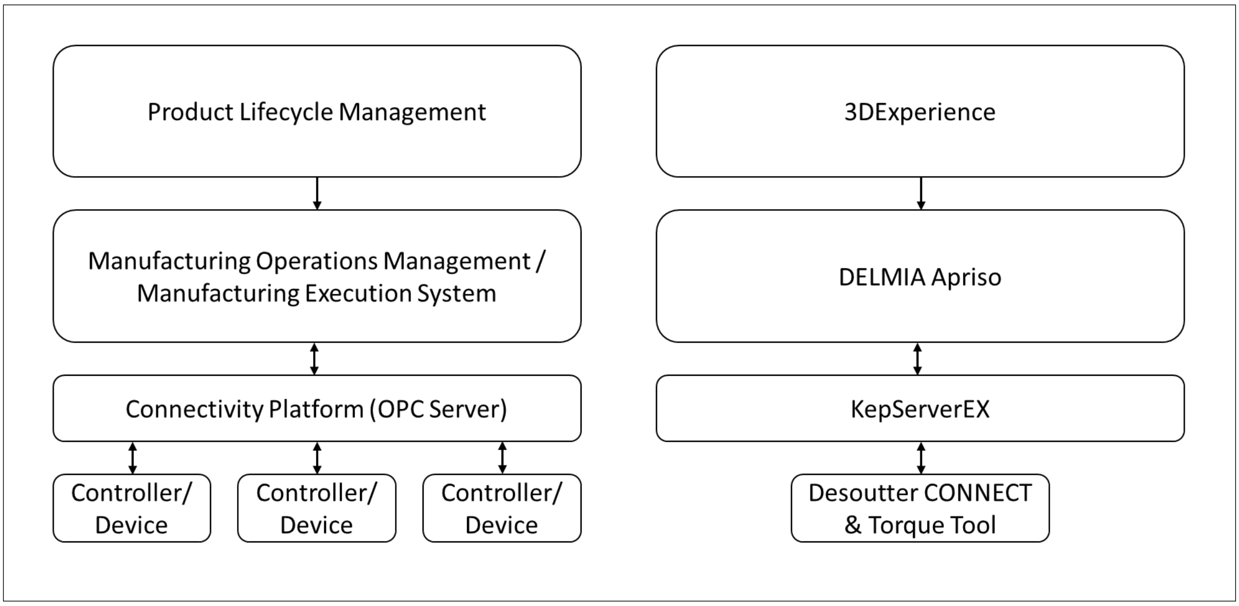


Figure 16 - Diagram to show the architectural hierarchy of the key components and their role in this research

The information flow and the context of each component is shown in Figure 17.

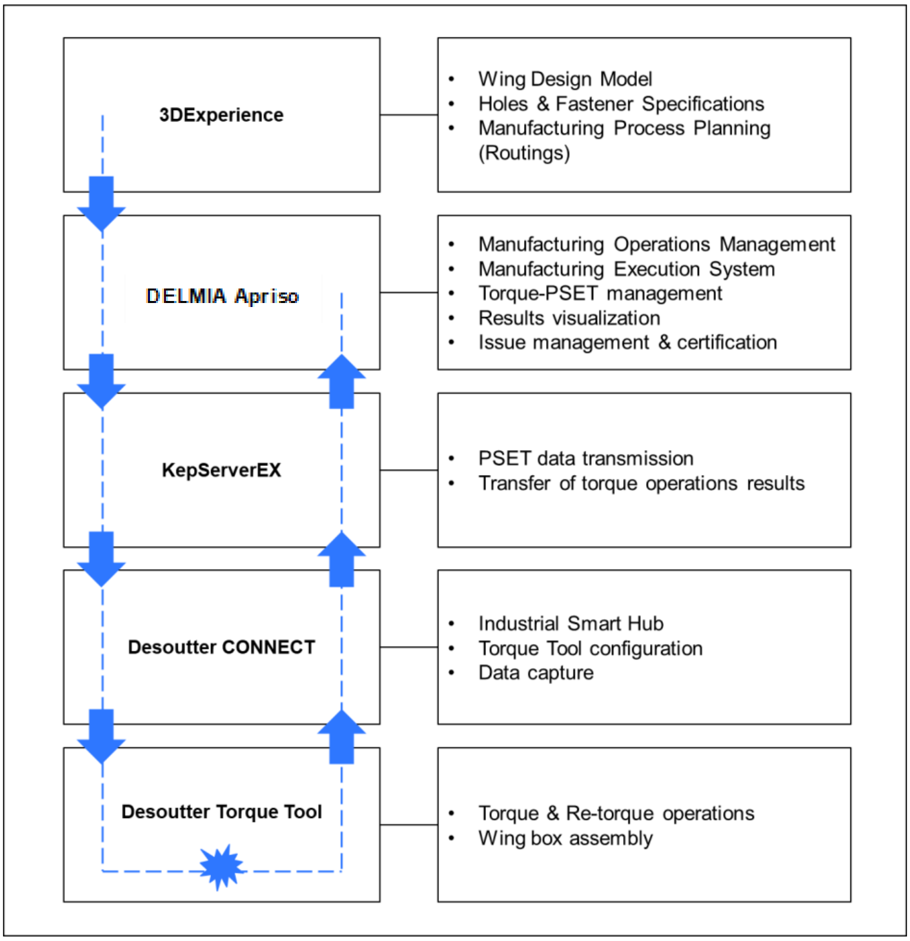


Figure 17 - Diagram to show the information flow and context of the key components in the digital architecture

3.5 Summary

This chapter presented the key components of the digital architecture for manufacturing with reference to the ISA-95 standard before the roles and functionality of each component with regard to the specific torque tool use case were explained. The digital architecture proposed for this research stretches from the design specification and models in the PLM platform through to the physical torque tool activity on the shop floor which creates a vertical integration to demonstrate digital continuity. The explanations presented in this chapter provide the context required to understand the methods proposed in the following chapter.

Chapter 4

Testing, Validation and Results

4.1 Introduction

This chapter of the thesis will describe the main steps taken to test the digital architecture in the frame of the research objectives. It will describe the method and main tests that were performed to ensure connectivity and digital continuity between the various key components of the digital architecture. This chapter will then discuss the results in order to assess the findings of this research.

4.2 Method of Testing

The method to test the functionality of the proposed digital architecture was to assess the connection between the key components in isolation before progressively introducing connectivity to the wider components until end-to-end digital continuity had been demonstrated. The testing sequence is as shown in Figure 18.

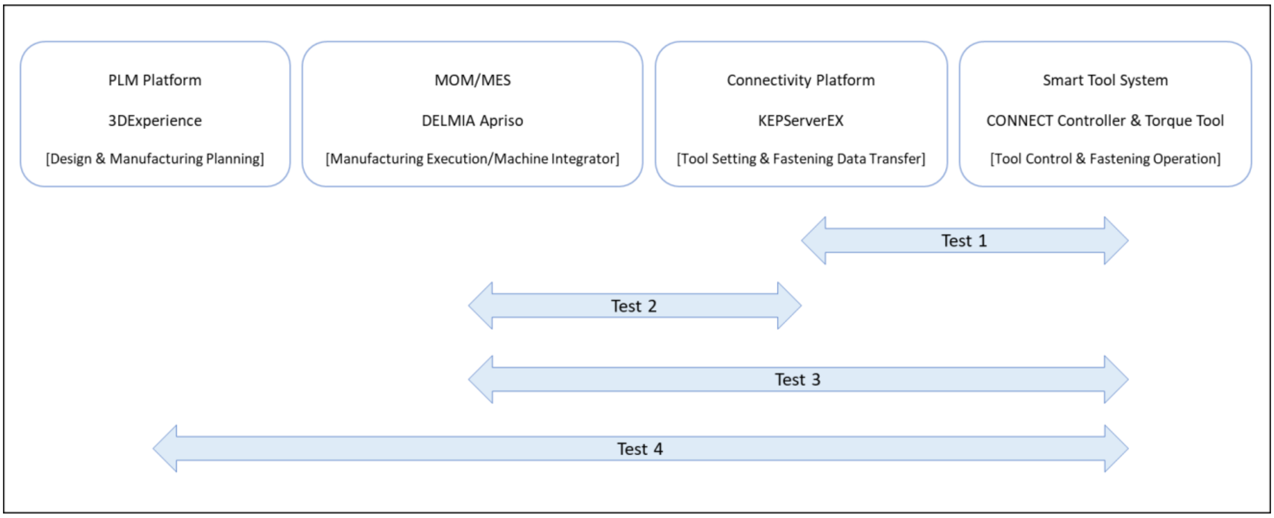


Figure 18 - Diagram to show the sequence of tests used to test the digital architecture for this research

The rationale behind the sequence of tests is that the connection between PLM and MOM/MES was anticipated as the least technically challenging as both systems are software products in the Dassault Systèmes software portfolio, and mock data could be used in DELMIA Apriso to represent the designed fastener torque requirements during the test phase; therefore the end-to-end test was introduced in Test 4.

4.2.1 Test 1 – Connectivity Platform to Smart Tool System

For test 1, the connection between KEPServerEX, the tool controller and the torque tool needed to be understood to 1) prove that the fastening cycle data was transferred to the OPC server after the completion of a fastening cycle and 2) prove that tool setting parameters could later be transferred from the OPC server and received by the torque tool.

The key steps for this test were as follows:

- Configure the tool controller with the settings required for assembly activities
- Establish connectivity between the torque tool and controller over the industrial network
- Configure the tool controller and KEPServerEX connection
- Run test fastening cycles to demonstrate data exchange with KEPServerEX

The first step was to configure the CONNECT hub tool controller with the variety of torque programmes required for various fastening activities. This step was carried out by a manufacturing engineer using the Desoutter CVI software to create the torque program specifications for settings within the controller. These settings, or Psets, would be later activated by communication from the OPC server.

The next step was to ensure that the wireless torque tool was connected to the industrial network so that messages could be transmitted between the CONNECT controller and the tool. This is validated by observing a solid blue light on the tool and by seeing the tool ID number on the controller display screen. When the torque tool was used in this state, the torque value and angle value recorded by the tool during test fastening cycles was shown on the screen of the controller, which further proves connectivity.

Once connectivity of the wireless tool was confirmed, the next step was to configure the endpoint address of the CONNECT controller and specific torque tool IDs to a KEPServerEX port as a data source; this is essentially an alignment of IP addresses and this creates a channel of communication. Tag names represent the parameters being captured by the data source, which in this case includes “Torque Target”, “Torque Minimum”, “Pset”, “Timestamp”, “Result Status”, etc. These tag names are selected as part of the configuration so that data related to the tags are published to KEPServerEX when new data is available, which as after a fastening cycle, and DELMIA Apriso reads the information from here. Similarly in the alternative direction, in order to send data from DELMIA Apriso to the tool controller such as a Pset requirement, the value for “Pset” is written on the OPC server.

The next step was to use the torque tool in this state and demonstrate that test fastening cycle data was published and visible in KEPServerEX. This test demonstrated that the communication channel between the torque tool and the OPC server had been achieved.

4.2.2 Test 2 – MOM/MES to Connectivity Platform

For test 2, the connection and transfer of data between DELMIA Apriso, Machine Integrator (OPC client) and KEPServerEX (OPC server) needed to be understood to confirm that the method, logic and data required to 1) enable the torque tool and activate tool settings and 2) receive fastening cycle data from the CONNECT controller and torque tool.

The key steps to this test were as follows:
- Import OPC points from KEPServerEX and configure Machine Integrator
- Run ‘Points Tests’ to validate configuration was carried out correctly.

This test was carried out to show that the method, logic and data required for torque tool activation and fastening cycle data transfer could be achieved by the configuration of

DELMIA Apriso, Machine Integrator and KEPServerEX. As one of the objectives of this research was to achieve dynamic (or rapidly interchangeable) torque settings, the overriding logic to the method was to submit only the torque setting for the next fastener in the sequence (a batch of one). This method allowed DELMIA Apriso to send the tool setting for the first fastener in the sequence, receive the fastening cycle data and determine whether it was in or out of tolerance. If the torque value that was received was within tolerance (i.e. between the upper and lower limits stated in the work instruction) DELMIA Apriso would send the tool setting for the next fastener and repeat. However, if the torque value was out of tolerance (i.e. outside of the limits stated in the work instruction) the next tool setting would not be sent, therefore the torque tool was disenabled, and a pop-up screen was sent to the Execution Screen (user interface) for the user to acknowledge a non-conformance and submit information before continuing. All of this was possible because the torque requirements and tolerances were contained within the work instruction and the fasteners were listed line by line.

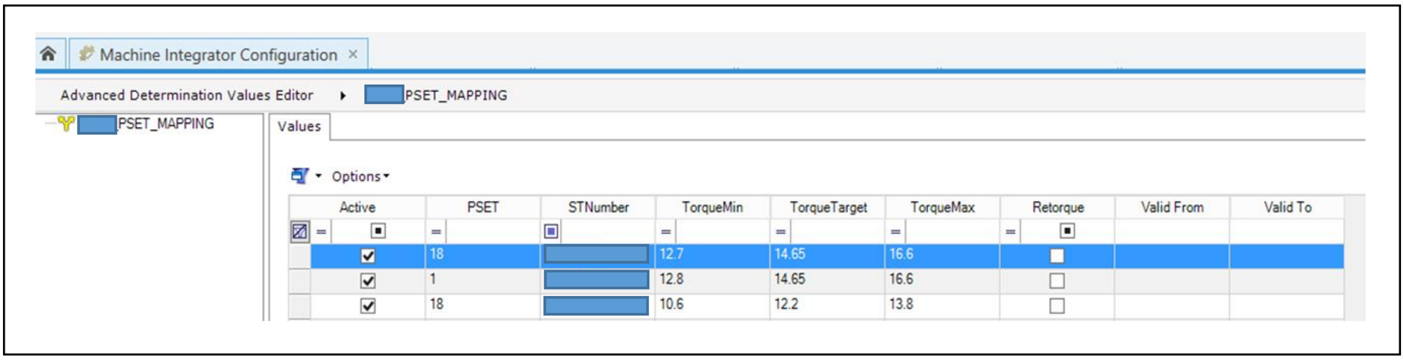
The key step was the configuration of the connection between Machine Integrator and the OPC server (KEPServerEX) in order to enable communication. This was achieved by using the ‘Machine Integrator Configuration’ settings within DELMIA Apriso where virtual point groups were created once the KEPServerEX OPC server had been selected from the available data sources on the network. From the parameters options, the OPC UA points (which refer to the tag names) are imported from the KEPServerEX data source and the relevant points were selected for configuration. These points were where Machine Integrator could read information from or write information to. The point groups chosen for this step were those that corresponded to tool status and fastening parameters (‘MIS’ and ‘ST’ relate to the torque tool ID): The point groups for Machine Integrator configuration are shown in Table 1.

Table 1 - DELMIA Apriso point groups for Machine Integrator configuration

Point Group	**Point Alias**	**Role**
Minimum torque	Channel1_MISXXXX_STXXXXX\LTR_TORQUE_MIN	The minimum torque value that can be achieved by the equipment
Target torque	Channel1_MISXXXX_STXXXXX\LTR_TORQUE_TARGET	The target torque value for the equipment
Maximum torque	Channel1_MISXXXX_STXXXXX\LTR_TORQUE_MAX	The maximum torque value that can be achieved by the equipment
Current torque value	Channel1_MISXXXX_STXXXXX\LTR_TORQUE_VALUE	The current torque value from the equipment
Pset ID	Channel1_MISXXXX_STXXXXX\PSET_NUMBER	The current torque setting of the equipment
Tool enabled	Channel1_MISXXXX_STXXXXX\TOOL_ENABLED	To enable/activate equipment when set to true
Tightening status	Channel1_MISXXXX_STXXXXX\LTR_TIGHT_STATUS	To validate the last torque value was correct according to the Pset configuration
Pset Batch size	Channel1_MISXXXX_STXXXXX\PSET_BSIZE	The batch size sent to the tool. The tool is disabled after each torque read in a batch

The last part of this step was the configuration of the DELMIA Apriso Execution Screen to refresh after reading new point values from the OPC server and displaying them each time the tag or point values changed in the OPC server, which was after every new fastening cycle.

Every time a new fastening cycle (batch of one) is conducted, the values for each tag name are updated by the tool controller in KEPServerEX along with a unique last tightening record ID (LTR) reference. As this is a change and a new LTR, DELMIA Apriso reads the new values from the KEPServerEX points and an action is processed to publish the torque value result in the Execution Screen (based on the last tightening record ID). DELMIA Apriso validates that the torque value is between the minimum and upper torque values.
The second step was to understand the data that was required by KEPServerEX in order to transfer information about the required tool settings down to the tool controller. Due to the 'batch of one' concept used in this research, KEPServerEX only needed information about the Pset required for the next fastener in the sequence. In order to provide the Pset information, a mapping table was created within DELMIA Apriso which contained various torque values and their corresponding Pset ID (Figure 19).

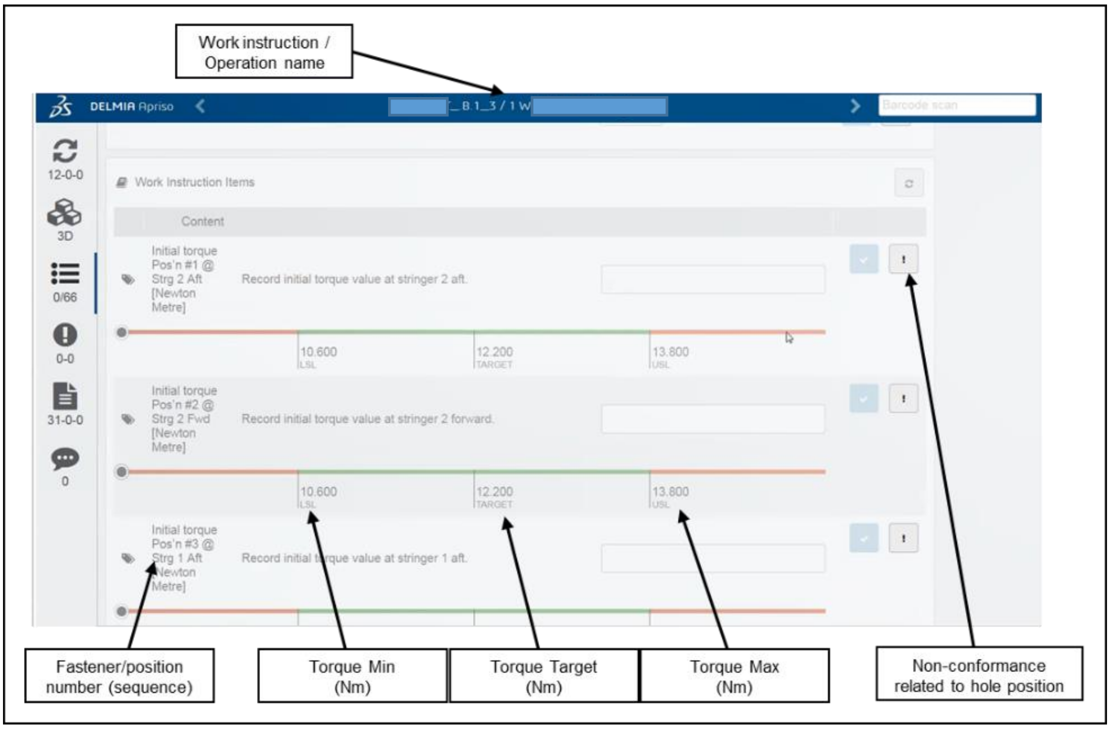


[redacted]PSET_MAPPING

Active	PSET	STNumber	TorqueMin	TorqueTarget	TorqueMax	Retorque	Valid From	Valid To
☑	18	[redacted]	12.7	14.65	16.6	☐		
☑	1	[redacted]	12.8	14.65	16.6	☐		
☑	18	[redacted]	10.6	12.2	13.8	☐		

Figure 19 - Mapping table for Pset allocation in DELMIA Apriso

When the torque tool was selected by the user within the work instruction "Execution Screen", DELMIA Apriso referenced the torque value requirements (known as TorqueMin, TorqueTarget and TorqueMax as show in in Figure 20) of the first fastener in the sequence and corresponded them to the relevant Pset in the mapping table; this was written on to the Pset reference in KEPServerEX. This step was taken in preparation for the following tests when the controller and torque tool were connected; once the transfer of information was completed, DELMIA Apriso waited for new point values to be updated.



[redacted]_B.1_3 / 1 W[redacted]

Initial torque Pos'n #1 @ Strg 2 Aft [Newton Metre] — Record initial torque value at stringer 2 aft.

Initial torque Pos'n #2 @ Strg 2 Fwd [Newton Metre] — Record initial torque value at stringer 2 forward.

Initial torque Pos'n #3 @ Strg 1 Aft [Newton Metre] — Record initial torque value at stringer 1 aft.

Figure 20 - DELMIA Apriso Execution Screen showing the fastener sequence and the torque value requirements

The final step was to run a series of 'Points Tests' between Machine Integrator and KEPServerEX to validate that values associated to the points that were changed in Machine Integrator were written in the OPC server. The 'Points Test' allows a setting to be changed manually in Machine Integrator and sent to the OPC server; the test case carried out for this research related to the Pset value. The first 'Points Test' changed the value to '3' and it was sent and checked in the OPC server, and the second test changed the value to '1' and it was checked in the OPC server.

4.2.3 Test 3 – MOM/MES to Smart Tool System

Test 3 was used to show that the sequence of data transfer was correct and to establish any issues with the method and logic that governed the order of events. This test was to demonstrate that 1) data transfer was operational between the MES and torque tool via the OPC server, 2) information held within the DELMIA Apriso digital work instruction could be used to dynamically control the torque tool setting for each fastener in the sequence and 3) demonstrate that if a torque value was received that was out-of-tolerance, DELMIA Apriso forced a non-conformance to be recorded before the tool could be used again.

The key steps for this test were as follows:

- Select the torque tool ID in DELMIA Apriso Execution Screen to enable the tool and send the first Pset
- Carry out test fastening cycles to show that the torque values were populated in the Execution Screen
- Carry out further fastening cycles to test that the Psets were sent for the following fasteners
- Produce an 'out-of-tolerance' fastening result to test the non-conformance pop-up feature

As this test was carried out to show the transfer of Pset data from DELMIA Apriso to the torque tool and the transfer of fastening cycle data from the torque tool to DELMIA Apriso Execution Screen, the first step was to open the work order and select the torque tool from the equipment list in order to activate and enable the tool with the first Pset. In order to show the transfer of data captured from fastening cycles, a number of test fastening cycles were performed in order to generate the data and the data fields within the Execution Screen were observed to ensure the torque values were populated as required. By performing a series of fastening cycles it also demonstrated that the torque tool settings were being transferred due to the batch of one concept.

To test whether the non-conformance pop-up screen was functioning as required, an out-of-tolerance test fastening cycle was performed and the Execution Screen was observed for the result.

4.2.4 Test 4 – PLM to Smart Tool System (End-to-End)

Test 4 introduced fastener data from the design model which was used to generate the manufacturing processes in 3DExperience; the data set related to the fastener models in the digital mock-up of the small scale structure (e.g. torque requirements) were carried through the manufacturing process planning stage and in to the work instruction in DELMIA Apriso. All previous tests were conducted using a different instance of the DELMIA Apriso server to this test. This is because Test 4 was carried out in a relative production environment with an Operator handling the torque tool; the previous tests were conducted in a testing environment. This test was used to show that the end-to-end digital continuity solution for the torque tool application could be achieved and the objectives of this research could be met.

The key steps for this test were as follows:

- Use the work order in ‘Production’ instance of the DELMIA Apriso server on small scale wing assembly activity
- Select the torque tool in the Execution Screen to enable torque tool and send first Pset
- Complete all fastening steps and acknowledge non-conformances as required if they occur
- Demonstrate that the torque tool is disenabled following the last fastener step

For this test the work order was created in DELMIA Apriso in order for the operation to be allocated to the Operator carrying out the fastening steps for this test. The Operator that was assigned to the work order used their own device to log in to the Execution Screen where they firstly selected the torque tool for the fastening steps, as instructed. Once selected from the equipment list on the Execution Screen, the torque tool was activated and enabled with the Pset for the first fastener position. The Operator followed visual prompts in the digital work instruction in order to follow the fastening sequence with the torque tool.

4.3 Results

4.3.1 Test 1 – Connectivity Platform to Smart Tool System

This test was to validate the connectivity between the smart tool system, the industrial network and the OPC server. The following figures show the results of various stages of this test.

Figure 21 shows the solid blue light on the wireless torque tool, which meant that connectivity was successfully achieved between the tool and the CONNECT controller (both pictured together). This result demonstrates that the industrial wireless network provided a working connection.

Figure 21 - The solid blue light on the wireless torque tool confirms connectivity to the CONNECT tool controller

Figure 22 shows the display screen of the CONNECT controller and the transition from “No tool connected” to “Tool connected” and ready to present the torque value (N.m) and angle (Deg) of the next fastening cycle. This further demonstrates wireless connectivity between the torque tool and the CONNECT controller over the industrial network.

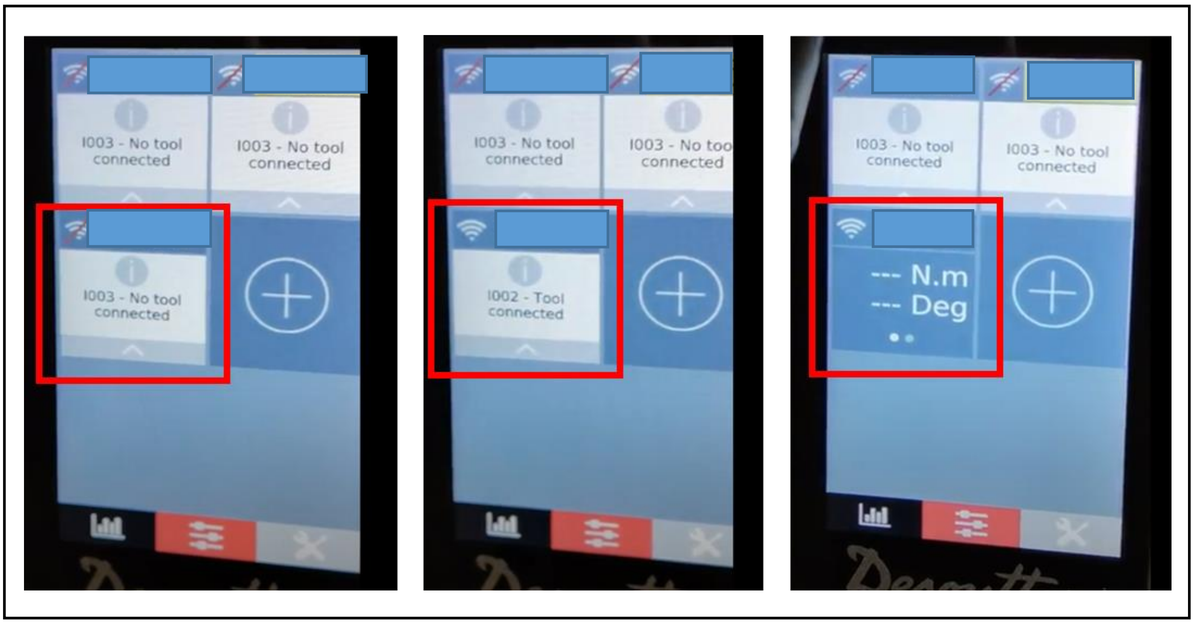
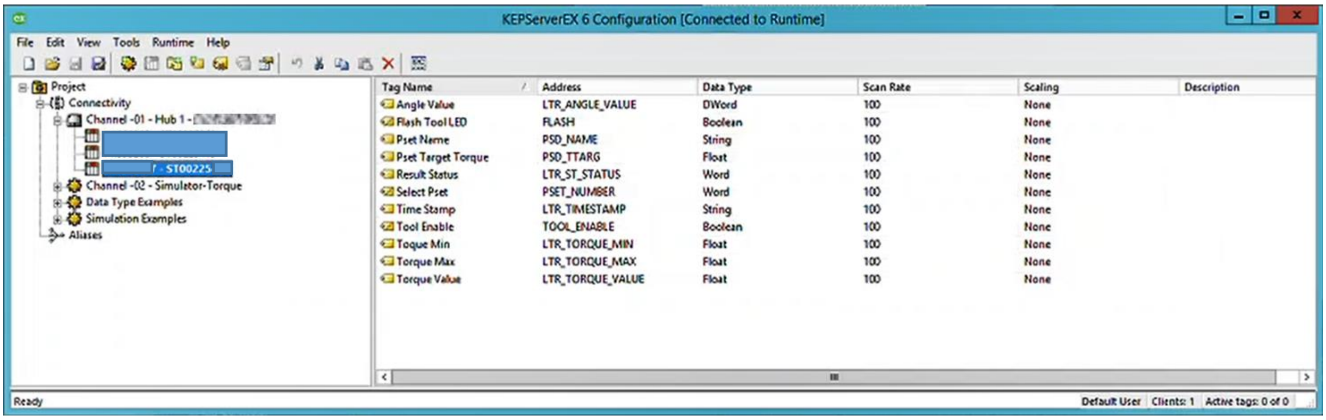


Figure 22 - Wireless torque tool to CONNECT controller connectivity via the industrial network

Figure 23 shows the tag names associated the data parameters available from the CONNECT controller as they were configured in the KEPServerEX OPC server. This shows that the port had been correctly set up for a communication channel between the smart tool system and the OPC server (connectivity platform).



Tag Name	Address	Data Type	Scan Rate	Scaling	Description
Angle Value	LTR_ANGLE_VALUE	DWord	100	None	
Flash Tool LED	FLASH	Boolean	100	None	
Pset Name	PSD_NAME	String	100	None	
Pset Target Torque	PSD_TTARG	Float	100	None	
Result Status	LTR_ST_STATUS	Word	100	None	
Select Pset	PSET_NUMBER	Word	100	None	
Time Stamp	LTR_TIMESTAMP	String	100	None	
Tool Enable	TOOL_ENABLE	Boolean	100	None	
Toque Min	LTR_TORQUE_MIN	Float	100	None	
Torque Max	LTR_TORQUE_MAX	Float	100	None	
Torque Value	LTR_TORQUE_VALUE	Float	100	None	

Figure 23 - KEPServerEx to Desoutter Hub/controller configuration

Figure 24 shows the CONNECT controller showing the torque value and angle of a fastening cycle. This data was shown on the controller display screen after the smart tool had completed a fastening attempt and the data was transmitted wirelessly over the industrial network to the controller. The data shown on the display screen was visible on the

KEPServerEX screen on a laptop, which shows that the communication channel between the OPC server and the smart tool system was functioning correctly.

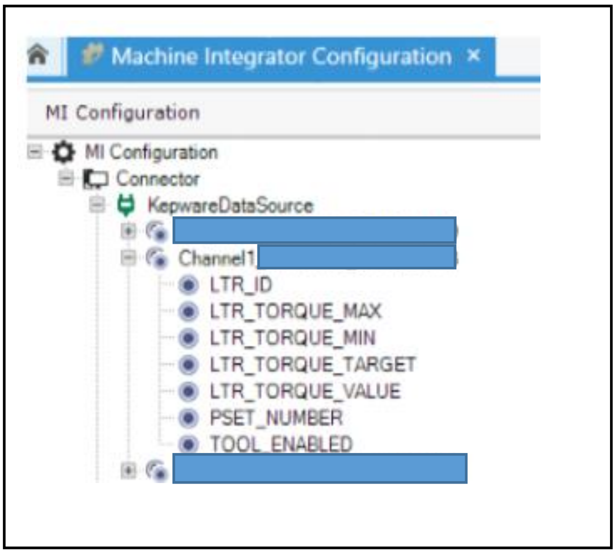
Figure 24 - KEPServerEX and tool controller testing

4.3.2 Test 2 – MOM/MES to Connectivity Platform

The following results come from the tests used to prove connectivity between the MOM/MES, DELMIA Apriso, and the OPC server.

Figure 25 shows that the “KepwareDataSource” (KEPServerEX, OPC server) had been configured in the Machine Integrator module (OPC Client) of DELMIA Apriso. In the image beneath the data source there are a number of tool IDs visible, and below them are the points of reference that have been imported from the OPC server.

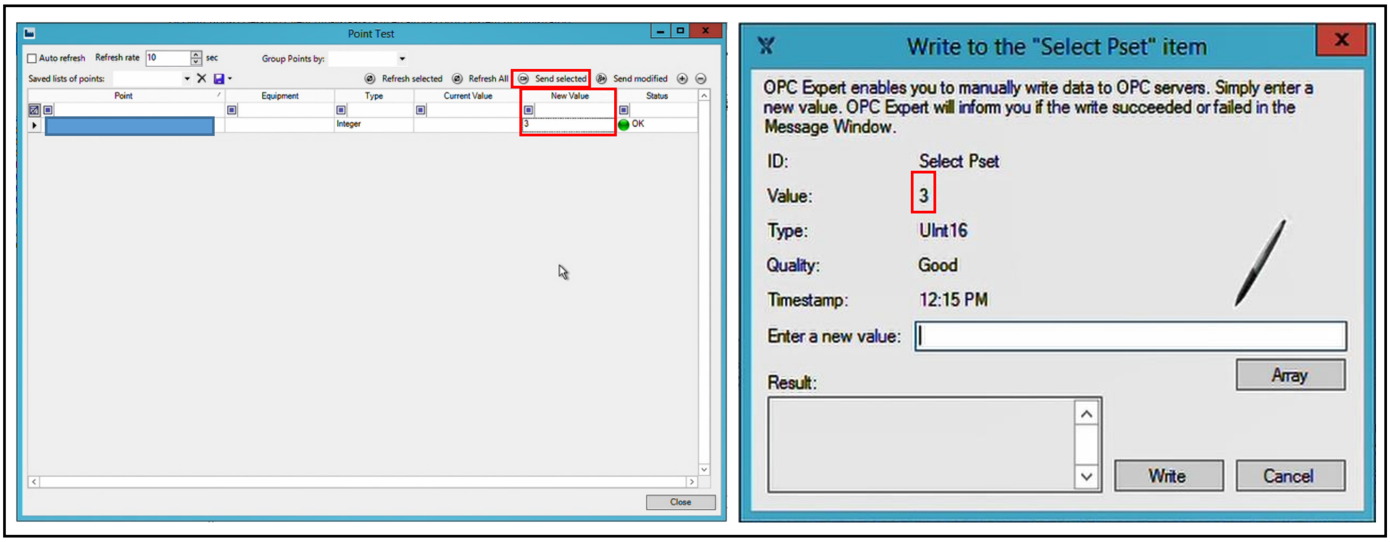
This demonstrates that configuration between the two components of the architecture had been achieved. This configuration enables data to be sent from DELMIA Apriso to KEPServerEX, and enables data within KEPServerEX to be read by Machine Integrator each time the values are updated.



- MI Configuration
  - Connector
    - KepwareDataSource
      - [redacted]
      - Channel1 [redacted]
        - LTR_ID
        - LTR_TORQUE_MAX
        - LTR_TORQUE_MIN
        - LTR_TORQUE_TARGET
        - LTR_TORQUE_VALUE
        - PSET_NUMBER
        - TOOL_ENABLED
      - [redacted]

Figure 25 - DELMIA Apriso Machine Integrator configuration with KepwareDataSource (KepServerEX)

Figures 26 and 27 show two identical Points Tests carried out between Machine Integrator and the OPC server in order to prove the configuration and communication channel. Figure 17 shows that a Pset value of '3' was sent from Machine Integrator on the left screen and the value of '3' was received in the OPC server on the right screen. Similarly, in Figure 18 a Pset value of '1' was sent from Machine Integrator on the left screen and the value of '1' was received in the OPC server on the right screen.



Refresh rate: 10 sec

Group Points by:

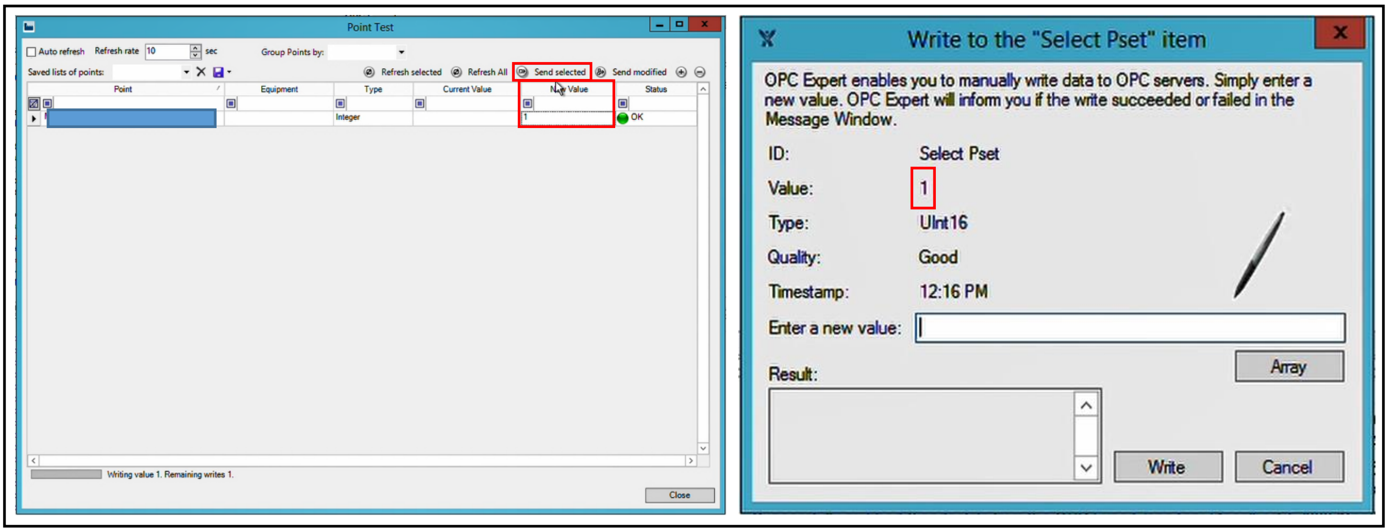
Saved lists of points:

Point	Equipment	Type	Current Value	New Value	Status
[redacted]		Integer		3	● OK

OPC Expert enables you to manually write data to OPC servers. Simply enter a new value. OPC Expert will inform you if the write succeeded or failed in the Message Window.

ID: Select Pset
Value: 3
Type: UInt16
Quality: Good
Timestamp: 12:15 PM
Enter a new value:
Result:

Figure 26 - Points Test 1: Left screen shows Machine Integrator Point Test and Right screen shows the OPC server value



Point Test

☐ Auto refresh Refresh rate 10 sec Group Points by:

Saved lists of points:

Point	Equipment	Type	Current Value	New Value	Status
[redacted]		Integer		1	● OK

Writing value 1. Remaining writes 1.

Write to the "Select Pset" item

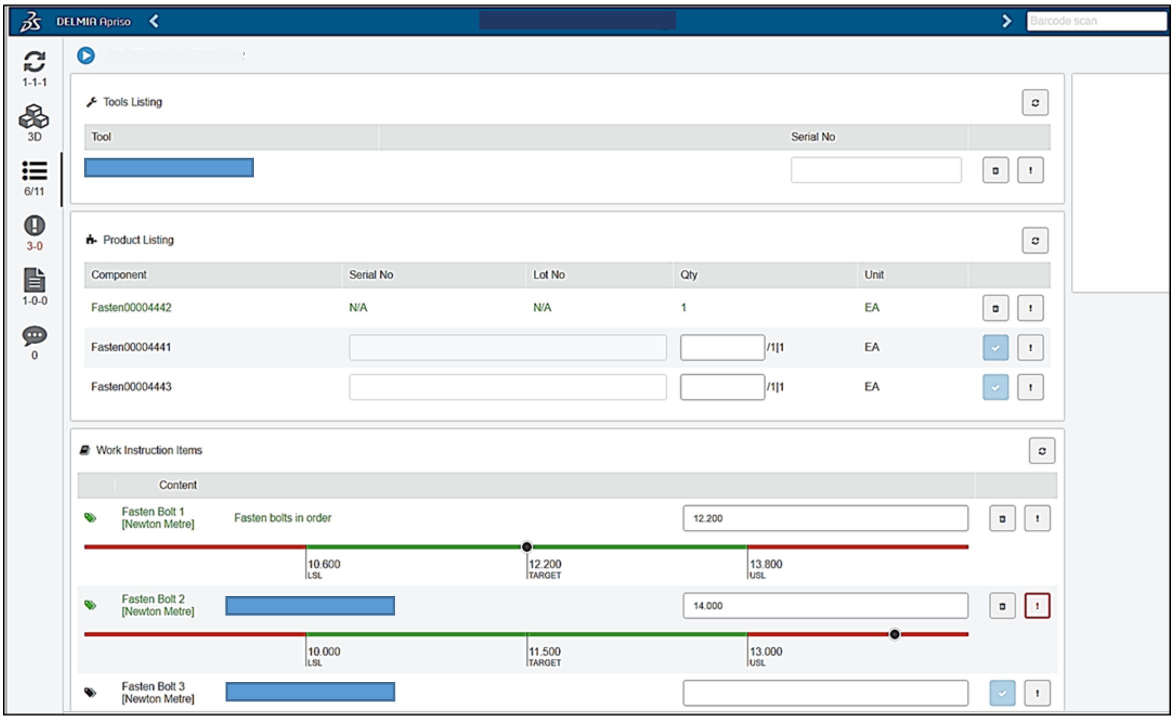
OPC Expert enables you to manually write data to OPC servers. Simply enter a new value. OPC Expert will inform you if the write succeeded or failed in the Message Window.

ID: Select Pset
Value: 1
Type: UInt16
Quality: Good
Timestamp: 12:16 PM
Enter a new value:
Result:

Figure 27 - Points Test 2: Left screen shows Machine Integrator Point Test and Right screen shows the OPC server value

4.3.3 Test 3 – MOM/MES to Smart Tool System

This test was to demonstrate connectivity between the DELMIA Apriso MOM/MES, the OPC server and the smart tool system; combining the results of Test 1 and Test 2.



[redacted]

Tools Listing

Tool	Serial No
[redacted]	

Product Listing

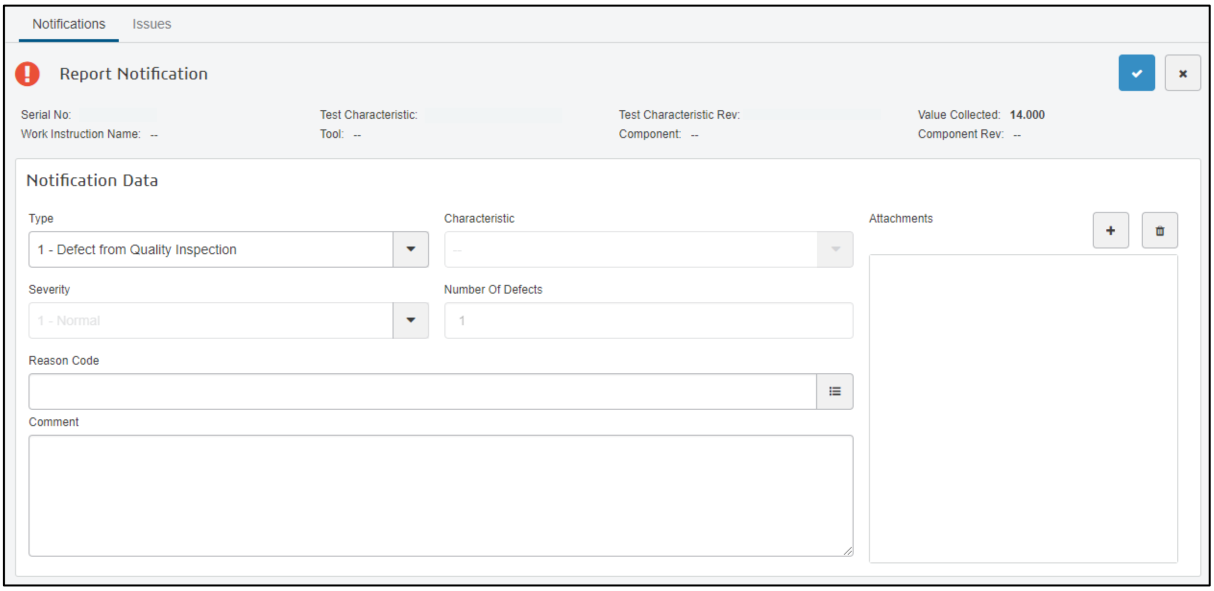
Component	Serial No	Lot No	Qty	Unit
Fasten00004442	N/A	N/A	1	EA
Fasten00004441			/1|1	EA
Fasten00004443			/1|1	EA

Work Instruction Items

Content		
Fasten Bolt 1 [Newton Metre]	Fasten bolts in order	12.200
Fasten Bolt 2 [Newton Metre]	[redacted]	14.000
Fasten Bolt 3 [Newton Metre]	[redacted]	

Figure 28 - Test values to validate connectivity of DELMIA Apriso and the Smart Tool System

Figure 28 shows the DELMIA Apriso Execution Screen which shows the results of two fastening cycles in the data fields and the visualisation of the torque results in the context of the torque limits on the red and green bar. In this test, the torque tool was selected (top left of image) which enabled the smart tool with Pset 18 from the mapping table within DELMIA Apriso as 12.2Nm was the torque target of the first fastener. The fastening cycle was carried out and a value of 12.2Nm was returned from the tool and was shown on the screen. This result was sent to the OPC server via the tool controller and updated in the DELMIA Apriso Execution Screen once it had been read and processed by the OPC Client, Machine Integrator.



Report Notification

Serial No:
Work Instruction Name: --
Test Characteristic:
Tool: --
Test Characteristic Rev:
Component: --
Value Collected: **14.000**
Component Rev: --

Notification Data

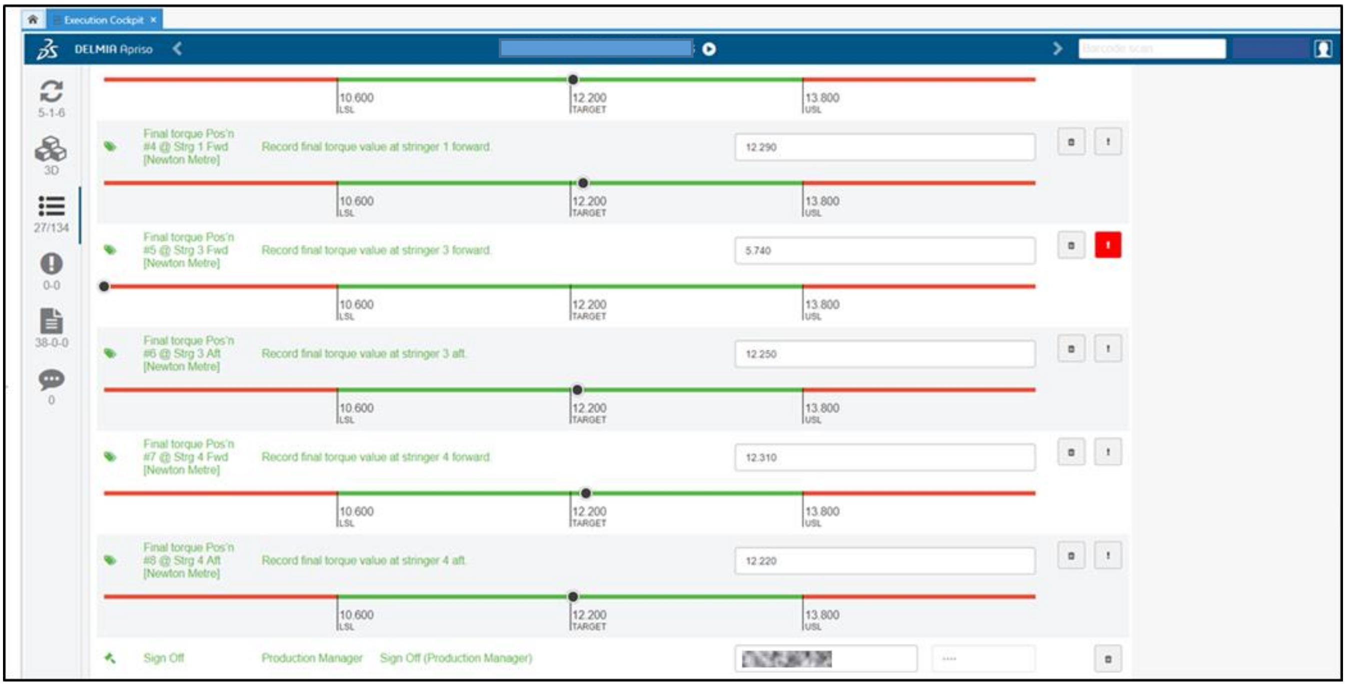
Type: 1 - Defect from Quality Inspection
Characteristic: --
Attachments
Severity: 1 - Normal
Number Of Defects: 1
Reason Code
Comment

Figure 29 - Non-conformance (Notification) pop up screen used to capture details of out-of-tolerance torque results

Once the first cycle was completed, DELMIA Apriso sent the Pset required to target a torque value of 11.5Nm and the result received from the torque tool after the fastening cycle was 14.0Nm, which was outside of the upper and lower limits. This out-of-tolerance value triggered a non-conformance pop up screen which is shown in Figure 29; during the time that the user was completing the fields on this screen, no further Psets were sent to the tool and it was disenabled. No further settings were sent to the tool and a non-conformance was registered to acknowledge the out of tolerance torque value.

4.3.4 Test 4 – PLM to Smart Tool System (End-to-End)

This test was to demonstrate the end-to-end digitalisation and digital continuity of the key components in the digital architecture solution presented in this research in a relative Production environment.



10.600 LSL | 12.200 TARGET | 13.800 USL

Final torque Pos'n #4 @ Strg 1 Fwd [Newton Metre] — Record final torque value at stringer 1 forward. — 12.290

10.600 LSL | 12.200 TARGET | 13.800 USL

Final torque Pos'n #5 @ Strg 3 Fwd [Newton Metre] — Record final torque value at stringer 3 forward. — 5.740

10.600 LSL | 12.200 TARGET | 13.800 USL

Final torque Pos'n #6 @ Strg 3 Aft [Newton Metre] — Record final torque value at stringer 3 aft. — 12.250

10.600 LSL | 12.200 TARGET | 13.800 USL

Final torque Pos'n #7 @ Strg 4 Fwd [Newton Metre] — Record final torque value at stringer 4 forward. — 12.310

10.600 LSL | 12.200 TARGET | 13.800 USL

Final torque Pos'n #8 @ Strg 4 Aft [Newton Metre] — Record final torque value at stringer 4 aft. — 12.220

10.600 LSL | 12.200 TARGET | 13.800 USL

Sign Off — Production Manager — Sign Off (Production Manager) — [redacted]

Figure 30 - DELMIA Apriso Execution Screen following Operator assembly of small scale wing structure with connected torque tool

Figure 30 shows the torque values received from fastening cycles on the small scale wing structure when an Operator used this solution as part of the assembly process. As in Test 3, the tool was selected and the tool was enabled with the required Psets for the fasteners in the sequence. One result raised a non-conformance screen for the Operator to acknowledge before the fastening cycles were continued. In this test the fastener data was cascaded from the design model dataset within the PLM platform in to the work instruction within the 3DExperience platform which demonstrated end-to-end data continuity from the design model to the shop floor execution phase. These results show that vertical integration from PLM through to shop floor tools is demonstrable.

4.4 Discussion of Results

This section will discuss the results that were achieved during the various tests carried out as part of this research.

4.4.1 Test 1 – Connectivity Platform to Smart Tool System

This test showed that connectivity between the smart tool system and the OPC server was possible over the industrial network. This was proven because the wireless torque tool was activated with the solid blue light and the tool ID was acknowledged on the display screen of the CONNECT controller. The controller used in this research was capable of connecting up to ten smart tools similar to the one used in the tests at one time, which is ultimately a limitation of the scalability of the solution; further controllers would be required for a larger roll-out of this solution. This test demonstrated that wireless technology connections are possible for the factory shop floor over the industrial network; the smart tool system needed cyber security certificates installed to enable connection to the industrial network. The ability to use wireless assets instead of wired assets can improve accessibility for manufacturing applications, particularly in wing assembly; however the downside of wireless connectivity is the dependability of network connection, latency of data transfer and possible interruption of signal around large metallic and composite structures or distance from the nearest router/receiver – each of these points was experienced in this research. During test sessions the tool would often disconnect from the network and would need to be activated again in order to continue.

This test demonstrated the implementation of an OPC server such as KEPServerEX in order to send information about certain data points in order to serve other applications that need to subscribe to that data. The implementation and alignment of the smart tool system was a standard process where the address of the tool controller was selected from the systems on the network, and the tag names were selected manually as part of the configuration. A variety of tag names were available from the tool controller, but for this research only key parameters such as those related to torque were the focus as there was a direct relation to design specifications for the fasteners.

4.4.2 Test 2 – MOM/MES to Connectivity Platform

This test showed that connectivity between DELMIA Apriso and KEPServerEX components was achieved as a result of importing the OPC points that were configured as part of Test 1 from the OPC server and configuring them within the OPC client application within the MES, Machine Integrator.

This result demonstrated that the methodology to use a mapping table to exchange torque limits from the work instruction step in to Pset values to submit to the smart tool system worked and supported the enablement of the dynamic configuration as a feature of this solution. A key lesson learned was that the MES should be the layer of the digital architecture where torque values should be translated in to a setting for the torque tool. The reason for this is due to the ability to contain the logic and information (e.g. mapping table) within this software system; it did not make sense to specify the tool setting at the design stage for two reasons:

- The tool setting information is influenced and controlled by the manufacturing engineer. By specifying the torque settings at the design stage, it would require the input of the manufacturing engineer as well as the design engineer.
- The tool settings may be specific to the vendor of hardware that is used and by specifying the tool setting at this early stage, you may be restricting the tools you can use to carry out tasks.

The Point Tests carried out between Machine integrator and the OPC server demonstrated that the Pset values could be written on the OPC server for the purpose of being transmitted to the smart tool controller when required. This test showed that the feature of sending Psets to the torque tool could be achieved providing that DELMIA Apriso could produce the Pset for the fastener from the mapping table.

4.4.3 Test 3 – MOM/MES to Smart Tool System

This test demonstrated data transfer from the MES, DELMIA Apriso, through to the smart tool in order to carry out fastening steps with differing target torque requirements. This test also showed that Machine Integrator ‘read’ data values from the points in the OPC server in order to post torque values in the data fields on the Execution Screen.

These results demonstrate that this methodology and the vertical integration of key architecture components enabled dynamic fastening setting changes between two fasteners, albeit the second fastener shown in Figure 19 is out of tolerance. This is because the fasteners in the test had different target torque requirements. The out of tolerance fastening demonstrated the non-conformance pop up notification feature where the user had to input information related to the abnormal torque result. This ability to trigger the capture of information in real-time is a benefit and achievement of this research. However, a limitation of this feature was that any under torqued fasteners would trigger the non-conformance screen when in fact the user could have continued to complete the cycle to the required torque value.

The use of smart tools which can dynamically change setting is a more sustainable option than having multiple tools for different torque ranges and the ability for the system to automatically change setting depending on the next cycle or step removes the non-value added time related to manual intervention.

4.4.4 Test 4 – PLM to Smart Tool System (End-to-End)

This test demonstrated the end-to-end digital continuity was achieved during a small scale wing assembly operation using the smart torque tool. The results show that the Operator was able to use the solution to carry out a series of fastening cycles, one of which required the acknowledgement of a non-conformance, and therefore the full functionality of this end-to-end solution was tested to demonstrate functionality.

The benefit of the automatic setting configuration of this solution meant that set up time was reduced and non-conformances were acknowledged in real-time by the Operator, which constitutes a time saving.

Test 4 introduced fastener data from the design model in to the work instructions; this was enabled by a feature of the 3DExperience platform that was not enabled during the generation of earlier iterations of the work instruction. Earlier iterations required manual insertion of torque requirements to enable prior tests. To enable the transfer of data from the PLM to the MES, it was discovered that the PPR (product-process-resource) structure had to be followed when the work instruction was generated otherwise the format and fastener data would not transfer in to the DELMIA Apriso MES as required for the following steps of data transfer. This was a lesson learned as a result of this research; although the text, images and 3D data supporting the work instructions were transferred and could ultimately be used, the transfer of the designed fastener attributes did not carry through to the work instruction when first attempted.

The boundaries of this solution include the application of fastening activities; this solution would need to be altered to support drilling or other use cases as the parameters from the design specification would change from torque values to more suitable parameters. The vertical integration could be used in the same way but the selection of data requirements and the information held within the work instruction would need to be tailored to the use case. Another limitation of this solution is the lack of control over the sequence physically followed by the Operator; the work instruction lays out a step-by-step process but this solution does not force the Operator to follow it. In addition, as the user interface requires the use of IT hardware such as a computer or tablet, the Operator often needs to stop the fastening process in order to view progress and/or enter information.

4.5 Summary

This chapter presented the method of testing the digital continuity and configuration of various key components of the digital architecture, starting with the torque tool system and the KEPServerEX middleware component and finishing with the end-to-end demonstration of connectivity through the vertical integration of all components within the project scope. The results of each test were presented and discussed in order to highlight the strengths and weaknesses of the solution.

Chapter 5

Discussion

5.1 Review of Objectives

- To identify the architecture and integration required to demonstrate digital continuity from a design model through to shop floor execution

The architecture components required to enable the transfer of data to enable digital continuity for the smart torque tool use case was proposed in section 3.4 and the method of testing the vertical integration between these components is discussed in section 4.2.

This research demonstrated that the proposed architecture made up of a PLM platform, a manufacturing operations management system, a connectivity platform and a smart tool system was successful in transferring the data required for 1) enabling a smart torque tool with the correct settings based on the design model and associated manufacturing work instruction and 2) capturing and validating the fastening cycle data from the shop floor execution within the manufacturing execution system. The architecture solution proposed in this research demonstrated digital continuity not only “down” the architecture from the PLM which contains the design model and data sets to the smart tool on the shop floor, but also “up” the architecture from the smart tool to the MES.

The architecture solution identified in this research is associated to the software and hardware products used. The ability to associate the design model to a manufacturing process plan within the PLM platform was testament to the capabilities and features of the 3DExperience software tool. Similarly, the ability to associate the data contained within the manufacturing process plan in 3DExperience to the work instruction in DELMIA Apriso may have been associated to the fact that both software tools are products of Dassault Systèmes and therefore there is likely to be a commonality in the way the systems integrate and operate. Alternative components such as an alternative MES or torque tool from different vendors were not tested as part of this research, therefore additional development activities may be required if adopted as the end-to-end solution may not function or integrate by adopting the same methods.

- To develop a case study focused on a torque tool fastening process and identify the range of parameters that need to be considered for the case study (e.g. target torque, angle).

This objective was discussed in section 3.2.

The range of parameters that need to be considered for a given fastening process were identified at the beginning of this research in order to explore the value and benefits that could be gained by capturing data from the fastening process. These parameters were originally identified as part of the product quality requirements associated to the production of aircraft parts and assemblies. Due to the requirement to improve the traceability of fastening operations in today's manufacturing processes, the use of connected and intelligent tools that can record the data from each cycle need to be considered. This research identified that the following parameters need to be considered, with the ultimate focus of the tests in this research being the final (current) torque value, rather than a value related to the angle, as the key visual parameter for the Operator who previously had no visibility of the torque values being achieved. This final torque value was also used to capture non-conformances if the value fell outside of the defined minimum and maximum limits.

- Torque Minimum
- Torque Maximum
- Torque Target
- Angle Minimum
- Angle Maximum
- Final Angle Target

These parameters were verified by a skilled manufacturing engineer who is responsible for the deployment of fastening tools within aircraft wing manufacturing.

- Develop methods for automated configuration of tools for specific tasks
    - Based on manufacturing work instructions, how can the automated configuration of tools be carried out?

This objective was discussed in section 4.2.

The automatic configuration of a torque tool was achieved during this research project. The method for how this was achieved had a strong reliance on a digital architecture which required the transfer of data form one system to the next; from a PLM collaboration platform through to hardware on the shop floor. As the components of this digital architecture were pre-determined, a solution needed to be designed that made this transfer of data possible between the software/system layers. This prompted the requirement to define the data that needed to be transferred at each stage, as well as the method for doing so.

The solution was started by targeting the assembly operation that would be used to demonstrate the output of this research; this was defined as the installation of a rib on a small scale wing assembly. The reason for this choice was due to an appropriate amount of fastenings in order to prove that this solution would work in a manufacturing/production environment on an active shop floor. All of the fasteners in this sample required the same tool and setting combination, and required the same torque to be applied to them. The method developed considered the scalability and flexibility required in wider applications and deployed the ‘batch of one’ concept which would enable the dynamic change of tool settings between fasteners if required; this was demonstrated in Test 3.

Once the assembly operation for demonstration was defined, the data attributed to the selected fasteners within the design model was verified to ensure that the lower, target, and higher torque limits were available. In the process of the manufacturing work instruction being generated, this fastener data would be consumed and carried through as part of the package of data within the PLM system. The type and class of tool that was used to carry out these fastening cycles needed to be assigned to the operation within the work instruction so that the Operator could select the tool.

To enable the transfer of data from the PLM to the MES, the PPR (product-process-resource) structure had to be followed when the work instruction was generated otherwise the format and fastener data would not transfer in to the DELMIA Apriso MES as required for the following steps of data transfer. This was a lesson learned as a result of this research; although the text, images and 3D data supporting the work instructions were transferred and could ultimately be used, the transfer of the designed fastener attributes did not carry through to the work instruction when first attempted.

Once in the correct format, the transfer of data from PLM to MES followed a file export/import transition; both systems are the products of the same vendor, Dassault Systèmes. When the data package associated to the small scale wing assembly activity was opened in the MES, a work order needed to be created in order to schedule the assembly operation and assign it to a user.

The connection between the work instruction and the torque tool controller was tested prior to the use in Test 4 to ensure that the correct tool setting was sent to the torque tool upon automatic activation (as described in section 4.2.3). A key lesson learned was that the MES should be the layer of the digital architecture where torque values should be translated in to a program/setting for the torque tool. The reason for this is due to the ability to contain the information (e.g. mapping table) within this software system; it did not make sense to specify the tool setting at the design stage for two reasons:

- The tool setting information is influenced and controlled by the manufacturing engineer. By specifying the torque settings at the design stage, it would require the input of the manufacturing engineer as well as the design engineer.

  - The tool settings may be specific to the vendor of hardware that is used and by specifying the tool setting at this early stage, we may be restricting the tools we can use to carry out tasks.

It was not possible to send raw torque values from the MES to the tool controller as the controller would not be able to receive this information and make a decision about which tool setting this related to.

The combination of events resulted in a design torque value being translated to a torque tool setting and activating a torque tool for a sequence of fasteners within a specific assembly operation. In this research, only one vendor of smart tool systems was tested and demonstrated due to time and cost factors.

- Develop methods for enabling dynamic configuration of tools during the manufacturing process

This objective was discussed in section 4.2.

This research developed a method for enabling dynamic configuration of the smart tool during a manufacturing process. This means that a method was produced that could dynamically change the torque setting of the smart tool between fastener positions if this was required by the design specification. The logic behind the method stipulated that only the torque setting of the next fastener in DELMIA Apriso was transmitted to the smart tool system as a batch of one at any one time.

If the torque requirement for the current fastener “a” was “x Nm” only the setting corresponding to “x Nm” is transmitted from DELMIA Apriso to the torque tool. No other information is sent until a value for the torque achieved in the fastening cycle is received. At this point, if the value that is returned is compliant (in other words, between the lower and upper torque limits) then DELMIA Apriso references the torque requirement of the following fastener “b” which may have a requirement for “y Nm” and the setting corresponding to “y Nm” is transmitted, and so on until no further fasteners are left to be referenced in the work instruction step.

- To raise non-conformance if the target torque value is not achieved for fastening operations

This objective was discussed in section 4.2.

This research demonstrated that a non-conformance could be issued if a fastening cycle experienced a target torque value outside of the lower and upper limits. This research focused on capturing key parameters from fastening cycles during assembly operations, where design tolerances were cascaded through to shop floor execution in order to ensure that assembly processes were being completed correctly and to provide traceability of fastening cycle data, especially torque values.

During this research, the communication channel between the MES and tool controller was demonstrated to be sending information about configured point values to the MES following the completion of each fastening cycle. To take target torque as an example, when the target torque is received by DELMIA Apriso it is verified by the MES to confirm that the value lies between two specified limits; the lower (min) and upper (max) torque limits of the fasteners within that work instruction step. To meet this objective, a further rule was implemented to send a pop-up notification window to the Operator on the Execution Screen if the most recent target torque value was below the lower limit or above the upper limit, as shown in section 4.3.3. As the overriding method for tool communication was to treat each fastening cycle as a batch of one, the torque tool was disenabled after the cycle data was submitted and the Operator was forced to acknowledge the out-of-tolerance torque value before the tool was enabled for the next fastener. The pop-up notification window asks for a description of the issue to explain and trace the reason for the abnormal value; this information is entered manually at the time of the incident by the user. After the explanation has been submitted, communication to the tool is resumed and the next cycle can be carried out. The MES allows the Operator to record information at any time, even if the torque value is within the limits; there may be scenarios where the target torque is reached and the system does not raise a request for information but there may be other issues with the fastening cycle (e.g. tool damage, aesthetics, hole position, etc.).

A key benefit of this feature is that non-conforming fasteners within the assembly structure will have traceability; they must be acknowledged and are therefore traced within the MES for review and further work by Quality Engineers. This feature ultimately improves the quality of the product by containing information about fasteners that are not within the torque limits.

- To develop a set of scenarios to test and identify the limitations of the vertical integration of the architecture components and methods developed

This objective was discussed in section 4.2.

During this research, a series of scenarios were set out to test the connectivity and transfer of data between the various software systems and a smart tool system that would ultimately enable the demonstration of end-to-end data transfer and digital continuity.

After the components of the digital architecture were defined, a series of tests were carried out to test the connection between different components in isolation. Once each of the tests confirmed the transfer or translation of information as required for the end solution, the end-to-end connectivity was demonstrated in a production environment using a small scale wing assembly demonstrator.

The first test was to test the transfer of information between the OPC server and the Smart Tool system. This was tested by having a Smart Tool connected to the Desoutter CONNECT controller over the industrial network and the commands to activate the tool settings were sent from the OPC server. The tool was activated, this was shown by a solid blue light on the device, and a setting was allocated to the tool. To ensure data transfer from the tool, a series of fastening cycles were carried out on a coupon (real fasteners on a small piece of material) and the data related to the selected the fastening cycle, which first appeared on the controller display screen, and then appeared in the OPC server screen. This test showed that network connections can be unstable and this could ultimately lead to unreliability of a scaled-up solution; the smart tool would frequently disconnect from the wireless network, meaning that the chain of data transfer was broken. This could be a problem in a production scenario as data from fastening cycles may not be recorded correctly. However, when the connection was stable the solution worked as planned.

The second test was to test the transfer of information between DELMIA Apriso MES and the KEPServerEX OPC server. This was tested in a virtual environment where the communication and exchanges could be easily visualised and monitored on a computer screen. The Machine Integrator OPC client of DELMIA Apriso had the ability to configure OPC UA standard communication and a selection of tag names were set up in the OPC server in order to test data being sent and received between the two end points

To take the first two tests further and to ensure progression of connectivity throughout this digital architecture, the next test was to automate the OPC server by sending data for tool activation and setting from DELMIA Apriso to the smart tool system and receiving data from fastening cycles in DELMIA Apriso for visualisation. This test showed that a connection between DELMIA Apriso and the smart tool system had been established but also uncovered issues with network stability.

The final test to demonstrate end-to-end digital continuity of the architecture added to the previous DELMIA Apriso to smart tool system test by automating the DELMIA Apriso MES step. The work instruction used in this test was generated in the 3DExperience PLM, and a work order was created in DELMIA Apriso as it would be in a production scenario in a scaled-up solution. This test took the outcomes of previous tests and combined them in order to prove that the transfer of data can happen automatically when an Operator activates the work instruction in DELMIA Apriso and has the correct torque tool for the assembly operation. This test ultimately showed that the design data contained within the manufacturing process plan (3DExperience PLM) was transferred as a work instruction within the MES (DELMIA Apriso) and the smart torque tool was automatically configured to the correct setting for the fasteners listed within the work instruction when the Operator started the assembly operation. The test was a further demonstration that fastening cycle data could be visualised within the Execution Screen of the MES.

5.2 Contribution to Knowledge

This research has contributed to the knowledge, integration and application of various digital architecture components in order to demonstrate digital continuity in the context of manufacturing and wing assembly through vertical integration.

This research addressed several areas that were exposed as gaps in current literature and research, such as end-to-end digitalisation from product design through to shop floor execution and reporting and the configuration of shop floor tools and assets based on the activity they were about to carry out.

This research continued from previous work such as Umer et al. (2018) to demonstrate data capture from shop floor manufacturing activities and the activation of events based on process data in real-time by implementing the non-conformance capture as an automated part of the overall process. Flexibility was added to the functionality of the solution through the implementation of the “batch of one” methodology for data transfer where the settings that were sent down to the shop floor asset rapidly changed depending on the requirements of the next step or cycle. This feature removes the need for multiple tools or manual manipulation of tool settings between steps or cycles.

This thesis contributes to the knowledge of the use of OPC servers and clients for the transfer of data up and down the digital architecture; not only for capturing and visualising data as presented in the review of literature, but also for transferring data down to the asset level of the architecture in order to automatically send settings based on specifications.

This research has contributed to the embodiment of lean methodologies as part of digital manufacturing use cases, where a process was made leaner with the application and integration of various technology components as part of this research. By exposing the opportunity to link processes with technological triggers such as the real-time non-conformance capturing feature of the solution in this research, other researchers should be inspired to implement similar concepts in order to automate decision making, save time by using real-time data and reduce non-value added actions.

5.3 Limitations

There have been a number of limitations recognised throughout the development of this research which are related to the architecture, the implementation and use, and to testing.

5.3.1 Architecture

Architecture Latency

The standard technical architecture causes the Execution Screen to load at each user event validation which makes the user experience relatively slow. The solution to this limitation could be to optimise the technical architecture of the system.

Connectivity

The Wi-Fi connection from the tool to the controller can be unstable which results in the tool becoming disabled when it needs to be enabled. The DELMIA Apriso Execution Screen was configured to re-enable the tool when it was disabled in order to work around the issue. The solution to this limitation could be to strengthen the network capability within the operational facility.

5.3.2 Implementation

Operation Validation

The steps or fastener cycles of the operation can be carried out in a random order due to there currently being no restriction within the DELMIA Apriso system. The solution to this limitation could be to configure the DELMIA Apriso system to ensure a specified order of steps is followed.

Sequence of Fastening

The fastening sequence is subject to the Operator following the work instruction steps, as the Execution Cockpit does not force the Operator to submit the fastener torque values in the order addressed within the work instruction. The solution to this limitation could be to integrate geolocation or real-time location mechanisms to ensure the correct sequence is followed.

Operator Visibility

The Operator using the torque tool is not informed of a non-conformance for a torque value as they may work away from the user interface (device screen). In the case of a non-conformance, the tool is not enabled with a new setting and is therefore disabled which forces the Operator to address the user interface to check the status or non-conformance notification. The solution to this limitation could be to introduce better visualisation mechanisms for Operators.

Tool Disablement

The fastening tool is not disabled from the Execution Screen upon completion of all torque values from the work instruction. The solution to this limitation could be to configure the DELMIA Apriso system to disable the fastening tool once all steps within the work instruction have been completed.

Tool Management

The same tool can be selected several times for different work orders (different instances of the same work instruction) at the same time without any restriction or alert from the MES. The solution to this limitation could be to configure the MES to make the specific tool ID unavailable once it has been selected in one work order. It is therefore unavailable in other work orders until it is deselected.

Non-conformance Management

The non-conformance feature which triggers the capture of information related to an out-of-tolerance torque value frequently gets triggered by under torqued fasteners that are mid-cycle. An Operator should be able to continue fastening the fastener to achieve the required torque value, but instead the solution disables the tool so that information can be captured. The solution to this would be to allow the Operator to complete their fastening attempt before analysing the torque value against limits.

5.3.3 Testing

Replication of Assembly Environment

The tests used to assess the data transfer to and from the torque tool were carried out in an open environment which is different to some of the environments the tool was used in during the final test in this research. During wing assembly the tool would be used in confined spaces surrounded by metallic or composite structures, jigs and machinery which affect the signal to the wireless tools and therefore can affect connectivity and data transfer.

Smart Tool Selection

This research was limited to the use of connected torque tools rather than any other type of hand held tooling activity one may find within a manufacturing set up such as drilling, welding or measurement activities. To demonstrate the flexibility and transferability of this architecture other use cases should be applied.

Participation of Operations Team

The tests were carried out by manufacturing engineers in the lead up to the final demonstration by an Operator. A limitation of this research was that these tests were not carried out with a wider, more varied audience in order to gather more reliable feedback and results.

Selection of Fastening Sample

The fasteners within the work instruction used in the final test all had the same torque requirements which restricted the demonstration of the dynamic or rapidly interchangeable tool setting, but this was demonstrated in test 3. The logic and method used in this research meant that the dynamic tool setting change was possible and therefore a different work instruction could have been chosen to demonstrate this capability further.

5.4 Further Work

The outcomes of this research have created further opportunities for development and topics to be considered for further work and future research. This research has demonstrated a solution to unlock certain benefits when software toolsets, data and connectivity are used to enable digital continuity for a smart tool application; the next step is to consider ways that this work can be developed further to enhance and support use cases in manufacturing and other sectors.

Although the objectives of this research were achieved there are some areas that need to be researched further and/or improved in order to improve the scalability and reliability of the solution, these include:

- Internet/network strength and consistency to support wireless devices
- Governance of network servers and configuration
- Certification and cyber security of wireless connections for industry
- External/wider technologies are needed to enable full automation of the solution
- The end user requirements need to be considered to avoid additional work or burden
- Issue management and traceability has improved due to the solution capabilities.
- Expansion of the fastening process needs to be demonstrated before serial use

Key areas of opportunity are highlighted in the following sub-sections.

5.4.1 Automatic Certification

The next step towards achieving automatic certification is the validation and consistency of data capture over time to ensure that once data is captured, it is correct and mitigates the limitations that have been highlighted in this research. A limitation of this research is that there is a reliance on the operator to follow the planned sequence of fasteners within the work instruction; to have confidence in automated certification, the solution demonstrated in this research should be coupled with a method or technology that confirms that the operator is following the correct fastener sequence, such as a real-time location system.

5.4.2 Integration of Events

The next step to integrating subsequent activities to this chain of digital continuity is to carry out connectivity tests with the assets to ensure that data related to the work instruction can be related to an event that will take place. For example, establish the connections between the systems so that when a fastening operation is almost completed, a signal is transmitted to another related asset. This development would also rely on the configuration of the logic within the MES in order to synchronise and manage these events.

5.4.3 Extension of Research to Other Architecture Components

The next step with regard to the architecture components and methods of vertical integration in this research is to integrate alternative solutions from different software and hardware vendors to test the transferability and scalability of this architecture solution. For example, alternative PLM and MOM/MES solutions that are available on the market could be tested, an alternative connectivity platform could be tested and alternative smart tool vendors could be tested. In addition, alternative applications of smart tools could also be tested such as drilling, which may require different inputs and produce different outputs but with the same core benefits associated to data capture.

5.5 Summary

This chapter presented a review of the research objectives with a discussion of the strengths and weaknesses of this research and the solution that was demonstrated for digital continuity with the smart torque tool use case. The contribution of knowledge was explained in order to show where this research contributes to the gaps in previous research and literature, before the limitations of this research and opportunities for further work were presented.

Chapter 6

Conclusions

The aim of this thesis was to research and demonstrate digital continuity in the manufacturing process by assembling a digital architecture and demonstrating how data is transferred through various systems, from design through to shop floor execution.

The key points of this work were to define the requirements for the use of connected tools on the shop floor in order to add value to the practices today and to take advantage of the opportunities offered by the technologies available. Two further key points of this work were to demonstrate a method of automatic setting configuration for connected tools, and to use the data captured during the use of the connected tool to highlight non-conforming fastening cycles.

Key outcomes from this project include:
- An end-to-end digital architecture and method of vertical integration that enables digital continuity in the context of a smart tool use case.
- The range of parameters required to validate a fastening operation and raise a non-conformance based on real-time results.
- A method of configuring and dynamically changing the setting of smart torque tools based on the requirements and sequence of the fasteners in the design model and associated work instruction.
- A set of scenarios to test and identify limitations of the vertical integration of the architecture components

The research carried out and the results demonstrated in this work are significant because they show the benefit of enabling a single source of information, a digital thread, through the vertical integration of the digital architecture components. The use case of a torque tool is widely applicable so learning can be applied to many manufacturing scenarios; this research could be taken further to explore the benefits of connecting other tools and devices.

Chapter 7

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