Digital Manufacturing on a Shoestring: Low Cost Digital Solutions for SMEs

Duncan McFarlane[1], Svetan Ratchev[2], Alan Thorne[1], Ajith Parlikad[1], Lavindra de Silva[1], Benjamin Schönfuß[1], Greg Hawkridge[1], German Terrazas[1], Yedige Tlegenov[1]

[1] University of Cambridge
[2] University of Nottingham

Abstract. One of the key findings in a number of recent studies has been that small and medium sized manufacturers (SMEs) have been slow in adopting digital solutions within their organisations. Cost is understood to be one of the key barriers to adoption. Digital Manufacturing on a Shoestring is an approach to increasing the digital capabilities of SMEs via a series of low cost solutions. The programme proposes using off-the-shelf, (possibly non-industrial) components and software to address a company's (digital) solution needs, adding capabilities one step at a time with minimal *a priori* infrastructure required. This paper will introduce the Digital Manufacturing on a Shoestring programme as a whole and demonstrate the way in which it addresses the need for low cost digital solutions for SME Manufacturers. It will discuss challenges associated with integrating low cost technologies into industrial solutions and the style of IT architectures best suited for integrating such solutions into industrial environments.

1 Introduction

This paper introduces a development focussed on developing low cost digital solutions for manufacturing Small and Medium-sized Enterprises (SMEs).

1.1 Low Cost Digital Manufacturing

Digital Manufacturing in its broadest terms refers to *the application of digital information [from multiple sources, formats, owners] for the enhancement of manufacturing processes, supply chains, products and services.*

This paper is focussed around the development of very *low cost* solutions which address particular aspects of digital manufacturing challenges. By *low cost digital manufacturing* in this paper, we refer to:

The *development of digital solutions to meet specific operational needs and for which the total cost of deployment (purchase, integration, installation and operation) is kept low.*

In this paper we specifically focus on low cost digital solutions and their use by manufacturing SMEs who not only desire to keep equipment / development / deployment cost low but also require that solutions be simple to deploy and maintain. In particular, we consider opportunities for exploiting off the shelf technologies and openly available software in addressing these joint goals of simplicity and low cost.

1.2 Digital Manufacturing on a Shoestring

Digital Manufacturing on a Shoestring is a programme initiated by University of Cambridge, involving Nottingham University and also a significant number of industrial partners. It aims at increasing the digital capabilities of small manufacturers (SMEs) via a series of low cost solutions. Low cost is ensured by using off-the-shelf, non-industrial components and software to address a company's (digital) solution needs one step at a time. The intent of the Shoestring project is to develop a pathway for digital engagement that even the smallest SME can consider and in doing so to transform SMEs into highly efficient digitally-enabled manufacturing businesses that can utilise available data to continuously improve performance, retain knowledge and manage uncertainty. It will seek to exploit the very lowest cost commercially available technologies for mobile computing, sensing, micro processing, communicating and even AI and will tackle the challenges associated with integrating these safely and securely into a small-scale manufacturing environment. Considering the standard features of an automated system, namely sense, communicate, control and actuate, Figure 1 shows some of the potential low-cost technologies that are being considered for providing the different capabilities in a digitally supported operation. (We note that at present some of these technologies would not be considered to be "industry ready". That is indeed one of the challenges).

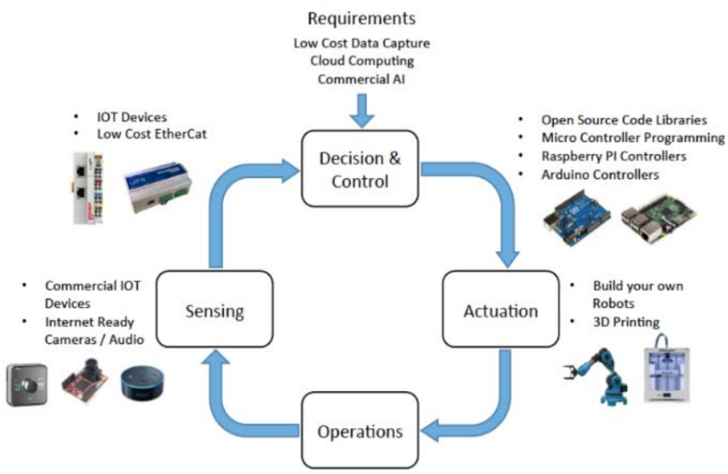


Fig. 1. Low Cost Technologies

Furthermore by supplementing low cost industrial technologies with commercially available technologies from outside the industrial domain (e.g. wifi-enabled cameras, home voice recognition, mobile phone apps, gaming controllers etc.) and open source software libraries it is intended that the Shoestring programme will encourage students and young graduates to become actively involved in industrial IT developments.

1.3 Paper Outline

The paper is structured as follows. In Section 2 we review some of the digital challenges faced by manufacturing SMEs, developments in low cost technologies and methods for integrating technologies into a manufacturing solution environment. Section 3 presents the research approach taken by the Shoestring programme to systematically develop solutions and architectures that address the needs of manufacturing SMEs. Further, we present the key challenges and opportunities arising from this research in section 4. The paper concludes by presenting the intended outputs and impact of the Shoestring programme.

2 Background

2.1 Digital Challenges for SMEs

The digitalisation of manufacturing is a key enabler in the UK Government drive to raise the level of industrial productivity[1] to match and exceed leading competitors. The UK Made Smarter review[1] and many other reports have identified the slow take up of digital solutions in SMEs, attributing this to the entry cost and complexity of existing offerings. In particular, Saam et al (2016) identified that *77% of companies consider missing digital skills as the key hurdle to their Digital Transformation* and *59% of companies cite high investment and operating costs as another major obstacle*. Hence, one of the critical challenges is how to support the digital manufacturing transformation of SMEs in a low cost manner which also takes into account a potentially low level of digital skills available. A further objective for SMEs (see Meijer et al, 2017) is to introduce new digital systems which take into account the latest control, communication and AI technologies. A more detailed review of the assessment of digital challenges for manufacturing SMEs can be found in Schönfuß et al, (2019).

2.2 Low Cost Digital Technologies

In recent years digital technologies have seen a significant reduction in price due to relentless updating of technologies. There are a number of classes of technologies have been identified as being relevant to developing low cost industrial solutions:

[1] Maier, G et al, UK Industrial Digitisation Review – Interim Report v3, July 2017

(i) *low cost industrial technologies* - Industrial system suppliers have developed offerings which support low cost components and software. Table 1 provides an illustration of some of these developments.

(ii) *low cost, non industrial technologies* - Developments aimed at broader markets in home, office, cities and other domains where a large number of applications is keeping the cost of these technologies low. Typical examples include cloud computing, web services, Internet of Things sensing and communication devices and micro-controller based computing (e.g. Raspberry Pi™ and Arduino™)

(iii) *(non industrial) mobile computing and communication devices* - although not low cost, portable computing and communications devices such as phones, tablets are increasingly being used by most of the workforce and can play a significant role if integrated effectively as part of an industrial solution.

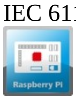
Area	**Typical Requirement**	**Low Cost Technology Example**	**Challenge**
Sensing	Low cost devices that service specific sensing needs e.g. Vision, Optical ID recognition, vibration	OpenMV Cam M7 	Skills required to implement solutions.
Comms	Coupler that allows low cost computing devices (e.g. RPi, Arduino) to use industrial communication network EtherCat	Arduino Ether-CAT 	Performance and reliability of the coupler.
	Connector for low cost industrial IO to independent networks	Beckhoff IO 	Range of net-works covered
Control	Programming environment on micro controllers for manufacturing engineers	IEC 61131 for Pi 	Ability to sup-port multiple micro controllers
	Low cost PLC capabilities using a low cost computing platform. Supports for web based applications	IONO Ethernet (Arduino based) 	Performance and reliability of the platform
Actuation	Very low cost flexible part and material handling support system	Niryo One Robot 	Selecting applications requiring limited payloads and repeatability reqs.

Table 1. Examples of Low Cost Industrial Technologies

While there is evidence of low cost technologies and/or non industrial systems being trialled and even deployed industrial there is limited evidence to date of a systematic coverage of this subject.

2.3 Methods and Architectures for Flexible Systems Integration

One of the challenges imposed by considering low cost digital solutions is that solutions are likely to be developed by combining disparate low cost elements. It is entirely likely that additional software and interfaces will be required to support such combinations. And further, a small company embarking on a digital programme might chose to develop solutions one by one rather than as an integrated whole. This issue was identified almost 15 years ago in a series of commentaries on low cost automation (Erbe, 2002a, 2002b, 2003) and workshops (e.g. IFAC, 2007) in which Erbe identified for the need for flexible shop floor architectures as critical to achieving and maintaining a low cost system. Surprisingly there has been only limited academic coverage specific to low cost industrial digital solutions in recent years.

The issue of developing information and control architectures that support distributed and incremental development has been the subject of much research since the Intelligent Manufacturing Systems programme began in the 1990s, much of which has been regularly reviewed in SOHOMA, HoloMAS and other conferences focussing on distributed intelligence in manufacturing. The former in particular has identified and developed the link between service orientation in systems architectures and distributed intelligence and this is likely to be exploited within the Shoestring programme. A more detailed review of the assessment of the architectural challenges associated with digital solutions for manufacturing SMEs can be found in Hawkridge et al, (2019).

3 The Shoestring Approach

3.1 Overview

In seeking to develop low cost digital solutions for SMEs the Digital Manufacturing on a Shoestring programme has developed its approach around the following key features:

1. A focus on low cost of components integration, operation and maintenance of solution.
2. Development of solutions that are of priority to large numbers of manufacturing SMEs.
3. The use of commercial off-the-shelf hardware and software.
4. A systematic “building-block” approach to combining different technology components.
5. Initial and subsequent solutions implemented via an “incremental architecture” which allows basic data and services to be shared between applications.

The aim of the last two features is to a) enable a distributed and repeatable approach to developing individual solutions and b) permit organisations to develop, implement and upgrade solutions individually on a prioritised basis while benefiting from earlier solutions deployed.

The approach being taken consists of three phases:

- gathering of a prioritised set of digital solution needs for SMEs
- a building block approach for preparing different low cost components and software for integration
- a systematic approach for integrating building blocks into solutions and for combining solutions

The interconnection between these stages is outlined in Figure 2 and each stage is briefly discussed in the next sections.

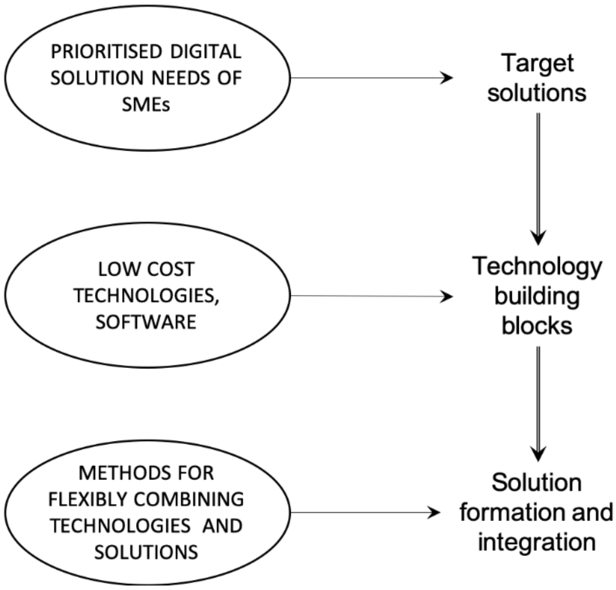


Fig. 2. Shoestring Approach

3.2 Digital Solution Requirements

As a preliminary phase, the programme is working alongside industry partners in the development of a set of tools for assessing the readiness of a small manufacturing organisation to extract benefits from enhanced digital capabilities and to determine the operational readiness of the organisation to implement new digital technologies. This work will be done against the backdrop of numerous Industry 4.0 Auditing tools already available but will take both a broader outlook in terms of digital scope and be specifically focussed and limited on SMEs. Once the readiness of the organisation has been assessed, the next step is to identify their requirements for specific solutions. The process being used for this is outlined in Figure 3.

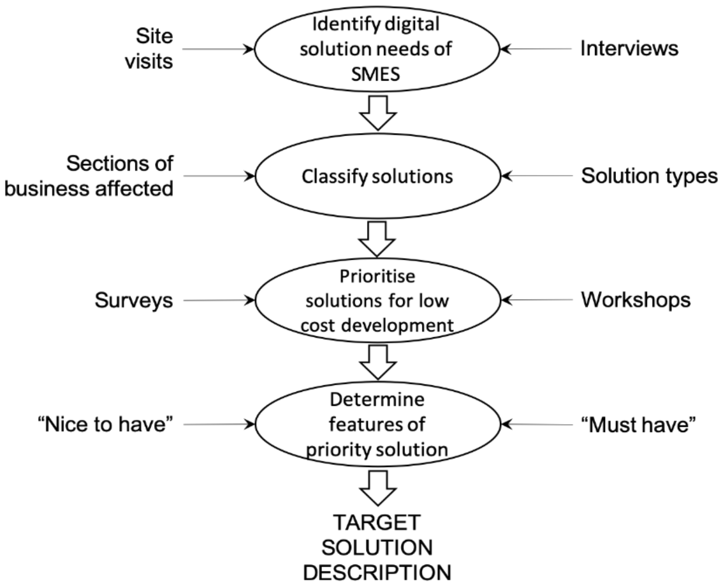


Fig. 3. Solution Requirements Capture

The reader is referred to Schönfuß (2019) for more details on this process which is being carried through a series of industrial workshops in the UK and overseas in 2019. The outcome will be a "Top 10" listing of digital solution requirements for manufacturing SMEs. By way of example, the top three solution types identified so far are:

- Real time tracking of jobs (location, status)
- Capacity monitoring of human and machine resources
- Digitised work instructions, photos and assembly procedures

3.3 Building Blocks from Low Cost Technologies

The digital transformation requirements introduced will be analysed and mapped to suitable technologies and areas of early applications for SMEs. The key to the development of these steps is the prioritised use of off the shelf, non-industrial technologies in order that the solutions be as accessible as possible to the potential SME end users.

The key steps involved with developing technology building blocks are:

- *methods for identifying relevant technologies from many diverse fields*
- *classifying technologies in terms of the way they affect digital manufacturing solutions*
- *selection of instances of different technology types to be used*
- *standardisation of the interfaces by which one building block will connect to another*

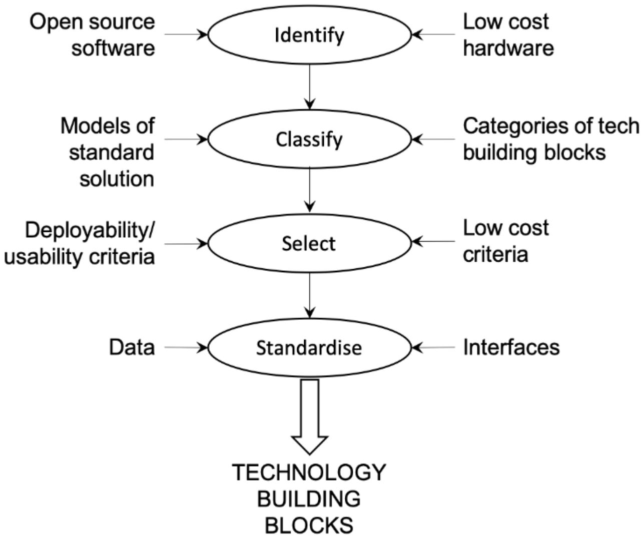


Fig. 4. Low Cost Technologies into Building Blocks

During the preliminary stages of the project - prior to establishing a definitive set of SME needs - a series of trial developments have been undertaken to assess potential complexities in integrating disparate technologies in an industrial environment. Figure 5 shows a schematic of a simple voice-driven production stop system developed within the automation lab at Cambridge. Learnings from this process included the complexity in dealing with a commercial, cloud-connected voice recognition system and the interfacing requirements needed to interface to a (legacy) PLC systems.

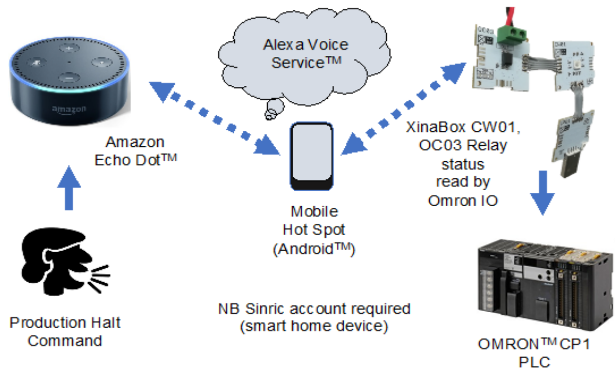


Fig. 5. Example: Voice Driven Production Control system

The building block development process will be the subject of a future paper de Silva et al, 2019).

3.4 Forming and Integrating Digital Solutions

This phase consists of two tasks: a systematic approach for integrating building blocks into solutions and efficient methods for combining solutions.

The first task involves determining the right combination of elements required to form a solution and ensuring that the interfaces are effectively and systematically specified. In some instances, intermediate or compound building blocks will be formed where it appears likely that a pair of technologies will be frequently combined (See Figure 6).

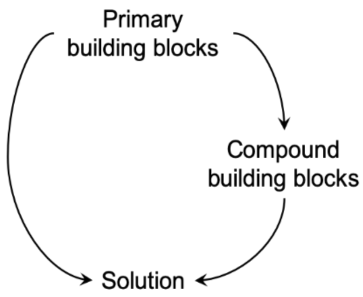


Fig. 6. Combining building blocks into Digital Solutions

The second task will involve the development of a conceptual model and reference architecture to support an incremental development of a digital solution environment. Figure 7 illustrates the basic concept of the incremental approach which draws heavily on the ideas of SOHOMA - service orientation in distributed manufacturing architectures (see Borangiu, 2018 and previous similar publications). An initial solution (Solution 1) is linked to a local area network within the manufacturing SME. Essential services required for that solution are made available.

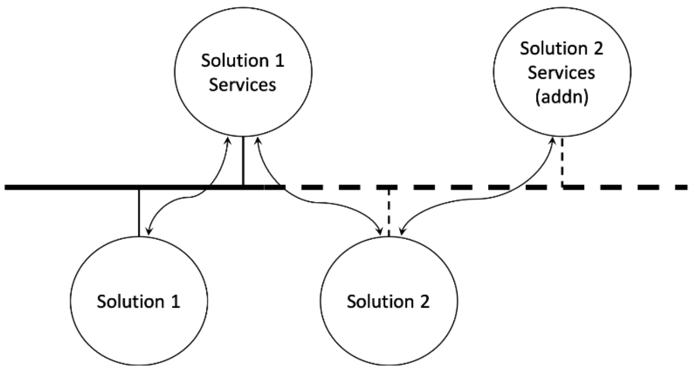


Fig. 7. Integrating Multiple Solutions

Further details of this section of the programme can be found in Hawkridge et al (2019).

4 Discussion

4.1 Research Challenges in Low Cost Digital Manufacturing

While being particularly practically oriented, the Shoestring programme must also address some more fundamental issues if it is to be able to impact on a large number of manufacturing SMEs. These issues are posed as questions here:

- Is it possible to identify a set of digital solution requirements that are common across a large number of SMEs?
- Can a systematic “building block” approach to combining different low cost technologies/open source software elements be developed?
- Can an architecture be developed for combining solutions that requires not a prior IT infrastructure but rather evolves as additional solutions are added?
- Will Shoestring solutions adhere to typical requirements for industrial digital systems such as reliability, interoperability and security?

Addressing these questions and others has the potential to impact significantly on the way digital solutions research is carried out within academic institutions.

4.2 Academic Impact of Examining Low Cost Digital Manufacturing

The primary impact of this research is on the field of industrial automation, control and management systems. By questioning traditional approaches to automation and control systems based on established industrial computing and communications, this project potentially opens a radically new paradigm – not only for researchers working in manufacturing automation but more broadly in the areas of distributed sensing, distributed control and industrial information systems. A very useful bi-product of this work will be that it will drive down the development costs of academic laboratory experimentation and make this field more accessible not only for researchers but also for graduate and undergraduate students.

The second area of academic impact is in the area of manufacturing data analytics where researchers have the potential to access types of data that were not available until now. If it is possible to integrate non-industrial technologies in manufacturing processes, it creates the opportunity for innovative ways to gather and assimilate data from the assets, the processes and the supply chain to create new insights and methods for controlling manufacturing operations. For example, researchers will be able to develop image recognition and analysis algorithms to use video data using a simple low-cost webcam to monitor worker fatigue and concentration or early-warning signs of equipment failure.

4.3 Comparison with Industry 4.0

Digital Manufacturing on a Shoestring is, in many ways, complementary to the approach taken by the Industry 4.0 movement initiated in Germany in the early 2010s (see Kagermann, 2014 for example). Industry 4.0 is a comprehensive approach to driving digital systems adoption across industrial operations. Different sources describe it in different ways but here we note that original documentation discussed Industry 4.0 supporting digital integration in three dimensions:

1. Vertical Integration
2. Horizontal Integration
3. Product Value Chain Integration

Shoestring by way of comparison takes a very tactical approach to digital solution adoption. It is targeted at organisations with only limited industrial IT capabilities and focused on one solution at a time where upfront capital cost is a critical factor. Subsequent solutions are then aimed at being backward compatible with the earlier ones. Further, initial Shoestring applications will be predominantly developed to meet needs for digital solutions within the business rather than focus on the supply chain

5 Conclusions

We conclude this introductory paper with a summary of the main anticipated outcomes. It is expected that the Digital Manufacturing on a Shoestring programme will:

- Develop a digital manufacturing readiness assessment method and prototype software platform capable of extracting the rationale and requirements for digital systems for an SME
- Define a conceptual model and reference architectures for digital transformation of SMEs
- Develop algorithms, models, decision support and automation logic compatible with the developed reference architecture that allow for sustainable and reliable operations
- Determine how to achieve industrial standards of security, safety and interoperability
- Deliver a series of prototype demonstrations and conduct company based trials for the evaluation and validation of the proposed models

Additionally, a stretch goal for the programme is to develop approaches for embedding advanced manufacturing concepts[2] (e.g. distributed agent-based control, iterative learning control, hybrid adaptation, AI driven decision support, customer-oriented order management, phone based maintenance apps) into the Shoestring environment.

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[2] See Fletcher, (2003), McFarlane (2013), Schrimeri (2017), Rasmekomen (2016) Srinivasan (2017) and the references therein for examples.

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