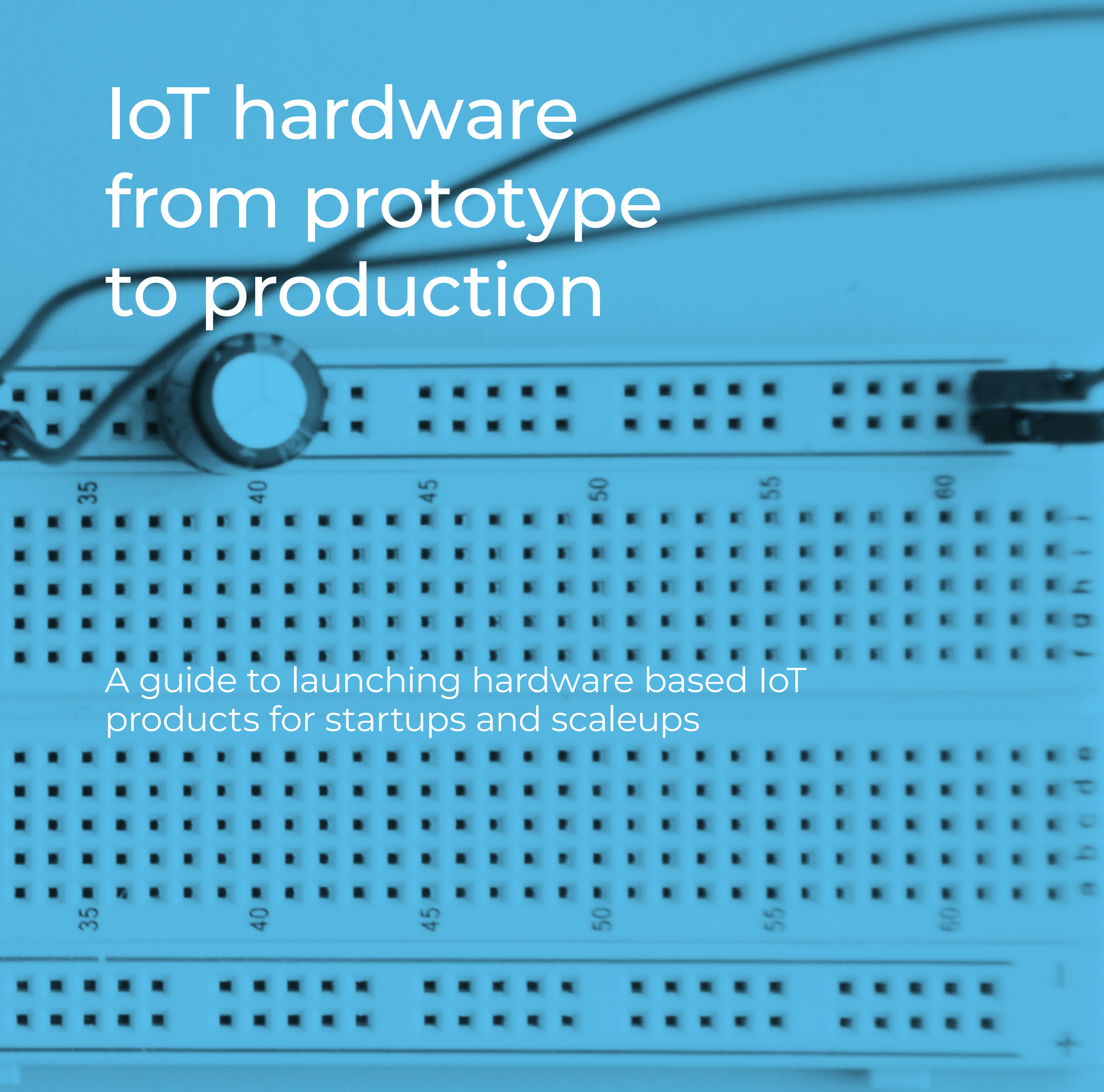
CATAPULT Digital

IoT hardware from prototype to production



A guide to launching hardware based IoT products for startups and scaleups

2019

AUTHORS' NOTE

This guide has been devised to support startups and scaleups who are developing IoT hardware products. By stepping through the product lifecycle process the document provides a starting point for businesses to understand the challenges and activities involved in launching an IoT product. There is much more to know and to learn along the IoT product journey that cannot be simply captured in a single document; we have therefore provided a set of references at the end of this document for useful further reading. We hope that the guide will help you on the road to success and we wish you the best of luck with your IoT hardware endeavours.

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FOREWORD

The internet of things (IoT) represents one of the biggest current business opportunities, as it underpins the digitisation of our economy, a transition towards what is hailed as the fourth industrial revolution.

The expected economic impact of the IoT within the next decade is in the trillions of dollars, touching diverse sectors from manufacturing to smart cities, from agriculture to healthcare.

While the opportunities for IoT innovation are limitless, IoT is more complex to approach for entrepreneurs and startups than pure software or cloud-based internet businesses. IoT solutions are based on an interplay between diverse end-to-end systems ranging from specialised hardware, communication networks and cloud-based service platforms, data-analytics and visualisations. The successful realisation of these requires a diverse set of skills and expertise that startups and scaleups often struggle to bring together due to the limited resources available to them. Having the right ecosystem partnerships plays a very important role in filling the skills and knowledge gaps but there are still unique challenges that IoT entrepreneurs are currently faced with.

Creating IoT hardware poses significant challenges because it needs a mix of specialised expertise in technology and product design, physical supply chain and testing, manufacturing partnerships (which may be geographically dispersed) and considerable upfront funding requirements that do not align well with existing funding and investment models. Moreover, the longer time to market compared to software products and limited opportunities to adapt iterative and agile development cycles makes IoT hardware development a much riskier business undertaking.

The emergence of the maker movement during the past ten years has lowered the barrier of entry for many technology enthusiasts. By flooding the market with easily programmable IoT prototyping platforms ranging from Arduino and Raspberry Pi, it has now become easier to build proof-of-concepts and prototypes of IoT devices. UK hardware pioneers such as Pycom provide ready to go OEM modules with IoT connectivity and reference designs to ease IoT product development.

Crowd-funding platforms such as Kickstarter and Crowd Supply make it easier to validate the market need for consumer-facing products and raise some initial funding for the first hundreds or thousands of IoT products.

Encouraged by this trend, more UK entrepreneurs and startups are tempted to embark on the journey of building their own IoT hardware-based businesses. However, there is still a long way to go from an initial prototype that proves the merit of the idea and functionality to a smoothly running manufacturing setup; churning out hundreds or even thousands of reliable IoT hardware products a month, ready for shipment at adequate price points.

After an initial phase of enthusiasm, many of these businesses end up being overwhelmed by navigating the complexity of designing for manufacture, establishing the right manufacturing partnerships, supply chain issues and regulatory approvals.

Dealing with production partners in the Far East adds further challenges to the endeavour. As a result, significant delays may occur before market launch, cash may be burnt due to unnecessary design iteration or initial manufacturing partnerships may fall apart due to slipping timelines or wrong considerations. This leads to many potentially viable IoT product innovations never seeing the light of day. Much of this could be avoided if entrepreneurs and startups were better informed from the outset.

This guide aims to provide orientation for an increasing number of UK entrepreneurs, startups and scaleups who are keen to launch hardware based IoT products and services. It provides guidance to navigate the entire process of IoT hardware production from the building of a basic prototype up to production at volume and end of product life. For each of these hardware manufacturing stages, the report highlights important considerations such as where to focus energy and provides a clearer understanding of the expectations that design and manufacturing partners may have, so an engagement with these can become more successful.

I would like to acknowledge the authors of this report, who are leading UK experts who have combined their wealth of experience in bringing IoT products to market. Richard Marshall from Xitex Ltd took on overall editorship and contributed a substantial part of the initial content. Lawrence Archard from uPBeat Product Development filled in the gaps and provided many fruitful suggestions during discussions. Steve Hodges from Microsoft Research helped shape the final report and provided useful additions to make it a complete reading experience. Where appropriate they have provided pointers to more background and further reading, so that readers can go into further depth where interested.

Whether you are an aspiring IoT entrepreneur or an already established IoT startup or scaleup, I hope that this report will help you reduce your risks and speed up your journey in bringing IoT hardware to market.

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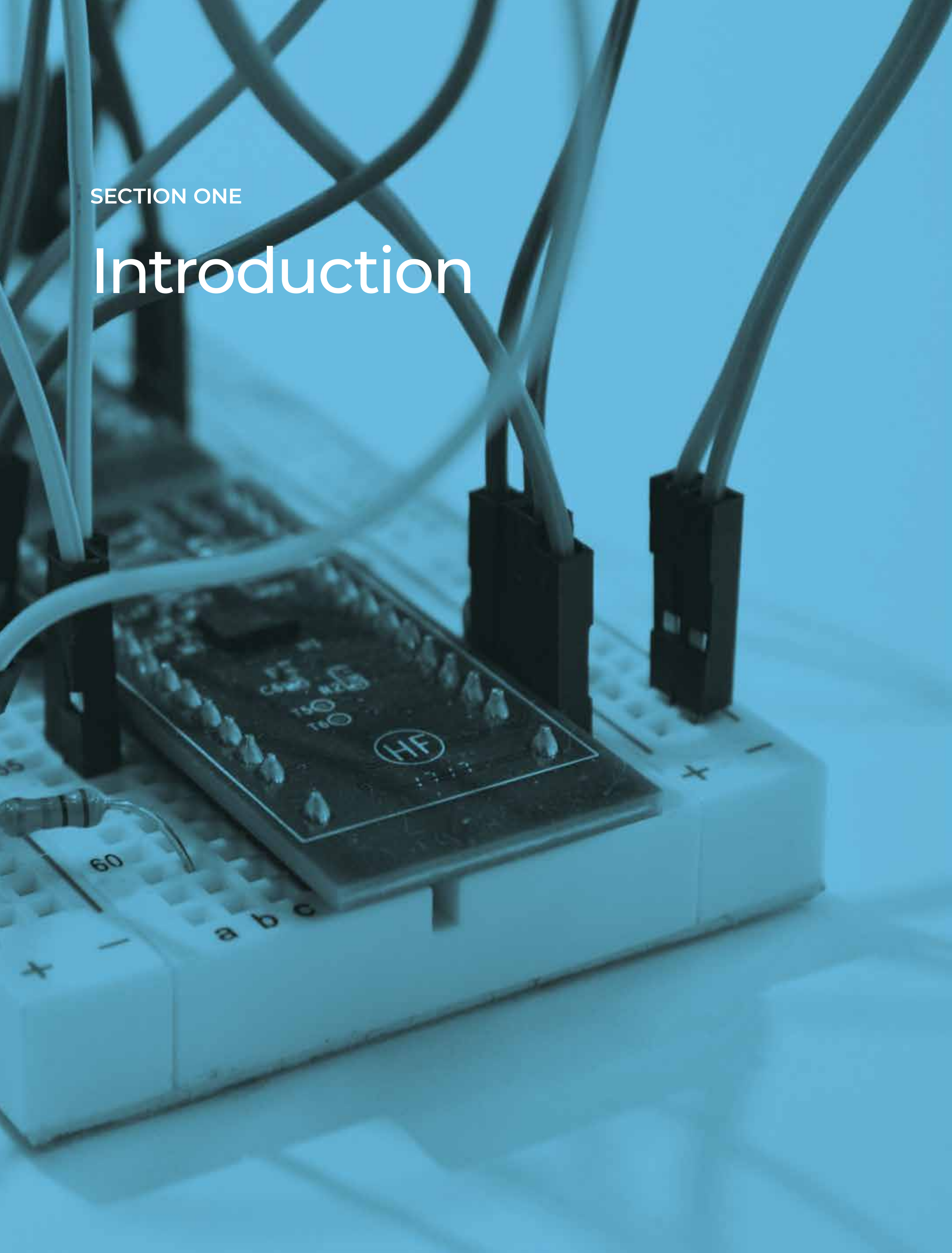
SECTION ONE

Introduction



INTRODUCTION

As the internet of things (IoT) becomes increasingly prevalent, more products are becoming connected or 'IoT enabled'.

IoT enabled products range from sophisticated industrial machines – which already contain complex electronic circuitry – to simple consumer products that traditionally have not been connected to the internet. Within the consumer space, there is already a diverse range of connected products including wearable devices such as step counters and heart-rate monitors, simple home electricals like power sockets, light bulbs and security systems, home appliances including kettles, refrigerators and washing machines, and many more.

This guide aims to support startups and scaleups that are developing IoT products by providing an overview of the product life cycle from prototype to production and exploring the specific considerations that need to be made when designing and producing an IoT product. The steps needed to successfully design and create an IoT product are not always obvious. Our hope is that this document helps startups and scaleups that are embarking on IoT product development to be able to accelerate their speed to market as a result of following the steps outlined here.

Block diagram of a generic mobile IoT device

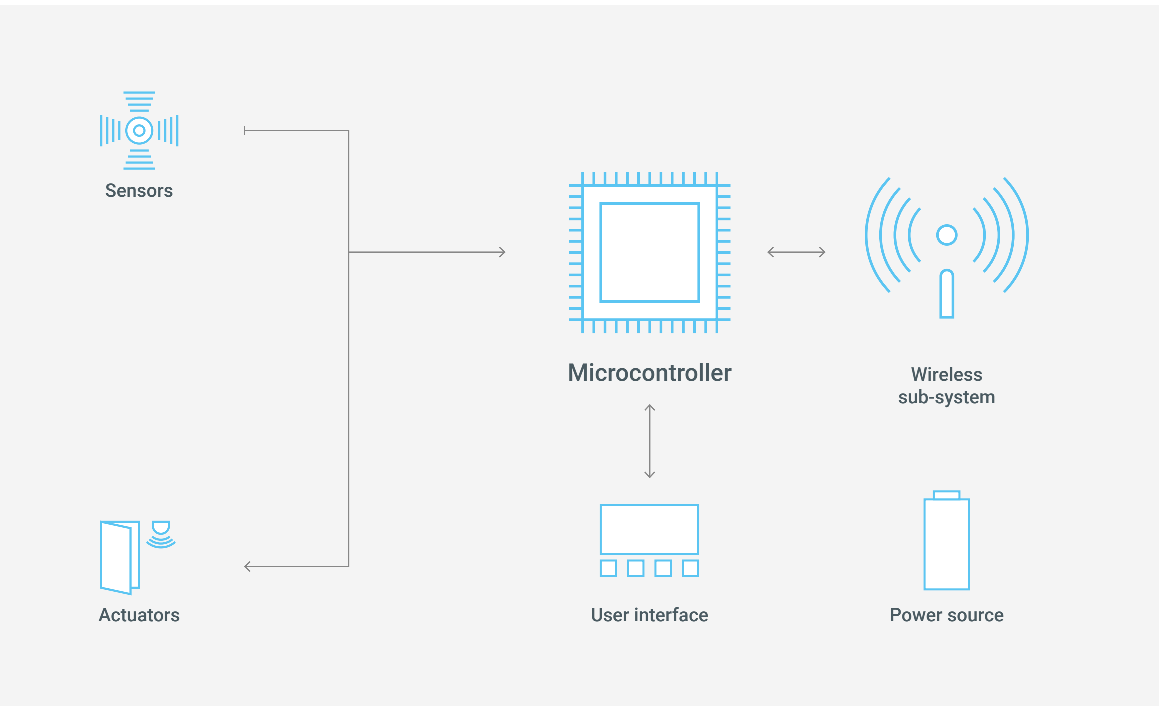


Figure 1

At a high level the IoT devices that this report refers to may be split into three types:

Sensing and mobile devices – At the simplest end of the spectrum, 'sensing' IoT devices require one or more sensors, a microcontroller, communications and power. Often such a device is mobile – meaning that it does not have to be physically connected to a network or to power. In this case, the communications will be wireless and the power source is a battery. Mobile devices may also incorporate basic actuators and a display to support a user interface, as shown in Figure 1.

Industrial IoT devices – Some IoT devices may incorporate more complex sensing and digital actuation. They often use wired communications due to the increased reliability requirements in an industrial environment, and they are typically mains powered.

Gateway devices – Some IoT devices act as 'gateways'; acting as a funnel, which assimilates information from a number of connected devices and relaying it onto the internet (and/or vice-versa). They may also act as secure end points for sensor devices that do not possess the processing power for more complex security protocols to connect to the internet. Gateways usually require considerably more processing, memory or storage power than simple sensing devices.

KEY DESIGN CHALLENGES FOR IOT PROTOTYPES

Developing an IoT prototype presents a great many challenges, some of the key design ones being summarised below:

- Selecting and integrating the appropriate radio frequency (RF technology). RF technology for communications can be either on a licensed or unlicensed spectrum. Depending upon the level of RF sub system design that is chosen, this can require either a detailed understanding of RF design or at the very least an appreciation of the techniques required to select and integrate an RF transceiver into a product
- Developing a low power hardware design with firmware that is optimised for low power, typically powered from a battery. The choice of battery is important not just to meet the energy density but also to ensure that the right battery chemistry has been selected for the application
- Ensuring regulatory compliance for wireless IoT products involves careful selection of the wireless transceiver and battery components to minimise the amount of regulatory and standards verification testing. Without suitable planning and component assessment, achieving regulatory compliance can have the potential to significantly delay the product launch through unexpected design changes and mitigations required to achieve compliance

Beyond these design challenges, the real difficulties come when making the transition from prototype to product.

MASS PRODUCTION

The term 'mass production' (MP) is often used to refer to any kind of factory production. However, only a few very dedicated production lines. More typical with outsourced production is a batch or cell based approach, where parts of the manufacturer's production line can be quickly reconfigured to process a different product line. This is especially true of printed circuit board assembly, where automated pick and place lines will often be switched between different models to suit demand. In some cases the line reconfiguration may be done in a matter of hours. This type of production carries no lesser challenges than continuous high volume, they are simply slightly different. Whereas a continuous high volume process will, through necessity, need a very high yield of working products, lower volumes lose the benefits of the stability of having a production line running continuously. Thus even at the smaller batch volumes, the stability and consistency of the design and the speed at which the production line can be stabilised to achieve maximum yield are important for minimising the overall product unit cost.

STRUCTURE OF THE REST OF THE REPORT

The rest of this report is split into two main parts:

Section 2 describes the product life cycle of a typical IoT device. The core of the section is a multi-page table, which presents a timeline from left-to-right, and for each stage in the timeline lists activities and characteristics that describe the product, grouped into rows of logical units. This provides a high-level overview of each stage.

Section 3-6 present context and detail regarding some of the key activities when launching IoT hardware, especially those aspects related to design, which are often ignored during the prototyping phase for an IoT device. These include careful consideration of 'make or buy' decisions, packaging design, design for manufacture, and assembly, various aspects of design testing and verification, factory production, regulatory issues, safety, security and quality.

In addition, **section 7** presents some insights into financial considerations, which is particularly relevant to startups or others with limited previous experience making the transition from hardware prototype to product.

The information provided here aims to offer a framework that provides sufficient context to help you spot gaps in your knowledge and thereby navigate the sometimes bewildering range of information available through other sources.

SECTION TWO

The product life cycle

THE PRODUCT LIFE CYCLE

The established product life cycle management model supports the move to mass production.

Although startups and scaleups often work in organic, ad-hoc and agile ways as they address their business needs, it is important to consider the established product life cycle management model to help manage the complexity of going to mass production.

> The product life cycle covers three phases: new product planning (NPP), new product introduction (NPI) and post-launch management.

In the context of a startup or a scaleup, the introduction of 'processes' and 'decision gates' may seem at odds with agility. However, the partners essential to success in factory production, such as an electronics manufacturing service (EMS), will almost certainly expect to follow key elements of the established NPI process. In addition, the NPP activities that include NPI will help startups define and plan for their new hardware product.

NPP provides a framework for the creative processes involved in determining a product's feasibility, the definition of exactly what the product is, and how to plan for factory production. For some readers this may seem at odds with software methodologies such as Agile or Kanban. It's important to understand that whilst software can and should be developed iteratively, every iteration of a hardware design involves more cost, time and verification effort than the analogous software iteration. For this reason, it is not practical to take the same approach to hardware development.

One example of the value of following the NPP process is to ensure that product features and requirements are suitably prioritised. Without this, a process known as 'feature creep' can happen – and this is one of the most common reasons for delayed hardware launches.

However, not all the desired features have to be present at the first launch; as long as the fundamental hardware architecture of the product can ultimately support the required range of features, many of these can be delivered by a subsequent software or firmware upgrade. This approach is taken by a number of global brands including Apple. For example the seemingly essential 'cut and paste' feature did not get delivered to the iPhone until iOS 3.0 in early 2009.

NEW PRODUCT INTRODUCTION

Following directly after the NPP phase is the NPI phase where detailed work is carried out according to the NPP plans, to ready the product design for factory production. In this execution phase, there are a lot of parallel activities – not just design work, but things like product marketing preparation, channel development and planning for pre- and post-launch support.

GATE REVIEWS

An overview of how the NPP, NPI and post launch phases are broken down into a range of activities is shown in Table 1. The phases are described in more detail later in this section. A 'gate' marks the end of each phase; to proceed from one phase to the next there should be a gate review to ensure that all the critical activities and decision criteria for that phase are complete. The formality with which the reviews are carried out will depend upon the culture of the organisation, but it is important that they are carried out with a suitable degree of due diligence to pick up potential issues as early as possible. If an issue is not resolved as promptly as possible, it will likely take longer and cost more to address.

Without such reviews it becomes very easy for issues that could prevent the product launch not being identified within the respective phase, with the inevitable negative impact on the launch milestone date and/or cash flow implications. For example, a design problem that is flagged late on may require a further iteration of hardware and additional test time (including with partners such as electromagnetic compatibility (EMC) testing houses). Thereby it could incur additional costs and a slipping schedule by several weeks and in some cases months depending upon certification test house availability.

There are a number of examples of startups that have been in this unfortunate position on some of the well-known crowdfunding platforms; where customer frustration at either over commitment or NPI issues have become all too public.

To assist with the criteria to be assessed with these phase gate reviews, sample checklists have been provided in the annex.

Simplified gateway flow

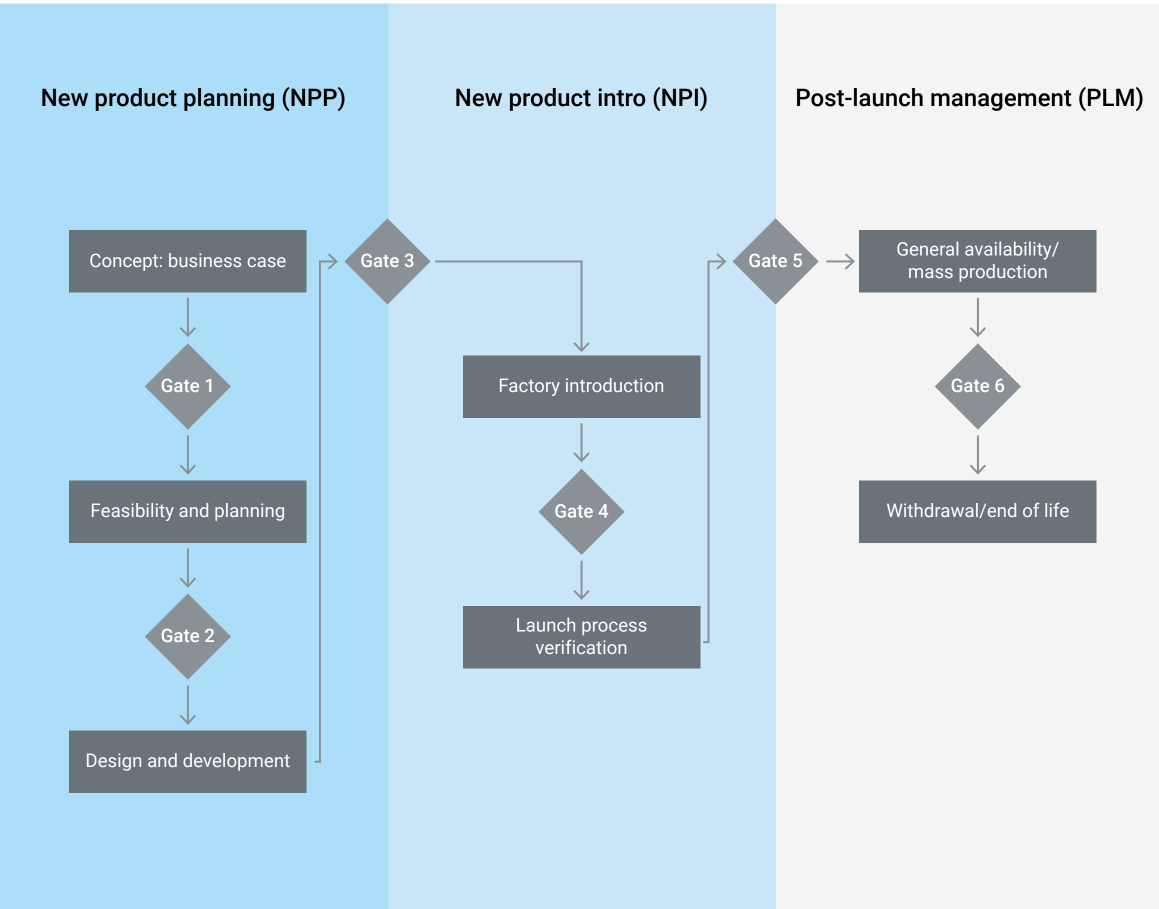


Figure 2

The following table captures the product life cycle at a high level and is intended as a helpful overview of the process as a whole.

		Status	Phase exit criteria	Typical product manufacturing quantities	Product management	Customer view and involvement	Sales and marketing
New product planning (NPP)	Concept	Business case	Is the business opportunity understood sufficiently to justify further investment?	None	– Market research – Customer 'problem' definition and use case development – Business case	Customer 'problem' definition	– Market assessment
	Gate 1						
New product planning (NPP)	Feasibility	Feasibility and planning	Is the product sufficiently defined to start development?	Small quantities of concept models	– Feature definition – Product/service pricing model – Product cash flow and budget – Product requirements – Cost of goods estimates	Customer feedback	– Marketing plan – Market preparation communications
	Gate 2						
New product introduction (NPI)	Design and development	Engineering verification trial builds 1 and 2	Is the product design mature enough for production introduction?	Less than 100 EVT prototype units	– Feature and release schedule – Customer documentation and/or online guide preparation – Product and order code (SKU) definition – Cost of goods estimate updates	Engineering samples for customer feedback	– Product/service launch planning – Sales forecast
	Gate 3						
New product introduction (NPI)	Factory introduction	Design verification trial	Is the product design verified and are all the manufacturing processes ready?	Less than 100 DVT production units	– Feature and release schedule finalised – Customer documentation and/or online guide ready for publication – Planning for early adopter customer validation – Units of supply, logistics and packaging definition	Pre-production samples for customer feedback	– Product/service launch preparation – Pricing finalisation – Sales forecast
	Gate 4						
New product introduction (NPI)	Launch	Process verification trial (Pilot run)	Is the product and line mass production ready to manufacture at intended velocity?	Less than 1000 PVT production units	– Early adopter customer validation – Product messaging	Full commercial product	– Product/service launch – Competitive messaging – Market collateral – Sales forecast
	Gate 5						
Post-launch management	General availability	Mass production		To suit the market – thousands to millions of units	– Manage customer feedback and improvements – Issue change communications to customers	Mass-production customer delivery	– Sales support: advertising, whitepapers, application notes – Sales forecast
	Gate 6						
Post-launch management	Withdrawal	End of life		None	– End of life planning – Communication to external customers and channel partners	Model replacement discussion	

Table 1 - continued on next page

Engineering and development	Production test and QA	Operations and procurement	Customer support	Essential documents	
Technical evaluation of concept				– Document market requirements – Develop business case and use case	Concept
– Create development plan and estimate the resources required – Write specifications	– Initial production testing strategy assessment	– Supply chain assessment and planning	Planning for supporting the product identifying any new support requirements	– Product requirements	Feasibility
– Electrical design – Firmware development – Mechanical and packaging design – 3D printed plastics – Design tooling – DFM, DFA and DFT reviews – Regulatory pre-compliance – Design verification – Environmental testing – RF design and antenna matching – Anticipate component obsolescence	– Documented test requirements – Develop production test procedures – Quality definition	– Manage engineering trials with CEM/EMS – Capacity planning – Run EMS RFI and RFQ processes – EMS/CEM contract negotiation – Demand forecast and procurement management	Support material creation	– Design specifications – Production test specifications – Manufacturing documentation – Gerber data, BOMs etc. – Draft quality plan – Draft user documentation – Regulatory test requirements and test plan	Design and development
– Manufacturing documentation – BOM freeze – Manufacturing tooling – Pre-production mechanical parts – Regulatory compliance – Stress testing – Firmware is fully functional with no major issues	– Test procedures and jig complete and deployed at EMS/CEM – Test operating at less than line speed – Test development essentially complete – Yield analysis	– Manage DVT with the CEM/EMS – Design and manufacturing documentation release management – Management of EMS/CEM communications	Make draft support material and product-specific training available	– Manufacturing documentation – assembly instructions etc. – Quality plan – Pre-publication user documentation – Regulatory test requirements and test plan	Factory introduction
– Final regulatory compliance and issuing of Declaration of Conformance – Production grade custom parts – cases, PCBs etc. – Production introduction support – Firmware is fully functional with no major or minor issues	– Test operating at full line speed – First Time Yield [FTY] optimisation – Ongoing FTY yield analysis	– Manage PVT with the CEM/EMS – Demand forecast and procurement management – Analyse manufacturing costs	Customer support ready – materials published and able to provide PVT product support	– Issue regulatory and safety test reports and Declaration of Conformance [DoC] – Complete user documentation	Launch
– Product tier 3 support – Alternate material support – Manufacturing cost optimisation support – Firmware maintenance and bug fixes	– Operating at line speed – FTY and cycle time optimisation – Ongoing FTY analysis	– Managing the mass production with the CEM/EMS – Forecast demand and manage supply chain	Support fully operational	– Product change notifications	General availability
		– Communicate with supply chain – Forecast demand and procurement management of the supply chain	Customer notification	– End of life notification(s)	Withdrawal

CONCEPT PHASE

The first phase of the product life cycle model is the concept phase. At this stage the aim is to clearly identify the new product, based upon the organisation's strategy, market observations and customer input.

The output of the concept phase can be simply summarised as answering the question:

> Does this product have sufficient merit to move onto the feasibility and planning phase?

Answering this question involves considering the following important criteria:

- Does the product concept have business merit?
- Does the product fit with the organisation's product strategy?
- Is the technology upon which the product is based available and feasible?
- What is the market opportunity? Has any potential competition been assessed?
- Has an outline financial and business case been prepared, and does additional funding need to be secured to support the project?
- Are the customer use cases clearly understood?
- Which are the intended markets for the product?

There are plenty of publications that cover these topics in much more detail (see reference 16 for example). For IoT products it is especially important to consider how the improved communication of data helps solve a customer need, and that the required combination of wireless and battery technologies is feasible.

Choosing the right wireless technology

When considering which wireless technology would be the best for a new IoT product, there are many considerations, such as which markets the product is for and the regulatory requirements. For example, in the case of the ISM bands, either a dual band radio is necessary or two product versions are required to support the different operating bands of 868MHz and 915MHz.

For cellular technologies the choice of radio technology is wide from 2G through to 5G, where the roll out and coverage for the different standards may vary on a country by country basis. This can often mandate a wireless sub-system for the product that supports multiple cellular or LPWAN technologies.

> On the subject of coverage, if the product is using one of the many new radio technologies, then does the network coverage of the chosen wireless technology create a dependency for the product launch?

This issue is key for startups, because it creates a significant risk of delaying the product launch with all its implications, not least financial, in the event that network coverage roll-out is delayed.

Considering energy consumption

With many IoT products being deployed either remotely or on a mobile basis, batteries are a typical source of power. This mandates a system level assessment of the device's energy consumption versus the battery size of a specific chemistry, to ensure that the theoretical battery life is sufficient for the product's application. In some cases, it may be beneficial to put together a proof of concept using off-the-shelf components or modules, to demonstrate that the intended battery service life and, in the case of secondary cells, the recharging period, are achievable. Such trials can often be used as a way of starting to prove 'customer fit' and gaining a better understanding of the product's intended applications. This may also be the basis of early customer field trials, which may be essential to complete before customers are prepared to commit to volume orders of the product.

These proof of concept activities can often provide useful insights into helping prepare the outline estimates for the development of the product's features and requirements.

Ultimately the culmination of the concept phase is a Gate 1 decision that the product has a sufficient business case for the product concept to be taken forward into the feasibility and planning phase.

Feasibility phase

Readers that are familiar with carpentry will know the old proverb "measure twice cut once". It can be equally applied to hardware product development and manufacturing – it is much faster and cheaper to double check early on than to rectify a mistake later. The planning and feasibility phase forms a substantial part of the 'measure twice' element for IoT product development. As with many creative activities, there is a tendency to want to start building as quickly as possible, but planning will allow the execution phase to move more quickly later. Insufficient planning and feasibility evaluation run the risk of overlooking system, architectural or operational details. These kinds of issues all have the potential to cause significant extra work for the development team. In the days of plated through hole (PTH) circuit boards and low clock speeds it was often possible to rectify boards with simple modifications and component changes. Today, however, fine pitch surface mount technology (SMT) components often make printed circuit board (PCB) modification during production impractical. Coupled with the use of wireless technologies with sensitive radio frequency (RF) board layouts in many IoT products, and the need for all electronic devices to meet stringent regulatory requirements, the costs associated with late changes can be prohibitive.

Questions the feasibility phase must address

Apart from the obvious technical feasibility and definition, there are a variety of questions that this phase must address, summarised here:

- What is the customer 'fit', in other words what is the customer problem that this product will overcome? Exactly who are the target customers and are they 'early adopters'?
- Will the proposed product adequately solve the customer's problem? Have all the requirements and related system elements been identified?
- Have the product's features been described and reviewed with potential customers?
- Have the technologies and platforms required to deliver the product been identified and has the technical feasibility of the product been confirmed?
- Are there any elements of the product for which 'make or buy' decisions are required?
- What is the product's projected manufactured cost and does it meet the sales price target with appropriate gross margin?
- Have detailed development and launch plans been prepared, identifying critical milestones including dates for main hardware trial production runs and general product availability?
- Have sufficient resources been made available for the development of the product, given its features and requirements?
- Has a project cash flow been created and is sufficient working capital or investment available to meet the key milestones?
- Is the production forecast aligned to customer demand? (Such analysis should be repeated regularly from this gate onwards.)
- Have the import tariffs for the intended markets been considered with respect to suitable manufacturing locations, is there any need to do final assembly either in or close to the chosen market?

For IoT products, additional questions include:

- Does the product require any specialist development such as antenna design?
- Has the right radio network technology, for example LPWAN, 2G, 3G, 4G, LTE-M1 or NB-IoT, been chosen for the product? Will the network coverage be available for the intended lifetime of the product?
- Can the business model support the associated wireless network provider's pricing model for all the expected markets for the product's lifetime?

- Are there mobile platform or third-party software dependencies that need to be identified and factored in, for example a specific release of Apple's iOS or Google's Android mobile phone operating systems?
- Does the product require support resources to be in place for early trials and at product launch?
- Does the product architecture meet requirements for performance, security, quality, regulatory compliance, serviceability and reliability?
- For the target markets, have all the regional regulatory requirements have been identified?

> The completion of the definition and planning phase is a Gate 2 decision that the product has been sufficiently defined to be taken forward into the design and development phase.

DESIGN AND DEVELOPMENT

Considerations for the design and development of a new IoT device

This is when execution starts in earnest: design and development work culminate in a working prototype and engineering validation builds take place. Key considerations in this phase are:

Design maturity:

- Have design verification tests on the most recent evaluation verification test (EVT) build units been completed and the results logged?
- Have design for test (DFT) reviews been completed?
- Have design for manufacture (DFM) reviews been completed?
- Have the mechanical tooling drawings been released for toolmaking?
- Have tests over the intended environmental operating range verified that devices from the final EVT run meet specifications?

Manufacturing:

- Has the production test plan has been created? This should include:
  - Production test firmware requirements
  - A well-defined test strategy including the test equipment required
  - Outline line production test flow, including test time targets for each test phase
  - Test fixture specifications
- Has a manufacturer been identified?
- Will the manufactured cost meet the sales price target with intended gross margin?

Deployment:

- Is suitable wireless service coverage available for customer trials and for the intended markets?

Regulatory:

- Has regulatory pre-compliance testing been completed?

Quality:

- Have the quality requirements been documented?

As can be seen, a number of documents must be ready for release at the end of this phase since they are essential for successful manufacturing partner engagement. A more complete list and description of these documents is provided in Section 5.

The exit criteria of this phase is critical because at the end of this phase, all the validation activities should be met before giving the go ahead for the start of factory introduction as part of Gate 3.

> The Gate 3 review is a critical aspect of the NPI process because considerable commercial commitments need to be made in the following phases, both in terms of manufacturing partner engagement and purchase of production tooling and materials for the production verification test (PVT) and subsequent production runs.

Taking an immature product design beyond this point without suitable validation runs a very significant risk of latent design or manufacturing issues that will incur considerable cost down the line and delay the product's launch date. This is compounded by the consequent extended exposure to production setup, tooling, raw materials costs and the delay in sales revenues, which can considerably increase working capital requirements.

To aid in the Gate 3 review decision a sample checklist is provided in the annex.

FACTORY INTRODUCTION

Getting the product ready for production trial

At this point in the process, a number of activities take place in parallel with a consequent increase in expenditure. In particular, the design verification test (DVT) production run typically incurs large non-recurring engineering (NRE) costs. The main goal of this phase is to get all of the constituents of the product ready for the PVT production trial in the subsequent phase. The major questions that must be answered for successful factory introduction are the following:

Costs:

- Will the manufactured costs meet the sales price target with intended gross margin (GM)?

Design maturity:

- Have design verification tests on the DVT build units been completed and the results logged?
- Have the recommendations from the DFT reviews been applied to the design?
- Have the recommendations from the PCB DFM reviews been applied to the design?
- Have the mechanical tooling drawings been released for toolmaking?
- Have the DVT samples been environmentally tested to ensure the product meets the specifications over the intended range of operating conditions? This should include tests for operating temperature range, humidity, flammability and drop analysis.

Manufacturing:

- Have the following documents been released to the production partner(s)?
    - Full bill of materials (BOM)
    - Approved vendor list (AVL)
    - PCB fabrication data and drawings, including panelisation details
- Is the following test collateral available?
    - Production test firmware
    - Test equipment and test fixtures for DVT and PVT trials
- Have the following test requirements been met?
    - Line production test flow approved by manufacturing partner
    - Production test cycle times meet the test time targets for each test phase
    - Test fixtures are available for DVT and PVT production trials
- Are the test steps meeting the budgeted cycle times?
- Are materials available for PVT production start?
- Is mechanical tooling available?
- Have sample product case parts from production tooling been approved?

Deployment:

- Are the necessary cellular or low power wireless services and coverage available for customer trials in the intended markets?
- Has service availability been tested for the product? Do SIM and eSIM profiles work and roam correctly in the intended markets? (This is especially important with products that use embedded SIMs.)

Regulatory:

- Have the pre-production samples passed all the required pre-compliance regulatory testing?

> The completion of the factory introduction phase is a Gate 4 decision for the product concept to be taken forward into the launch phase.

To aid in Gate 4 review a sample checklist is provided in the Annex – sample checklists.

Launch

At this stage in the NPI process momentum builds as this is the phase that signs off the product and manufacturing line. It is the stage at which everything is ready for mass production of the product and that the intended mass production velocity can be achieved. The key activity in the launch phase is the PVT run during which up to 1,000 production units are manufactured at the intended speed on the line in exactly the way that is planned for on-going factory production. The PVT run is the last chance to iron out any issues before committing to factory production.

Therefore, many of the considerations and prerequisites for passing through Gate 4 (as listed in the previous section) need to be re-reviewed as part of the Gate 5 review based upon the key performance indicators from the PVT run. In particular:

- Have design verification tests been completed on the PVT units and the results logged?
- Have the DFT and DFM reviews been completed in light of the PVT run, and the recommendations applied?
- Have the PVT samples been environmentally tested to ensure they still meet the specifications over the intended range of operating conditions?
- Do production and test cycle times still meet the targets?
- Do the manufactured costs still meet the sales price target with intended GM?
- Have the PVT production samples passed all the required regulatory and approvals processes, with certificates being issued where necessary?

> The completion of the launch phase is a Gate 5 decision for the product concept to be taken forward to factory production and the delivery phase.

To aid in the Gate 5 review a sample checklist is provided in the Annex – sample checklists.

General availability

After all the preparation to get to full production, if the product is steadily coming off the production line and is proving reliable it is relatively easy to lose sight of the ongoing activities that are necessary to maintain operations and quality.

Of particular concern for an IoT product are the following:

- Product support is available for end users covering initial setup to ongoing operation and if required any actions at the end of life of the product
- The availability of ongoing firmware support including the release of security patches
- Are there any mobile platform dependencies that need to be tracked and software updates that need to be released for ongoing compatibility, especially in the light of mobile operating system updates?
- What vulnerability disclosure procedures are in place in the event that a security vulnerability is identified with the product and its software or hardware components?
- The product needs to be regularly reviewed for discontinuation. The following indicators are signs that discontinuing a product should be considered:
  - The product's market share is declining rapidly
  - Sales revenue for the product is falling very quickly
  - The product no longer fits into the organisations' strategic view
  - Other products have been introduced, which customers are encouraged to purchase instead of this product
  - The business development and sales teams are no longer committed to the product
  - The product is losing its financial viability through rising production and/or maintenance costs

In the last case, where the product is considered for discontinuation, it is important that this is planned for and the preparations are reviewed as part of the Gate 6 review, before informing customers and the supply chain. For industrial products this is often critical when a product may have needed to go through acceptance testing for a customer's application.

In such cases it will be essential to give the customer sufficient notice in the event that the replacement model is required to go through acceptance testing. Consideration also needs to be given for identifying that the product should not be designed into new products/systems and when the last time buy (LTB) and last shipping dates are. For those products that include serviceable parts, commitments may need to be made for how long service and spare parts will need to be available for after the last time ship date.

From a supply chain perspective it is important that the timing of the discontinuation of the product is considered. This is essential to ensure that any resultant obsolete component inventory, especially custom parts are minimised and that any outstanding raw material purchase orders are within their order cancellation periods.

Withdrawal

Once the product discontinuation preparations have been reviewed, a process known as end of life (EoL) management is then used to prevent taking further customers orders and to ramp down and stop production. This is normally done through product change notification(s) (PCNs) to customers, channel partners and the entire supply chain. Some of the subjects that the product discontinuation notifications should cover are as follows:

- LTB date for the product; the date after which the product to be discontinued is no longer customer orderable
- Last time shipping date for the product; the date after which the product to be discontinued will no longer be despatched
- Product alternatives; advice to customers as to what alternative products are available and whether they are 'form and fit' compatible with the product being discontinued
- LTB date for the product's spare parts (if appropriate); the date after which spare parts for the product to be discontinued are no longer customer orderable
- End of support/service date; the date after which product support, including software updates, credential update and servicing for the product to be discontinued is no longer available
- Security credential expiry date(s), where appropriate; the date upon which any security credentials, such as X509 PKI certificate(s), shall expire for the product to be discontinued

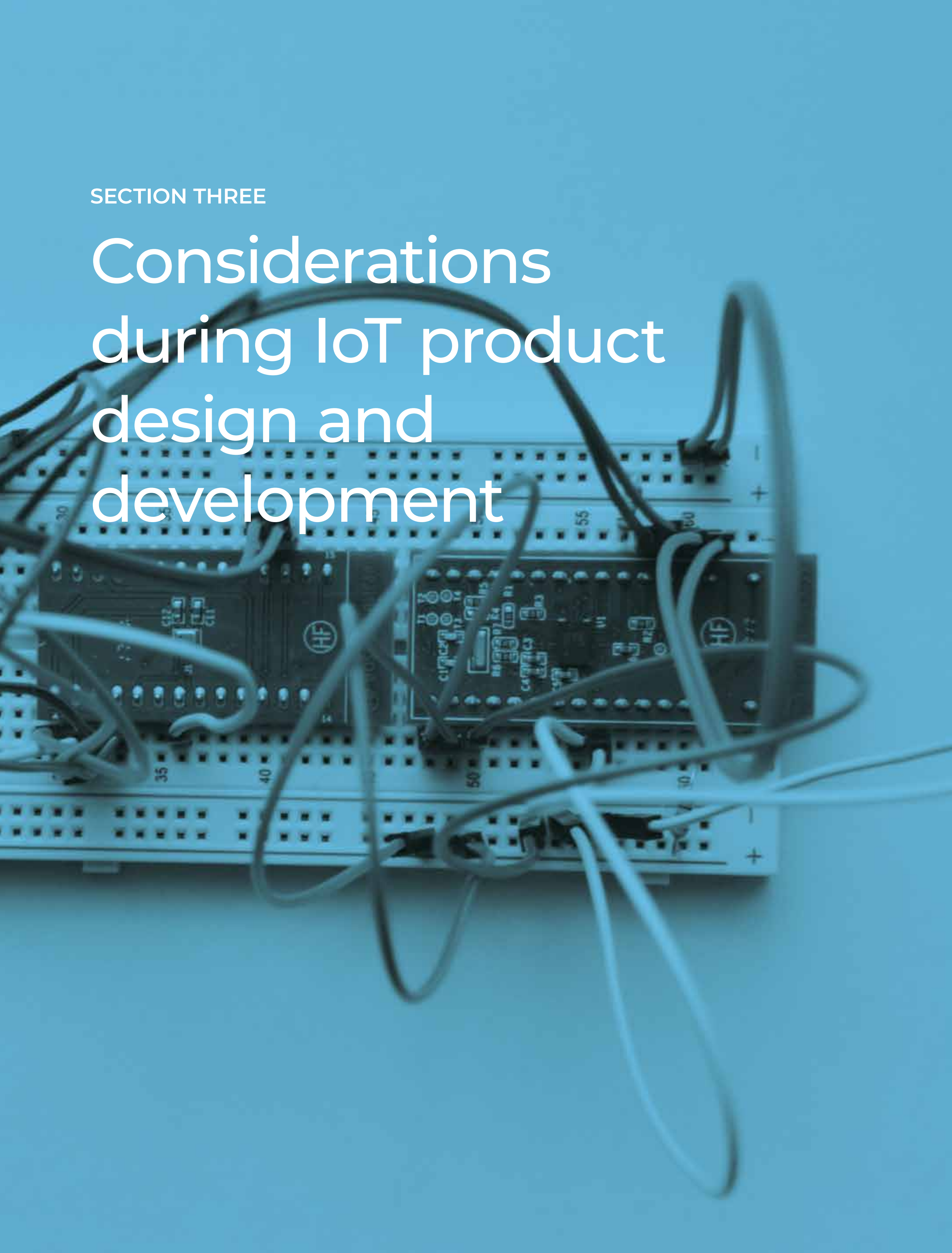
For a connected product an important part of the end of service life process is the removal or revocation of digital credentials associated with the product. This is important to ensure that products that have been taken out of service do not reveal any confidential information or allow unauthorised service reinstatement.

In some cases, it may not be possible to revoke the credentials, and instead it may be necessary to implement a 'kill switch' to permanently decommission a device. However, any such mechanism needs to be secure to prevent a hacker from mounting a denial of service attack.

Many other steps are required as part of the EoL management process and these are not covered here. Examples include: management of any remaining liabilities associated with the product, such as warranties; disposal of excess stock; and archival of design collateral.

SECTION THREE

Considerations during IoT product design and development



CONSIDERATIONS DURING IOT PRODUCT DESIGN AND DEVELOPMENT

MAKE OR BUY?

Early on in the design phase for a new product, consideration should be given to whether parts of the product should be 'bought in' rather than designed and manufactured. For connected IoT products, typical subsystems for which this 'make-or-buy' decision should be considered are:

- Power supplies
- Wireless subsystems
- Processor subsystems
- 'Accessories' that enable or enhance product operation

Regulatory considerations can have a significant bearing on the make or buy decision – achieving regulatory compliance adds risk, is usually costly and may have a substantial impact on schedule.

ELECTRICAL DESIGN

Battery power supply

IoT devices are often battery powered and whilst lithium ion or lithium polymer batteries are an obvious choice in many applications, a range of battery chemistries and technologies are available, each with different pros and cons. These include:

- Operating temperature range, which may be particularly important for industrial IoT applications
- Rechargeable (also known as secondary) batteries vs. one-time use (disposable, or primary) batteries
- Battery life for rechargeables, typically specified as the number of discharge and recharge cycles that may be applied before the battery capacity is reduced to a certain fraction of its original value
- Energy storage density in terms of weight and/or volume, known as gravimetric energy density and volumetric energy density respectively
- Self-discharge current, which must be sufficiently low not to impact the power budget between charging cycles

Wireless subsystem solutions compared

Criteria	Custom wireless design	Wireless module
Component cost	Lower	Higher
Physical design	Most flexible, great for space constrained designs	More constrained, as module form factor is fixed
Development cost	Higher	Lower
Design risk	Depending upon radio technology can be significant risk, requiring several PCB layout iterations	Lower risk, especially if the module vendor provides good design-in documentation
Time to market	Longer	Shorter
Production test	Likely to require production line calibration with consequent test equipment capital cost	Should be limited to functional test
Protocol verification	May require protocol certification/validation	Protocol certified by module vendor
RED/CE/FCC certification	Will require full radio and emissions testing	Module manufacturer should provide CE/RED/FCC pre-approval to reduce the radio testing to spurious emissions only
Antenna design	May use antenna reference design or off-the-shelf antenna design, but significant RF design and qualification needed	Often built into module, significantly reducing the design and regulatory effort; otherwise many modules come with suitable reference design

Table 2

In parallel with battery power supply selection, the product design process should include evaluation and ideally improvement of the product's power consumption. Typically, hardware, firmware and software architecture all impact power consumption and it's important to take a holistic approach to design at an early stage to ensure system-level optimisation.

Wireless subsystem

With most IoT products having one or more wireless interfaces, a key decision is whether or not the wireless subsystems utilise original equipment manufacturer (OEM) modules or if they should be implemented as a custom design. Whilst the BOM cost of a discrete design can appear to be lower cost than the equivalent module, there are additional factors that may be more significant and which can ultimately mitigate the module's increased unit cost.

A further consideration is software support: modules may be provided with a certified protocol stack that can dramatically reduce the amount of software development and testing required. Examples include Bluetooth, WiFi and cellular radio modules.

A number of RF communications module providers, silicon vendors and other online resources provide information, which can help with the make-or-buy decision. Please refer to the references in Section 9 for more details.

Processor modules vs discrete designs

Modern microprocessor designs involve high speed double data rate (DDR) RAM memory subsystems regularly operating at clock frequencies over 250MHz, requiring high speed printed circuit board design techniques and signal integrity analysis to ensure all signal timings are consistently met. The fast memory signal edge rates can often be the source of unintentional radiated emissions. As well as having the potential to exceed allowable levels of radiated emission, with the consequent delay in achieving regulatory compliance, these signals will also interfere with any sensitive wireless receivers in the product and thereby degrade performance.

To mitigate these risks, it is recommended that a proven processor vendor's reference design is adopted, including schematic design, PCB layout and PCB layer stack-up.

The alternative is to integrate an OEM processor module into the product. In this case the processor, memory, and other critical components are integrated in a design that has been optimised and verified by the OEM. This greatly reduces risk and NRE cost.

PCB design

IoT products come in all shapes and sizes, and to meet the form-factor requirements of any particular application it may be necessary to use multiple PCBs, perhaps carrying sensors or switches, which have to be conveniently positioned for usability. Unfortunately, inter-PCB connectors and cables are costly, often end up occupying significant space, introduce a point of failure, and add assembly steps. As a result, flexi-rigid PCBs are increasingly being used.

Flexi-rigid PCBs use a flexible polyimide layer embedded in the traditional PCB stack-up to carry interconnecting copper layers between rigid PCB sections, thereby alleviating the need for inter-PCB connectors and cables. Components are mounted on the rigid sections in the standard way, but the flexible sections allow the finished assembly to be folded. Where a flexi-rigid PCB is incorporated into a product, it is important to specify whether the design will require dynamic and repeated bending while in use, or if a single manipulation during the assembly process is sufficient, to ensure the right substrate materials are selected for the flexi-rigid PCB. Designing flexi-rigid PCBs has become much easier in the last ten years but it does require a professional CAD system and an appreciation of what the manufacturing process and materials will allow.

The consequence of demanding form factors has meant that PCB design for IoT devices represents a very significant element of the product design, not least because of the non-uniform outlines for the product's constituent PCBs. One approach for such designs and the associated component density is to consider the use of multi-layer high density interconnect PCBs, which whilst being expensive also don't lend themselves to mounting on curved or irregular surfaces.

By comparison flexi-rigid PCBs can have a number of advantages over rigid PCBs, with as their names suggest greater flexibility, the ability to eliminate inter board cables and their associated connectors, which can increase the packing density.

If any RF path, such as the antenna feed, is incorporated in the PCB then the CAD system must support RF design parameters, in particular impedance matched trace design. A further side effect of irregular shaped enclosures and their constituent PCBs, is that close integration is required between PCB layout and mechanical case design.

Without such cooperation and integration of the two design flows when it comes to putting the components together, there is the potential for some nasty surprises. Fortunately, many modern professional PCB CAD systems have native 3D mechanical support, allowing case profiles to be brought into the PCB CAD system, so that the PCB designer can design rule check the PCB envelope against the actual mechanical design. Similarly, the same PCB CAD system can export a 3D mechanical model of the PCB for importing the PCB as a component in the mechanical 3D CAD system. In some CAD system combinations this can be a real-time process, aiding fast feedback loops and mitigating the risk of the PCB(s) not fitting correctly into the case.

There are many more space-saving techniques that we cannot explore here. For example, if the design has serious challenges and sufficient production volumes it is possible to print passive components, potentiometer tracks and switch contacts using conductive polymers. It is also possible to bury passive components within a PCB, and to mount bare silicon dies onto or within a PCB. There are prototyping houses in the UK that can perform such advanced processes – if necessary by hand – to create proof-of-principle units that can subsequently be adapted for production. Make sure you have sufficient knowledge of the final production solution before prototyping something that is impossible or uneconomic in volume.

RF design and antenna matching

For an IoT product, having a high radiated RF efficiency is especially important for those products that are battery powered allowing them to achieve the longest battery life from the product's design. Without efficiency optimisation, typically known as matching and radiated pattern testing, the RF antenna and its associated circuitry can waste significant amounts of the product's energy, through inefficient transfer of the RF energy between the antenna and transceiver.

For most wireless designs there will need to be, at the least, the antenna feeder trace from the module to an external antenna connector or, for an internal antenna where the antenna is integrated into the PCB, both options mandating RF controlled impedance PCB trace design. To achieve controlled impedance in a PCB, the PCB's copper stack up and the dielectric performance of the PCB laminate become critical factors in determining the PCB trace impedances. This means that for successful characterisation of the design, both in the prototype and mass production phases, the same laminate and stack up material needs to be used in all the engineering and production builds. Care needs to be taken with the laminate choice to ensure that the one chosen is available not just for the prototype manufacture but also to the intended partner who will mass produce the product.

Where the product does not have an antenna that is integrated into a module and which is mounted on the product's PCB, both the antenna feeder(s) and the antenna(s) will require impedance matching.

The matching work will need to be done in conjunction with the controlled impedance PCB design. Impedance matching is necessary to maximise the RF transmission efficiency through ensuring that as much of the intended RF transmit signal is transferred to the antenna and not reflected back to the RF transceiver.

A major challenge for many IoT products is the integration of the RF transceiver with other subsystems in close proximity within the product and in particular radio frequency and electromagnetic interference. This impacts in a number of areas, briefly summarised as follows:

- Coupling of unwanted signals into the RF antennas and their feeders, typically this manifests itself as considerably reduced RF range, either as a result of reduced receiver sensitivity or poor transmit signal to noise ratios
- The product's radio transceivers/receivers having noise from the device's microcontroller/microprocessor, power supplies or other subsystems being coupled into them through their control interfaces. Like the RF paths, this typically manifests itself as a loss of range or receive sensitivity
- The product's sensors do not meet their specifications through noise being coupled to them from the device's microcontroller/microprocessor, power supplies and/or other subsystems

PACKAGING DESIGN

An often-overlooked area of a hardware product is its physical packaging. Insufficient or poor design of packaging can mean increased distribution costs and damage to product during distribution and/or delivery to the end customer. In addition to protecting the product during shipping, in a retail supply context the packaging may also be important for describing and promoting the product at the point of sale. In many regions the packaging must also carry information about the product's certification, safety, recyclability and origin of manufacture. Some countries require information printed on the packaging to be presented in more than one language.

It may be important to identify the hierarchy of packaging that will be used during distribution. If a packaged product is packed into a master carton that can afford additional protection. But ultimately, if individual products are delivered directly to customers then the packaging must protect it and ideally not sustain damage itself.

Shipping quantities for distribution are also a consideration: how many products will be packed into a master carton, and how many of these can be fitted onto a shipping pallet? These numbers may vary depending on the intended market. In distribution having to split pallets or master cartons can create issues with cartons being damaged, or product being difficult to handle because it is no longer packaged to suit the logistics processes. These are all requirements that should be identified and defined in the product requirements document, so that manufacturing can easily cost and procure them.

DESIGN FOR MANUFACTURE AND ASSEMBLY

> Design for manufacture (DFM) is the part of the design process where consideration is given to ensure ease of manufacture and thereby minimisation of production cost. Design for assembly (DFA) is particularly focused on easing assembly with the aim of reducing the product assembly cost. These subjects are critical to the success of a product because they can have a big impact on the product's manufactured cost, quality and production cycle time.

DFM and DFA are the subjects of many books and presentations that go into much greater depth than is possible here, but from an electronic design perspective some key considerations are listed below:

- Optimise PCB assembly yield by using component PCB footprints that comply with the IPC standards such as IPC-2221, IPC-7251 and IPC-7351
- Consider the appropriate form of the PCB panelisation and separation method
- Does the PCB layout make optimal use of the PCB panel material to minimise waste?
- Does PCB component placement on both sides of the PCB take into account the requirements for reflow soldering for SMD components?
- Where wave soldering is used for through hole and SMD components on the bottom side of the PCB, ensure that only the appropriate SMD component sizes are placed on there
- Ensure that any through-hole components that are

polarised or have directional constraints are placed with a consistent alignment throughout the layout

- If any heatsinks are required, their location should be carefully considered so that they do not foul other components. Similarly, their placement should be such that their heat output does not affect other thermosensitive components including oscillators
- Sufficient test points are provided and on a pitch that is compatible with the EMS partner's testing capabilities, so that the product can be functionally tested

DESIGN FOR TEST

Testing during production normally has three overall goals: to carry out a functional test, to verify manufacturing was correct, and, if required, calibration. Functional testing is intended to verify that each instance of the product works as designed given the particular parts it was made from. Additional manufacturing testing validates that the product demonstrates the expected characteristics (for example power consumption) and is in a saleable condition. Calibration is sometimes required for wireless or sensing products, to adjust each product so that it meets the published performance specifications. An example of this is the initial adjustment of the frequency source of an RF transceiver with respect to a known frequency reference, which can be required with some ISM band designs. Often testing will be done in multiple stages. For example, if a product comprises several separate PCBs then each of these may be tested individually after PCB assembly to catch issues early on and to prevent a fault with one PCB in a product inducing failure of other boards or components in the product. If there is flexibility in the sequencing of steps in the production process, it may be beneficial to perform lower-yield steps first to simplify rework and reduce the value of any stock which has to be written off. Different approaches are possible depending on the nature of the product so this is something that should be discussed with the chosen manufacturing partner. Once production is up and running, it's possible that additional tests will need to be introduced or occasionally that some tests can be relaxed.

A lack of planning for how the product is intended to be tested in production has the potential to cause significant schedule slip in the production line bring-up for the DVT and PVT production runs, with a consequent impact in the factory production start date. The ideal situation is that product manufacturing repeatability is so good that only a minimal amount of testing is required, but in reality, production testing will often take longer than the PCB build on a high speed SMT manufacturing line. It is therefore essential to identify any process issues in the manufacturing line as soon as possible so that they can be rectified without the build-up of faulty 'work in progress' (WIP) material.

In addition to detecting manufacturing problems, the production test process often involves programming of programmable devices such as microcontrollers, EEPROMs and FPGAs. This includes loading firmware, configuration and unique identifiers such as MAC addresses, serial numbers etc. A further complication may be any security processes such as cryptographic key generation or key insertion. To facilitate both defect detection and any programming it is essential that the product design provides sufficient access – this is often provided using a dedicated test interface such as JTAG, a serial port, USB interface or some other port on the product.

When an IoT product has one or more wireless transceivers, part of the test strategy must include testing the RF subsystems. If an RF module with a built-in antenna is used, a relatively simple functional test may suffice. For products with custom antenna, solutions testing is likely to be more involved; small changes in impedance, gain and/or loading can make a significant difference to overall system characteristics and it is important to verify that the complete module-plus-antenna system meets the relevant regulations. A further consideration for RF testing, especially functional tests, is ensuring that the frequencies the device normally operates on are suitably licensed in the place of manufacture. In the case where licensed bands are not available or coverage is not available, suitable RF screening of any test fixtures that involve radiated RF tests becomes mandatory.

The development of production tests alongside the main product development has the benefit in that after initial design verification testing, the 'prototype' production test system(s) can be used for testing early trial builds as well as for DVT and PVT production runs. Without such early test capability, it then falls to the development team to carry out testing of the early trial builds, and if a significant number of early trials units are manufactured such testing can occupy a significant portion of the development team's resources. In such circumstances the development team tests are likely to be high level functional tests that will not expose circuit margin issues. The early availability of the test system – even a prototype one – will flag underlying design issues early on and reduce the time needed to fix them.

If an issue is caused by circuit margins, it could easily take a couple of months for an engineer to resolve the issue without access to test system results from a number PCBs of the same design.

A manufacturing partner will want to know the amount of test coverage required, for example the amount of the circuit that is exercised and captured during the testing process. In an ideal world test coverage would be 100%, for example every signal in the system is stimulated and measured during testing. The reality with modern PCBs, especially ones with one or more RF subsystems, is that this is usually not achievable.

Production testing is a significant cost, both in terms of the NRE costs associated with test design and test equipment procurement, and in terms of the time required to test each product. In some cases, it will take longer and cost more to design the test process than it does to design the product itself! Careful preparation of a test strategy and effective DFT area is critical to the NPI process.

FIRMWARE AND SOFTWARE DEVELOPMENT

Firmware and software development and testing are outside the scope of this document. There are typically decisions relating to the choice of operating system (none, real-time operating system (RTOS), or high-level operating system (HLOS)), the use of third party libraries (for example networking stacks, file systems and GUIs), development tools and programming languages. These choices have deep implications for product characteristics such as cost and functionality, and for development time, test strategy and so on. They also have an impact on aspects of the electronic design including the choice of processor and the amount of memory necessary.

REGULATORY PRE-COMPLIANCE TESTING

Regulatory pre-compliance testing is done using samples typically from the EVT and/or DVT stages. The goal is to discover early on if there are EMC or safety issues that need to be rectified, ideally before factory introduction.

Both pre-compliance and compliance testing often require preparation from the development team who will need to support various 'test modes', which makes it easier to carry out the various EMC tests.

Typically, custom software builds will allow the product to be configured to transmit continuously and have ways to clearly demonstrate the product is working during immunity tests. Other considerations for cellular products will be test SIMs required for testing and if the product incorporates an embedded SIM how the test SIM will be connected to the equipment under test (EUT).

DESIGN VERIFICATION

Design verification ensures that the electronic design meets the product requirements within the expected component and manufacturing tolerances. Particular areas of scrutiny should include:

- Power supply components, for example correct voltages, currents and power dissipations
- Start up conditions, for example correct supply rail sequencing and reset timings
- High speed interfaces including USB, SATA and memory interfaces
- RF subsystems and antenna paths
- Components are working in the design within their recommended operating conditions

The creation of a document that describes how the design of the product is to be verified can be very useful. It should consider how hardware testing is to be carried out and what critical signals must be accessed during early engineering and production. Given the component density and inaccessibility of signals on modern SMT designs, it is important to think through what test point access should be provided during the design of the first prototypes and engineering builds. The alternative is discovering that a crucial signal is almost impossible to access with an oscilloscope or logic analyser probe.

ENVIRONMENTAL TESTING

As part of the verification of the design the product must be tested over its full environmental operating range. Typically, this involves testing the product over its specified range of temperature, humidity, pressure and vibration.

Unless the organisation has the facilities to carry out this type of testing in-house, it will be necessary to book time with a test house that has appropriate chamber facilities to provide the range of operating conditions.

LIFE CYCLE TESTING

Most products are supplied with a warranty and for hardware products it is important that the design has been tested to expose any potential weaknesses of the product design that would cause the product to fail during the warranty period and expected service life. To carry out this reliability testing requires what is known as accelerated life testing where the product is tested under operating conditions significantly beyond the normal ones. This type of testing in the design phase is commonly known as highly accelerated life testing (HALT), and when carried out on production samples is known as highly accelerated stress screening (HASS) and can also be known as "burn-in" testing. The aim of the two test types is to quickly discover problems associated with product design (HALT) and production (HASS). The two test processes are based upon the methods of test that reduce the time to identify potential causes of failure. Both use the application of higher stress levels than the product would experience in normal operation.

Some of the methods which are used to stress a product are as follows:

- Operation at higher than normal operating temperature and vibration
- Cycling of the ambient temperature
- Applying over-voltage or cycling the operating voltages

The HALT test levels are higher than the HASS testing extremes since HALT testing is intended to find weaknesses and to 'break' the product, whereas HASS testing is intended to identify good product.

It is normally essential to have obtained the HALT test results so as to be able to determine suitable HASS test conditions. Like environmental testing this normally requires submitting products to a test house with the appropriate test facilities for HASS and HALT.

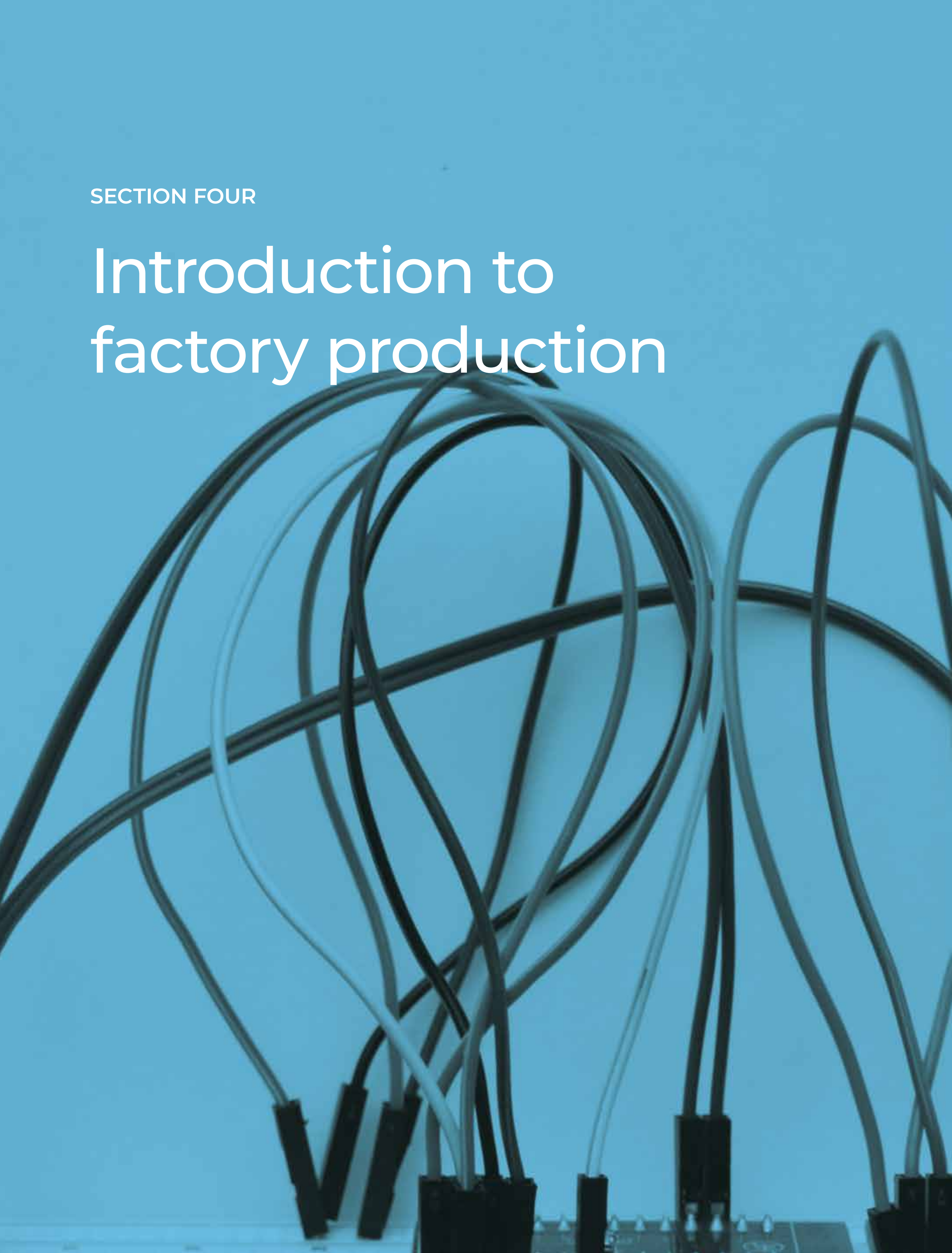
ANTICIPATING COMPONENT OBSOLESCENCE

It is important to ensure that all components used in the product's bill of materials will be available when mass production starts, and ideally for the lifetime of the product. If a component becomes obsolete this will obviously cause disruption, with the potential to stop a production run. If components are available from multiple sources this can help mitigate problems, but as soon as one of the sources stops active production, and while the second source is being used as a buffer, an alternative back-up plan should be put in place.

Another consideration for component selection is the lifetime of the component: will it be long enough for the expected product lifetime? This is especially important for industrial and medical products, whose lifetimes can be 10 years or longer. In some cases where a short life component is the only viable option consideration may be given to pre-ordering sufficient quantity for the expected life of the product and to cover warranty commitments.

SECTION FOUR

Introduction to factory production



MANUFACTURING DOCUMENTATION

Manufacturing documentation is a crucial element of communication between a startup or SME and the production partner. A recommended minimum set of documentation describing how the product should be manufactured and tested is listed below:

- Product requirements document
- Bill of materials (BOM) and schematic drawings
- Approved vendor list (AVL)
- PCB CAM data
- Assembly and mechanical drawings
- Assembly instruction(s)
- Test specification
- Packaging specification

These documents are considered in more detail in the following sections.

Product requirements document

This document provides a high-level description of the product and includes the detailed specifications that every manufactured product needs to meet. An early version of this document should also capture all the regulatory standards and any safety approvals that the product will need to comply with.

Bill of materials (BOM) and schematic drawings

A critical part of the product documentation, the BOM may be made up of more than one document. The top level BOM contains a list of sub-assemblies that make up the product and then there are BOMs for each of the sub-assemblies. Each includes BOMs for the PCB assemblies and any mechanical assemblies such as switches or connectors not mounted on a PCB. For each PCB assembly, the BOM should include every component that is to be mounted on the PCB and including the bare PCB itself, along with identifying or serial number labels.

Normally, rather than listing every component individually, the components are listed by unique part number and a list of designators for each part is included in the relevant row. For each part the quantity, description, manufacturer and manufacturer's part number should be specified. It's useful to include information such as where to purchase the part, especially in the case of parts for which the manufacturer has provided volume pricing. Any parts which the startup or scaleup expects to 'free issue' to the manufacturing partner should be indicated.

Custom parts such as pre-programmed microcontrollers, CPLDs or security devices, should be indicated in the BOM and refer to a specification document, which describes how the parts are marked, to aid correct identification.

The schematic drawings may not technically be necessary, but many manufacturers understand circuit design and may be able to provide useful suggestions based on an evaluation of the schematics.

Approved vendor list

An AVL captures which component suppliers are approved. It may also capture which of the alternative parts to the ones specified in the product's bill of materials are acceptable. Typically, it includes a cross reference from the original manufacturer and manufacturer's part number to alternative part or parts either from the same manufacturer or a different manufacturer. In some cases an alternative manufacturer's resistor or capacitor series can be specified as an alternative for the one specified in the product's BOM. This is useful to minimise the size of the list, especially for passive parts such as resistors or capacitors.

PCB CAM data

Printed circuit board manufacturing data can be transferred in two main formats RS-274x Gerber or ODB++. The former is the older standard and involves a Gerber file for each layer in the PCB and in some cases a separate aperture file, along with the need to supply an Excellon NC drill file. The newer ODB++ standard has the benefit of including much more information about the design such as net names, inner layer information, and component data. However, it can expose considerably more intellectual property associated with the product's design.

The older format Gerber data is universally accepted by PCB manufacturers, whereas ODB++ is only accepted by approximately 80% of PCB manufacturers. According to the ODB++ Solutions Alliance, "the top-10 largest EMS companies are fully ODB++ compatible, as are more than half of the top-50".

Assembly and mechanical drawings

Modern printed circuit boards rarely allow identification of component designators on the silkscreen, so an alternative way of identifying component locations is by the assembly drawing. Whilst the majority of CAD systems can generate the x, y coordinates for the automated pick and placement of the components, assembly drawings are valuable for checking component locations during other QA steps.

Any custom mechanical parts must have suitable drawings or CAD files. In the case of parts for injection moulding this will typically take the form of 3D CAD files, which will be supplied to the injection moulding toolmaker for the creation of the injection moulding tooling.

Assembly instruction(s)

Assembly instructions are a key part of the manufacturing documentation, whether they are produced internally or by a design partner. A well-written set of assembly instructions helps ensure that the product assembly is consistent and that there is no unintentional damage to the product's components or sub-assemblies during the assembly process or processes. An EMS partner will normally consider this a prerequisite as part of their quality control processes, so if the organisation is unable to provide this document, the EMS partner will need to create one to be able to meet their quality requirements.

Test specification

The test specification is the document that captures the critical parameters that need to be tested in production. The amount of testing the product requires and the associated testing time(s), will have a direct impact on the production line arrangement, the production throughput and the manufactured cost.

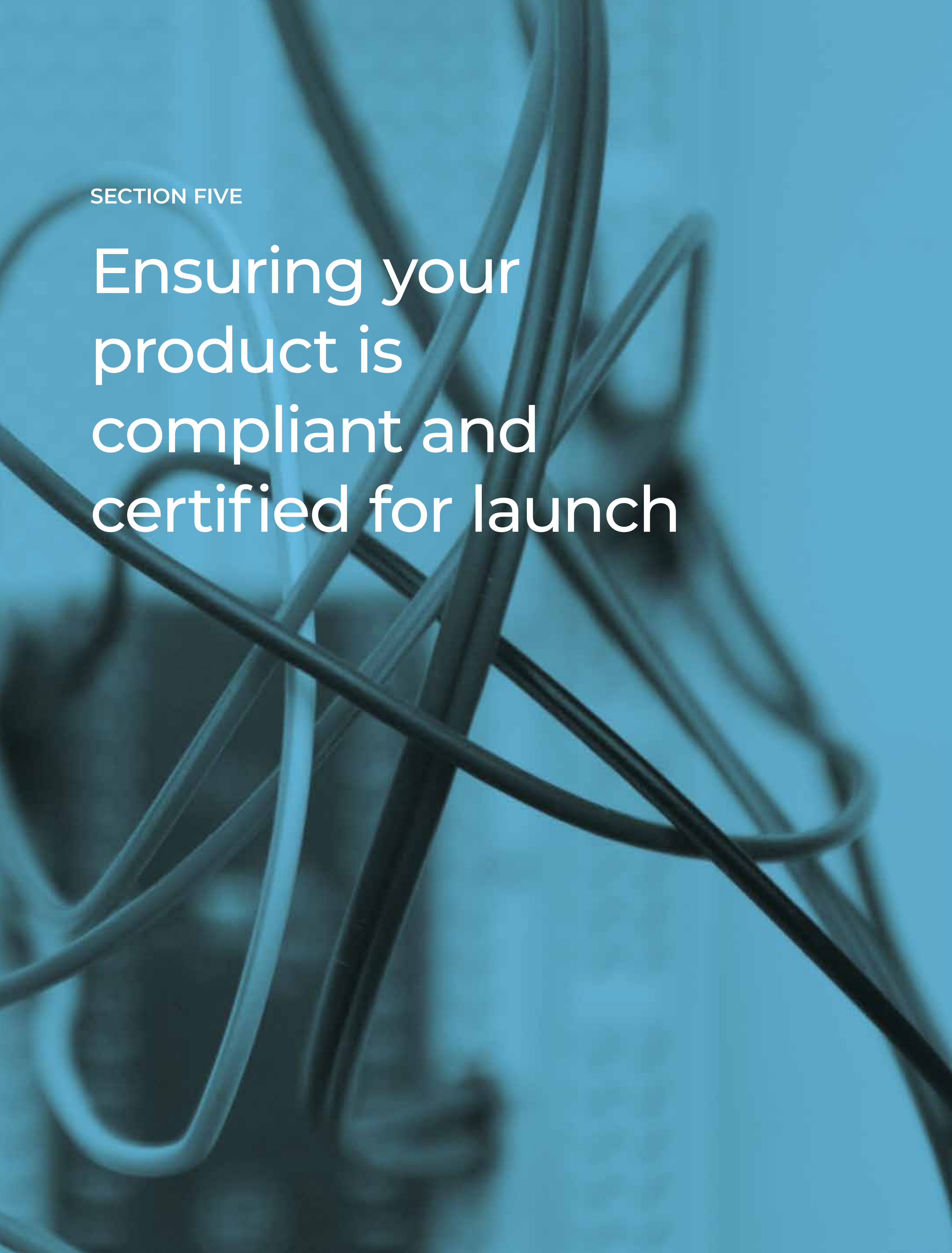
If the hardware design verification tests have been documented, as described previously, then the test specification can often be an abridged version of the design verification tests, with adjustments for the differences in the way the tests would be carried out in development and on the production line.

This document forms an essential part of an RFQ request to an EMS partner, since their understanding of the test requirements will have a significant impact on the resources required for the product's production line, its associated throughput and hence cost.

Manufacturing partners

There are a number of types of electronic manufacturing partner, which can offer a range of services depending upon the level of support a potential customer requires. The terms that are often used to describe these different engagement models, the main ones are described below:

- Original equipment manufacturer (OEM) — an organisation that typically supplies components or subsystems, which they have designed or own the intellectual property for their products. Historically the OEM also manufactured the product in their own production facilities, although today the OEM often outsources some or all of their manufacturing
- Electronics manufacturing service (EMS) providers — supply design, manufacturing and product support services to OEMs. Such providers often supply more than PCB assembly, box build or testing, where additional services can include supply chain management, forward and reverse logistics support, customer support and warranty repair. Such vendors include the Sony UK Technology Centre
- Contract electronics manufacturers (CEMs) — suppliers who manufacture products for other companies, typically taking on some or all of the manufacturing of OEMs
- Original design manufacturers (ODMs) — companies that design and manufacture products, which are typically rebranded by their customers. This allows brand holders to sell a product that they did not design or have to manufacture. Good examples of this are found in the PC notebook market where there are a number of companies who manufacture PC products that are then sold by other household brands. A good example of an ODM is the Taiwanese company Compal who supply a variety of PC makers such as Acer, Dell, Hewlett Packard and Lenovo
- A joint design manufacturer (JDM) — an organisation that supports both design and manufacturing but doesn’t completely manage or control either (unlike an ODM)



SECTION FIVE

Ensuring your product is compliant and certified for launch

ENSURING YOUR PRODUCT IS COMPLIANT AND CERTIFIED FOR LAUNCH

REGULATORY COMPLIANCE AND CERTIFICATION FOR LAUNCH

IoT products typically involve one or more wireless interfaces, which necessitates more regulatory consideration than a product without an intentional radio transmitter. The importance of identifying which regulatory standards the product needs to comply with cannot be overstressed. There have been numerous examples of products being launched on crowdfunding platforms where the product has been described as designed, just needs to complete regulatory testing and the product would be available in two to three months. Then the project updates go quiet whilst the scale of the product's regulatory requirements are determined, the product goes through pre-compliance testing and the product fails. This then results in the product design being re-spun one or more times with the consequent delay, so the project's crowdfunding pages illustrate the product is likely to be six, nine or over 12 months late with the understandable reaction from expectant project supporters.

CE AND RED AND FCC APPROVALS

If the initial markets for a wireless IoT product include the EU and the USA, then the RED and FCC regulations (respectively) need to be considered. Other regions typically have different regulations.

As discussed in the previous section, the choice of designing a discrete RF subsystem and purchasing impacts the scope of the regulatory testing, where a discrete design will not only have to pass all the normal emissions and immunity tests but also all of the associated radio standards that relate to its intended radio transmissions. In the case of modules, the selection of them should consider the level of regulatory support the module vendor provides, not just in terms of the test certificates that are available for the module but also the test reports that describe how the certifications were achieved.

These module vendor test reports can be used to form part of the supporting documents in the technical file that need to be created for the product, which can be used as evidence for compliance with the standard requirements. Engaging suitable expertise in this area determines exactly which tests can be mitigated by the module vendor's testing and their appropriate use in the product's technical file.

An important point to consider when integrating more than one radio technology, is that the module test reports typically only cover the module when it is the only radio in the product. As soon as more than one radio sub-system is incorporated in the product, further testing will be essential to ensure that the co-location of the radios has not impaired each of the radios' receive and transmit performance.

In the case of FCC certification it may be possible to reuse the module's FCC approval number providing the module is integrated according to the requirements of the module vendor, such as maximum antenna gain. Again, the details of how to make this assessment are outside the scope of this document and suitable expertise should be sought to evaluate if the vendor's FCC approvals can be used for the product without additional radio testing.

WEEE AND RoHS

> Apart from the electrical, magnetic and safety regulatory tests, other regulations that need to be considered for products shipped within the EU are the WEEE and REACH directives involving product disposal.

The Waste Electrical and Electronic Equipment Directive (WEEE Directive) is the European Community Directive 2012/19/EU on waste electrical and electronic equipment (WEEE) and is closely associated with the ROHS Directive 2002/95/EC, both of which originally became European Law in February 2003.

For any electronic device in the UK or the EU, the organisation must comply with the WEEE directive, full details of the compliance requirements can be found at the UK Government website:
www.gov.uk/guidance/electrical-and-electronic-equipment-eee-producer-responsibility

The RoHS directive scope was expanded to update the original 2002/95/EC legislation in 2011 under the directive 2011/65/EU, which became law in nation states by 2 January 2013. In January 2018 the EU started a further review of the list of restricted substances. At the time of writing the date at which these new restrictions would come into force is yet to be announced. The main change was that cables and spare parts must also comply with the restrictions in use of hazardous chemicals, such as lead, mercury and cadmium. It is essential that in the choices made about the materials and components used in the product that they are RoHS and RoHS 3 compliant and that a record is kept of the products', materials' and components' RoHS status.

> For any electronic device in the UK or the EU, the organisation must comply with the RoHS directive.

Full details of the compliance requirements can be found at the UK Government website:
www.gov.uk/guidance/rohs-compliance-and-guidance

Further information on RoHS can be found at:
eur-lex.europa.eu/summary/EN/uriserv:2004_4

GDPR

For any UK or European organisation compliance with GDPR has been mandatory from 25 May 2018. For those shipping connected product at the very least, the following areas of an IoT product need to be considered and assessed for compliance:

- What is the context of the data of the IoT product?
- Any data sharing is covered by EULA licensing agreements and is compliant with the legislation
- Is there a need to anonymise any of the product's data?
- Has the life cycle of the data been considered?
- Is any product data that could fall under the legislation suitably secured throughout the product's ecosystem?
- Does the "cloud" element of the service offering have suitable security and data life cycle management?
- Given the complexity of the regulations and their implications, it is recommended that organisations seek appropriate advice to ensure their IoT offering is GDPR compliant

SECTOR-SPECIFIC REGULATIONS

Whilst scoping the regulatory requirements for the common standards such as CE, RED and FCC, it is important to evaluate if there are other market sector specific regulations that need to be complied with. Some example markets where such regulation exists are as follows:

- Medical products
- Products for use on railways
- Automotive
- Products for deployment in the petrochemical industry
- Civil aviation
- Toys
- Robotics

In such markets it may be possible to carry out small scale trials ahead of full certification. It may be necessary to carry out pre-compliance testing and FMEA analysis for a risk assessment for trial deployment.

SECTION SIX

Safety, security and quality

BATTERY SAFETY AND REGULATIONS

> It is important to be aware of the implications of including a lithium battery chemistry in an IoT product from a safety perspective, not just the certification of the battery but also the transportation implications of the lithium batteries themselves and the products that use them.

This is because both primary and secondary lithium batteries come under the international Dangerous Goods Regulations, which cover both domestic and international transportation. These regulations, depending upon the battery capacity, can mandate a variety of shipping restrictions, from the number of devices that can be shipped in a consignment, how the product is packed and what labelling has to be applied to the shipping carton(s). Another consideration is that if the battery pack is a custom one that needs certification, then any pre-certification samples need special handling, in some cases within specialist metal packaging, under the Dangerous Goods Regulations. All of which add to the logistical activities of bringing such a lithium battery powered product to market.

Sources of reading for a better overview of the regulations surrounding the transportation of lithium batteries and products that contain them can be found at:

- www.dhl.co.uk/content/dam/downloads/g0/express/shipping/lithium_batteries/lithium_ion_batteries_regulations.pdf
- www.dhl.co.uk/en/express/shipping/shipping_advice/lithium_batteries.html
- www.fedex.com/gb/learn/lithium-batteries.html
- www.tnt.com/dam/tnt_express_media/de_ch/download_documents/HELPCENTER_downloads/2017-ROAD_and_SEA_Transport_of_SP188_Lithium_Batteries-December%202016_1.pdf

> Any product that incorporates batteries must meet the battery safety requirements.

As a result, it is essential when selecting battery cells or packs to ensure that the vendor has all the relevant certifications for them. Otherwise there is the possibility that additional battery testing may be required and that it may not be possible to import the batteries until the testing has been carried out and the certifications have been issued. In some cases this additional testing and certification may involve a supply chain delay of three to four months and further expense, before the certified parts are available for production. In the case of pre certified lithium batteries, engineering samples may be used in development prototypes but will require special shipping and handling arrangements – carriers will not accept uncertified batteries or products which contain them, without suitable special containers and Dangerous Goods documentation.

Given the critical nature of battery safety certification, rather than making recommendations on what is a very broad subject, the choice of battery and supplier should be assessed by someone with the relevant expertise to ensure the product's battery is appropriately certified.

SECURITY

> The technology press regularly covers the hacking and insecurity of IoT devices and services.

There is significant activity in bringing forward compliance regimes for IoT security, particularly in the wider context of the recent cyber security regulations such as the EU Cybersecurity Act (reference 1), which was approved by the European Parliament in March 2019. In the UK, the Department for Digital, Culture, Media & Sport (DCMS) has developed the Code of Practice for Consumer IoT Security (reference 2), which was released in October 2018. The DCMS code of practice was then rapidly, in standards terms at least, evolved into the ETSI technical standard TS 103 645 (reference 3), which was released in January 2019. There are also discussions taking place around the possibility of security requirements being included in the scope of the Radio Equipment Directive under the directive's existing delegated clauses 3.3 (e) Safeguards personal data and privacy and (f) Protection from fraud.

Further afield in the USA NIST have a Cybersecurity for IoT Program, which is actively investigating the state of standardisation on cybersecurity for IoT. At state level, California has already passed legislation, "SB-327 Information privacy: connected devices" (reference 4), that prohibits the use of default passwords from 1 January 2020.

There have already been cases of IoT products being withdrawn from sale or even use. One major example was the child's doll Cayla. Cayla was designated a spying device by the Bundesnetzagentur, the German telecommunication watchdog. The watchdog banned all further sales of the dolls in Germany and warned parents that possession of the toys is illegal, as an unlicensed radio device.

With all this focus on IoT security on a global scale and the concerns around cybersecurity, IoT product designers and manufacturers should assume that regulation in some form or another will affect products being designed now. In particular the choice of hardware platform upon which to base an IoT product from a security perspective is crucial to ensuring that the product is able to be made compliant with future regulation. Making an IoT product secure requires a suitable hardware root of trust, since there is no such thing as a solely software based security system. Fortunately there are a number of emerging cross-vendor industry initiatives to create secure software systems based upon secure roots of trust, such as ARM's Platform Security Architecture (PSA) (reference 5), Microsoft's Azure Sphere and others.

Without consideration of the security requirements, in particular secure roots of trust, IoT products being designed and launched now run the risk of having their lifecycles cut short through future security non-compliance. In the event of a premature product recall or end of life, there is the additional risk of the consequent loss of brand image that goes with the end user having to replace or use alternative devices.

This is an extensive topic but for a starting point on the best practices and requirements for IoT products and services, the Internet of Things Security Foundation provides a free of charge Compliance Framework, Vulnerability Disclosure Guidelines and Best Practice Guides, which can be found at:
https://www.iotsecurityfoundation org/best-practice-guidelines/

For a useful perspective on the technical requirements for secure IoT devices, which will stand the test of time, Microsoft Research have published their whitepaper entitled "The Seven Properties of Highly Secure Devices" which provides (reference 6).

(1) EU Cybersecurity Act, March 2019
https://www.europarl.europa.eu/doceo/document TA-8-2019-0151_EN.html?redirect#BKMD-20

(2) UK Government Department for Culture Media and Sport Code of Practice for Consumer IoT Security, October 2018
https://www.gov.uk/government/publications/code-of-practice-for-consumer-iot-security

(3) ETSI Technical Standard TS 103 645, January 2019
https://www.etsi.org/deliver/etsi_ts/103600_103699/103645/01.01.01_60/ts_103645v010101p.pdf

(4) California legislature SB-327 Information privacy: connected devices.
https://leginfo.legislature.ca.gov/faces/billTextClient.xhtml?bill_id=201720180SB327

(5) ARM PSA https://www.arm.com/why-arm/architecture/platform-security-architecture

(6) Galen Hunt, George Letey, and Edmund B. Nightingale, The Seven Properties of Highly Secure Devices https://aka.ms/7properties

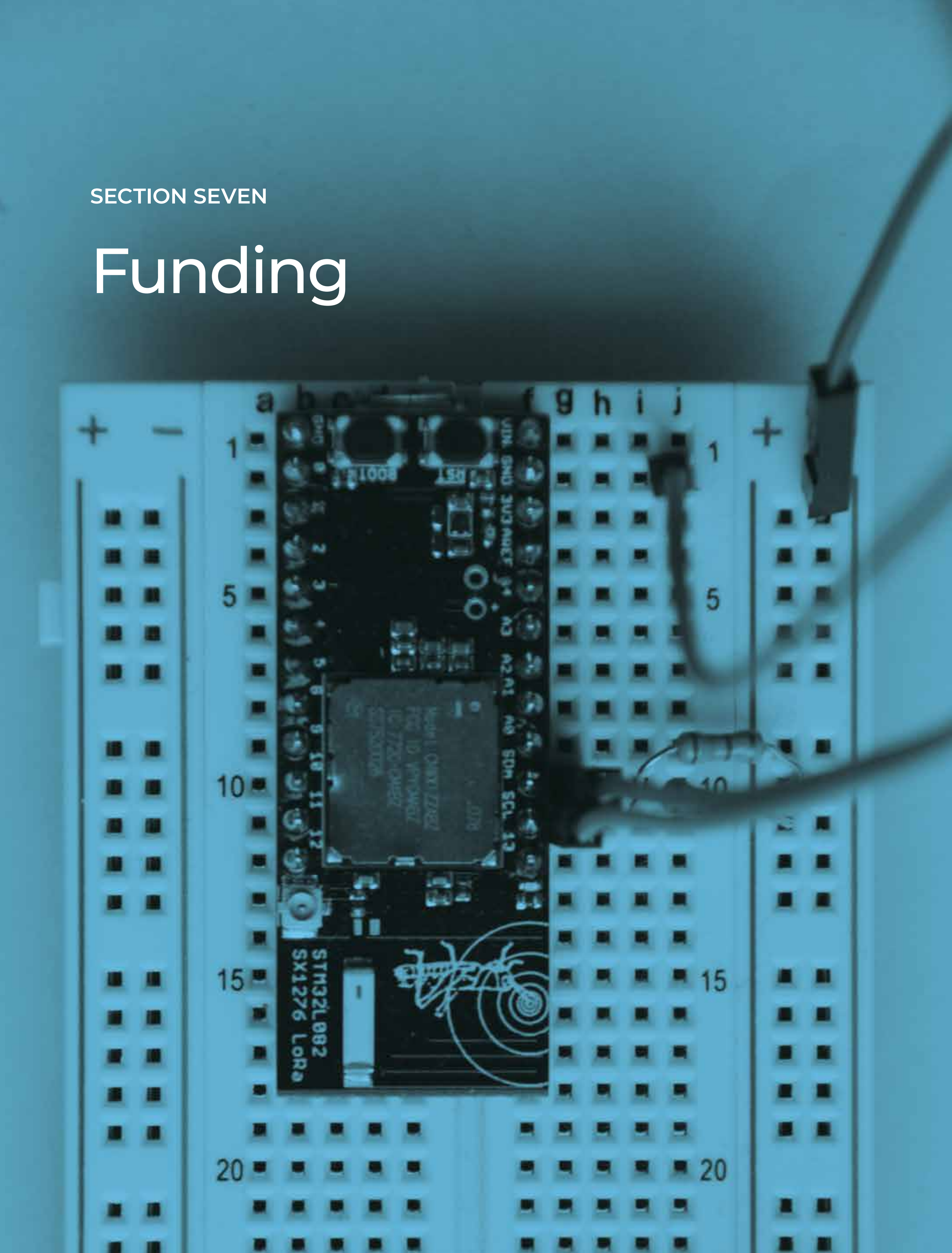
QUALITY MANAGEMENT APPROACHES

As part of the engagement with the EMS partner, the EMS partner will want to know what level of quality management is required for the product's manufacture. EMS providers will have systems to handle normal commercial quality levels, but certain markets may require higher quality management levels and traceability, such as those for medical, aviation or automotive sectors.

As part of the EMS agreement the quality level should be stated, in particular the average quality level, unit sampling frequency and any cosmetic inspection requirements.

SECTION SEVEN

Funding



INVESTMENT AND CASH FLOW

One of the major things that differentiates hardware product development from purely software products is the required level and timing of investment in materials and NPI activities. Whilst it can be relatively inexpensive to create a hardware proof of concept or prototype, a much higher level of investment is subsequently required to take that prototype to production. There is often a 'hockey stick' profile to NPI cash flow.

Taking a notional battery-powered IoT product with a wireless interface and some sensors, an outline development plan and rough order of magnitude (ROM) budget for hardware builds and compliance testing is shown in Table 3 and Figure 4. (Note that design labour costs are not included given the wide range of hardware, firmware and software engineering time that may be necessary.) From this ROM cash flow, it can be easily seen that UK Seed Enterprise Investment Scheme (SEIS) funding of £150k is insufficient to take a typical wireless hardware product into production; additional investment is necessary.

The numbers shown in Table 3 and Figure 4 are based upon the following assumptions:

- Hardware, firmware and software development labour costs are not included. In a startup these may be provided through a variety of engagement models ranging from founders providing their time in return for equity, to the use of paid consultants for various areas of the design
- The notional product assumes a single wireless interface with some sensors, all powered by a lithium battery
- The costings for the initial DVT and PVT production trials are based on a low-volume BOM cost of £150
- The costings are based on a product with a three-part injection moulded case
- The product will be shipped into Europe and the USA, thereby requiring pre-compliance and full regulatory testing for CE and FCC regulations
- Proof of concepts can be based on off-the-shelf evaluation or development kits

FINANCIAL RISKS

It is important that a startup seeking funding can demonstrate that it understands some of the key risks in taking a hardware product to market. In particular, early stage investors will want to see early demonstration of 'customer fit' typically with customer feedback from proof of concepts or prototypes. The major technical risks of taking a hardware product to market are as follows:

- Lack of experience. Hardware product development is a complex, expensive and time-consuming business. Few projects ever go exactly to plan even for the large brand name technology companies
- Requirements creep. This is a real challenge for most startups and it is important that before a requirement or feature is added that it has the associated business case and the production cost has been estimated. This can often be a major factor in not getting a product launched on time and burning through cash more quickly than planned
- Over commitment. This has been seen a number of times on Kickstarter. Don't make hard delivery commitments until the product development and validation are complete and the early production trials are showing high yield
- Insufficient design validation and quality testing. This can result in poor quality products being shipped to customers or require a product recall of early units. The latter issue is always a concern for major brands but has the potential to sound a death knell for a startup
- Misjudging the sheer complexity of moving to production is a common issue. Lack of experience means that production bring-up takes a significant amount of time and significant effort from the development team, perhaps in a foreign country with associated time zone and language barriers along with travel costs
- Understanding and managing cash flow. This is a combination of managing the costs associated with product development against investment and income. Where a product is sold directly to the end customer, for example online, then payment is typically received within a day or two of the sale

However, where the product is supplied through a retail or B2B channel, the product may not be paid for until 30 to 90 days after shipment. What also needs to be factored in is what the payment terms to the EMS partner are. They will typically need to receive payment before the customer has paid for the product. This can represent hundreds of thousands or even millions of pounds of working capital, depending upon the product COGS and volume forecast. Customers often take much longer to place volume orders than expected, where the deployment of the product has an impact on the operational procedures and processes of the customer, all of which extend the time delay to mass orders

- Underestimating manufacturing cost. The bill of materials is sometimes used as the basis of the cost of goods without factoring in the actual manufacturing, testing and warranty costs, which may be substantial
- Ensuring the full scope of regulatory compliance. Finding out that, for example, a wireless module does not have all the supporting regulatory collateral or that a lithium battery is not fully certified can impact both the NPI schedule and also the budget. In the case of having to certify a lithium battery, this can mean a delay of two to three months

Example of startup hardware ROM material and testing costs

Cost category	Costs to Gate 2 (£)	Costs to Gate 3 (£)	Costs to Gate 5 (£)
Initial market assessments	3,000	0	0
Proof of concept hardware assembly	2,000	0	0
Development setup costs (test equipment etc.)	3,000	6,000	0
EVT Spin 1 PCB materials costs	0	6,000	0
EVT Spin 2 PCB materials pre-pilot costs	0	15,000	0
EVT mechanical parts	0	2,000	0
DVT and PVT materials costs	0	0	170,000
Mechanical tooling costs	0	2,000	30,000
Pre-compliance and antenna testing	0	5,000	5,000
Compliance, safety and environmental testing	0	0	50,000
Production tooling (including an allowance for production test equipment)	0	0	55,000
PCB, RF, regulatory and test system design support costs	0	4,000	25,000
Travel costs to production partner	0	2,000	15,000
Sub total	8,000	42,000	350,000
Total			400,000

Table 3

A worked example of an IoT product timeline and ROM budget

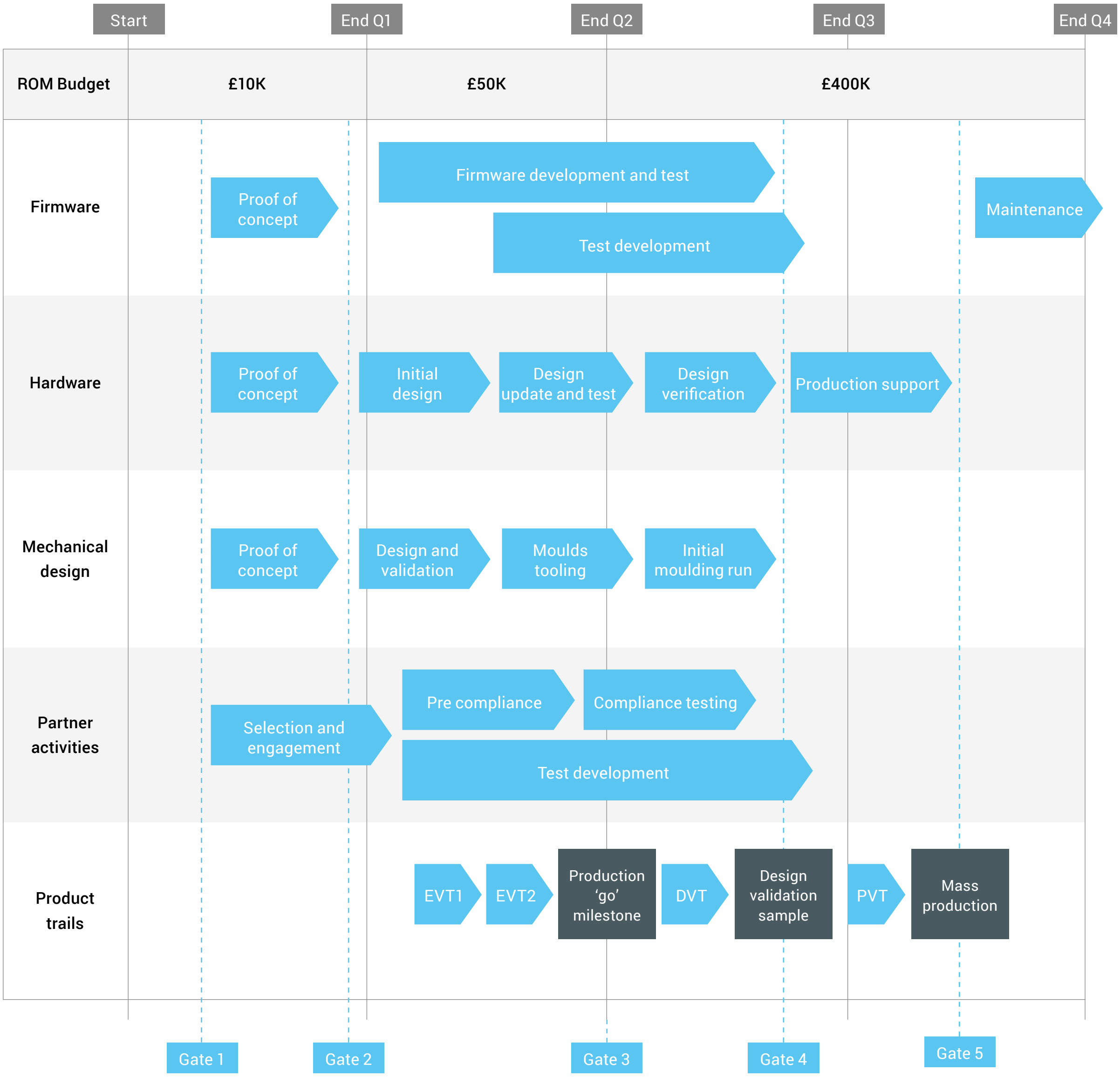
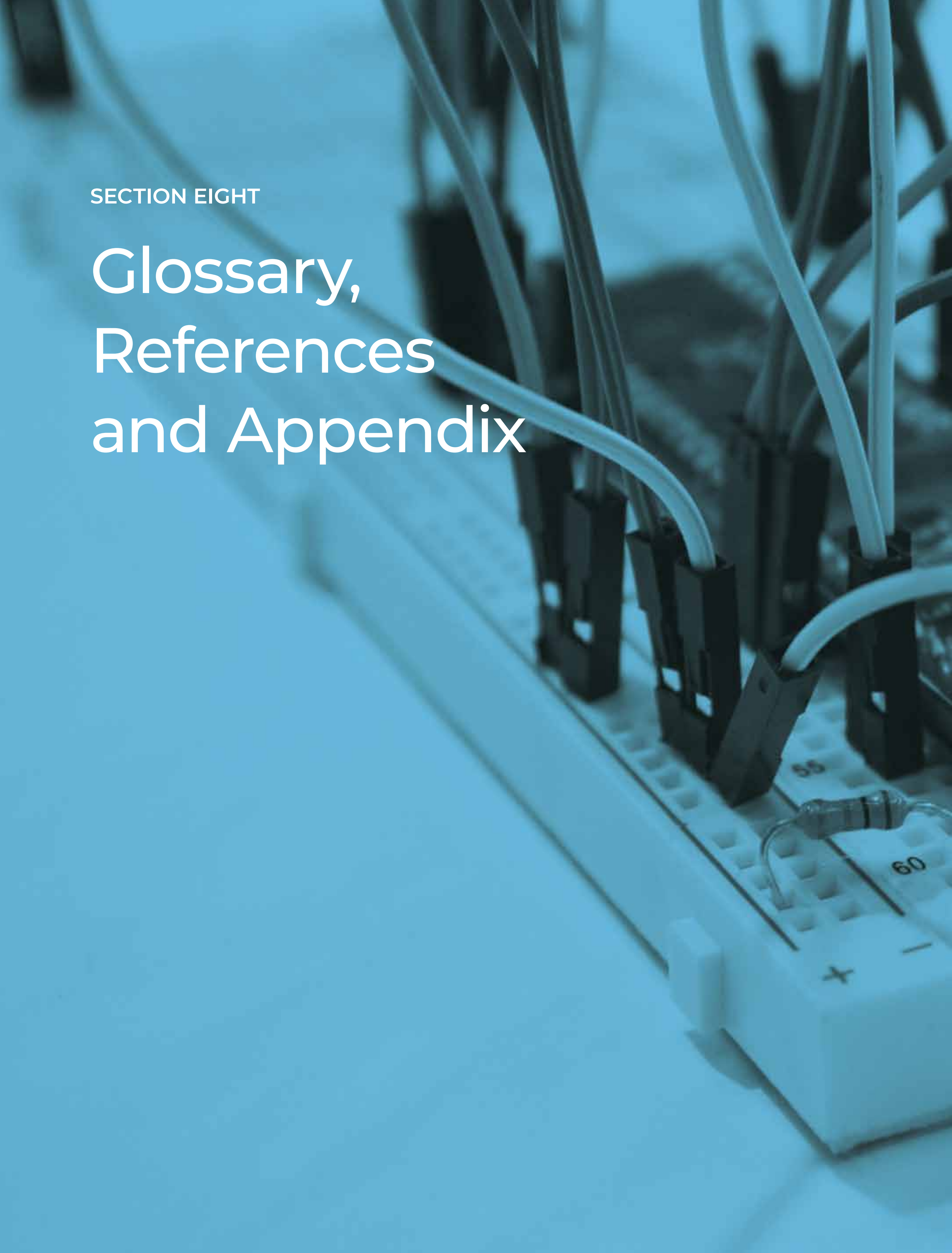


Figure 3

SECTION EIGHT

Glossary, References and Appendix



GLOSSARY

For the purposes of this document, the following abbreviations apply:

AVL	Approved vendor list
BOM	Bill of materials
CAD	Computer aided design
CAM	Computer aided manufacturing
CAR	Corrective action request
CDVA	Cost down value add
CE	Conformité européenne (European conformity)
CEM	Contract electronic manufacturer
CM	Contract manufacturer
COGS	Cost of goods sold
CPLD	Complex programmable logic device
DDR	Double data rate
DFA	Design for assembly
DFM	Design for manufacture
DFT	Design for test
DUT	Device under test
DVT	Design verification test/trial
ECO	Engineering change order
EEPROM	Electrically erasable programmable read only memory
EMC	Electromagnetic compatibility
EMS	Electronics manufacturing service
EOL	End of life
eSIM	Embedded subscriber identity module
EU	European Union
EULA	End user licence agreement
EUT	Equipment under test
EVT	Evaluation verification test/engineering verification trial production run
FCC	The US Federal Communications Commission
FPGA	Field programmable gate array
FT	Final test
FTY	First time yield
FMEA	Failure modes and effects analysis
GDPR	General data protection regulation
GM	Gross margin
GUI	Graphical user interface
HASS	Highly accelerated stress screening
HALT	Highly accelerated life testing
HLOS	High level operating system
IDH	Independent design house
IoT	Internet of things
IQC	Incoming quality control
ISM	Industrial, scientific and medical
JDM	Joint design manufacturer
JTAG	Joint test action group
LPWAN	Low power wide-area network
LTB	Last time buy
LTE	Long-term evolution, a cellular radio protocol generation
MAC	Medium access control
MP	Mass production
NBIoT	Narrow band IoT, a low bandwidth cellular protocol for IoT
NPP	New product planning
NPI	New product introduction
NRE	Non-recurring expenses
ODB++	Open data base (with component descriptions)
ODM	Original design manufacturer
OEM	Original equipment manufacturer
PCB	Printed circuit board
PLM	Product life cycle management
PVT	Production verification test/process verification trial, also known as the pilot run
QA	Quality assurance
RAM	Random access memory
RED	Radio equipment directive
REACH	Regulation for registration, evaluation, authorisation and restriction of chemicals
RF	Radio frequency
RFI	Request for information
RFQ	Request for quotation
RMA	Return materials authorisation
ROHS	Restriction of hazardous substances directive
ROM	Rough order of magnitude / read only memory
RTOS	Real time operating system
SATA	Serial advanced technology attachment
SEIS	Seed enterprise investment scheme
SIM	Subscriber identity module
SKU	Stock keeping unit (for example. product part number or order code)
SME	Small to medium enterprise/ subject matter expert
SMT	Surface mount technology
SWAG	Scientific wild ass guess
TBC	To be confirmed
TBD	To be determined
TH	Through-hole technology
UI	User interface
UL	A company previously known as Underwriters Laboratories (now just 'UL'), with expertise in product safety and testing
USB	Universal serial bus
WEEE	Waste electrical and electronic equipment directive
WIP	Work in progress

REFERENCES AND FURTHER READING

The following books and articles provide useful additional reading.

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(2) Elaine Chen, Bringing a Hardware Product to Market: Navigating the Wild Ride from Concept to Mass Production, CreateSpace Independent Publishing, 2015. Available as a free PDF.

(3) Elaine Chen, Hardware Product Development Process, Concept Spring blog, 2014.

(4) Alan Cohen, Prototype to Product: A Practical Guide for Getting to Market, O'Reilly Media, 2015.

(5) D-Terra Solutions LLC, Product Innovation: Why a stage-gate process is critical to new product development.

(6) Digital Catapult, "Partner Selection for IoT Product Manufacture" 2018.

(7) Ben Einstein, The Illustrated Guide to Product Development – Part 1, Ideation, Bolt, October 2015.

(8) Ben Einstein, The Illustrated Guide to Product Development – Part 2, Design, Bolt, October 2015.

(9) Ben Einstein, The Illustrated Guide to Product Development – Part 3, Engineering, Bolt, October 2015.

(10) Ben Einstein, The Illustrated Guide to Product Development – Part 4, Validation, Bolt, October 2015.

(11) Renee DiResta, Brady Forrest and Ryan Vinyard, The Hardware Startup: Building Your Product, Business, and Brand, O'Reilly Media, 2015.

(12) Andrew "Bunnie" Huang, The Hardware Hacker: Adventures in Making and Breaking Hardware, No Starch Press, 2017.

(13) Haje Jan Kamps, Apple is an exception to nearly every rule - The world's most valuable company isn't the best example for how you should build your startup, TechCrunch, March 2018.

(14) Kickstarter Campus, What has everyone discovered going through testing and certifications of their product? (FCC CE), December 2016.

(15) ODB++ Solutions Alliance, ODB++ Solutions Alliance Fact Sheet.

(16) Alexander Osterwalder and Yves Pigneur, Business Model Generation: A Handbook for Visionaries, Game Changers, and Challengers, ISBN-13: 978-0470876411.

(17) Cypress Semiconductor - Accelerate product development with Bluetooth® low energy modules

(18) Blue Radios - Bluetooth 4.0 Low Energy Single and Dual Mode Intelligent Modules

(19) ST - Wireless connectivity for IoT applications

(20) BLE Central Blog - SoC and Modules for Bluetooth Low Energy (BLE)

(21) RF Modules – Pre-certified vs. Non-Certified and How to Design Your Own

ANNEX – SAMPLE CHECKLISTS

The following checklists are provided to give a starting point for the criteria to be evaluated for each gate assessment.

GATE 1				
	Checklist item	Applicable	Yes/No	Comment
G1.1	Has an outline business case been prepared?		Y/N	
G1.2	Does the product fit into the organisation's product strategy?		Y/N	
G1.3	Has the market opportunity been identified?		Y/N	
G1.4	Are the customer use cases and their consequent requirements clearly understood?		Y/N	
G1.5	Has a feature set been clearly identified?		Y/N	
G1.6	Pricing - has a sale price target been identified, end user and/or wholesale?		Y/N	
G1.7	Technical feasibility, is the product technically feasible: for example can the form factor provide sufficient space for the battery size required to support the intended service life between recharges?		Y/N	
G1.8	Is there a way of creating a proof of concept requiring minimal development that allows demonstration of technical feasibility and to support customer trials to qualify 'customer fit'?		Y/N	
G1.9	Are there key milestones that need to be met to achieve the planned launch date?		Y/N	
G1.10	Are customer trials likely to be required before the receipt of customer volume orders and acceptance?		Y/N	
G1.11	Will the product being launched have any dependencies on other products or services, for example network coverage?		Y/N	
G1.12	Have outline estimates been prepared for the development of the product's features and requirements?		Y/N	
G1.13	Are there sufficient resources available for the development of the product, its features and requirements?		Y/N	
G1.14	Is there sufficient funding available and where will the funding come from, the customer as NRE, or some other route?		Y/N	

GATE 2				
	Checklist item	Applicable	Yes/No	Comment
G2.1	Have the features been described and reviewed with potential customers?		Y/N	
G2.2	Has the product been confirmed to be technically feasible?		Y/N	
G2.3	The architecture has been completed and meets the requirements for performance, security, regulatory compliance, serviceability, reliability and quality.		Y/N	
G2.4	What is the product manufactured cost budget to meet the sales price target with appropriate gross margin?		Y/N	
G2.5	More detailed development plans have been prepared identifying when the main hardware trial production runs are to be scheduled and the effort required to meet the trial production run dates.		Y/N	
G2.6	Are there sufficient resources available for the development of the product, its features and requirements?		Y/N	
G2.7	A project budget has been created and sufficient working capital or investment is available to meet the key milestones.		Y/N	
G2.8	Analysis has been done to ensure production forecast aligns with customer demand, this analysis should be repeated regularly from this gate onwards.		Y/N	
G2.9	The product's intended markets have been fully defined. (Important for identifying suitable manufacturing locations and that all the regional regulatory requirements have been identified.)		Y/N	
G2.10	Are there any elements of the product for which 'make or buy' decisions are required?		Y/N	
G2.11	Does the product require any specialist development such as antenna design?		Y/N	
G2.12	Does the product require support resources to be in place for early trials and/or at product launch?		Y/N	

GATE 3				
	Checklist item	Applicable	Yes/No	Comment
G3.1	Have necessary regulatory compliance approvals testing been completed?		Y/N	
G3.2	Are the draft user manual(s) available?		Y/N	
G3.3	Are the draft support documents available for example branding, RMA processes, accessories and spares listings?		Y/N	
G3.4	Costs: is the manufactured cost meeting the sales price target with intended gross margin?		Y/N	
G3.5	Design maturity: has the design verification tests on the last EVT build units have been completed and the results logged?		Y/N	
G3.6	Design maturity: have the design for manufacture (DFM) reviews have been completed?		Y/N	
G3.7	Design maturity: have the mechanical tooling drawings been released for toolmaking?		Y/N	
G3.8	Design maturity: the last EVT trial product has had preliminary environmental testing carried out to ensure it meets the specifications over the intended environmental operating range?		Y/N	
G3.9	Manufacturing: the production test plan has been created, to include: — Production test firmware requirements? — The test strategy is defined and the intended equipment identified to support such tests? — Outline line production test flow to include the test time targets for each test phase? — Test fixtures specified and a manufacturer identified?		Y/N	
G3.10	Deployment: are the wireless service and coverage available for customer trials and are the products available for their intended markets?		Y/N	
G3.11	Regulatory: has the regulatory pre-compliance testing been completed?		Y/N	
G3.12	Quality: have the quality requirements been documented?		Y/N	

GATE 4				
	Checklist item	Applicable	Yes/No	Comment
G4.1	Costs: are the manufactured costs meeting the sales price target with intended gross margin?		Y/N	
G4.2	Design maturity: have the design verification tests on the DVT build units been completed and the results logged?		Y/N	
G4.3	Design maturity: have the DFT reviews' recommendations been applied to the design?		Y/N	
G4.4	Design maturity: have the PCB DFM reviews' recommendations been applied to the design?		Y/N	
G4.5	Design maturity: have the mechanical tooling drawings released for toolmaking?		Y/N	
G4.6	Design maturity: the DVT samples have been environmentally tested, for example: temperature, humidity, drop testing, flammability, to ensure it meets the specifications over the intended environmental operating range?		Y/N	
G4.7	Manufacturing: the following have been released to the production partner(s): — Full bills of materials — Approved vendor list — PCB fabrication data and drawings, including panelisation details		Y/N	
G4.8	Production test: — Is production test firmware available? — Is test equipment available for DVT and PVT production trials? — Is line production test flow approved by manufacturing partner? — Do production test cycle times meet the test time targets for each test phase? — Are test fixtures are available for DVT and PVT production trials? — Are the test steps are meeting the budgeted cycle times?		Y/N	
G4.9	Manufacturing: — Are materials available for PVT production start? — Is mechanical tooling available? — Have sample product case parts of production tooling been approved?		Y/N	
G4.10	Deployment: are the cellular or low power wireless service and coverage available for customer trials for the products intended markets?		Y/N	
G4.11	Deployment: if cellular service is to be used, that the service availability has been tested for the product, for example ensuring that the SIM profiles work and roam correctly in the intended markets. This is especially important with products that use embedded SIMs.		Y/N	
G4.12	Regulatory: have the pre-production samples passed all the required pre-compliance regulatory testing?		Y/N	
G4.13	Sales and marketing: is competitive messaging available?		Y/N	
G4.14	Sales and marketing: is market collateral available?		Y/N	
G4.15	Sales and marketing: is the sales forecast in line with production?		Y/N	

GATE 5				
	Checklist item	Applicable	Yes/No	Comment
G5.1	Costs: is the manufactured cost meeting the sales price target with intended gross margin?		Y/N	
G5.2	Design maturity: have the design verification tests on the PVT build been completed and the results logged?		Y/N	
G5.3	Design maturity: have the DFT test reviews been completed and the recommendations been applied to the design?		Y/N	
G5.4	Design maturity: have the PCB design for manufacture reviews been completed and the recommendations been applied to the design?		Y/N	
G5.5	Design maturity: have the mechanical tooling drawings been released for toolmaking?		Y/N	
G5.6	Design maturity: has the PVT product been environmentally tested or assessed for example, temperature, humidity, drop testing, flammability etc., to ensure it meets the specifications over the intended environmental operating range and are the reports available?		Y/N	
G5.7	Manufacturing: the following have been released to the production partner(s): — Full bills of materials — Approved vendor list — PCB fabrication data and drawings, including panelisation details		Y/N	
G5.8	Manufacturing: are materials available for mass production start?		Y/N	
G5.9	Production test: — Is final production test firmware available? — Is test equipment available for mass production? — Do production test cycle times meet the test time targets for each test phase? — Are all the production test assets to fulfil mass production line velocity available? — Are the test steps meeting the budgeted cycle times?		Y/N	
G5.10	Deployment: are the wireless service and coverage available for launch for all the products intended markets?		Y/N	
G5.11	Deployment: has all the service availability and roaming testing been completed in the intended markets?		Y/N	
G5.12	Regulatory: have the PVT production samples passed all the required regulatory and approvals processes, with certificates being issued where necessary?		Y/N	
G5.13	Sales and marketing: is sales support material available: — Advertising — Whitepapers — Application notes — Training material		Y/N	
G5.14	Sales and marketing: is the sales forecast in line with mass production?		Y/N	
G5.15	Sales and marketing: has the final price book been finalised?		Y/N	
G5.16	Sales and marketing: are the sales channels ready?		Y/N	

WITH THANKS TO OUR PARTNERS

Xitex Ltd provides consultancy services to scale up and startup businesses in the internet of things technology sector. Xitex specialise in supporting the design, manufacture, regulatory compliance and security of IoT connected devices and other electronic products for our customers.

Xitex engineering services range from product, systems, security and antenna design, to supporting the key activities necessary for going to mass production: CE/FCC regulatory compliance; design for manufacture and test (DFM/DFT) reviews; design validation; production test development; new product introduction into manufacturing partners.

The teams' expertise comes from working within startups and multi-national companies, dealing with manufacturers and their processes at all levels from prototype through to mass production. Xitex has worked with manufacturing partners in the UK, Europe and in the Far East.

More details can be found at **xitex.co.uk**

For more information contact us at: sales@xitex.co.uk

Microsoft (Nasdaq "MSFT" @microsoft) enables digital transformation for the era of an intelligent cloud and an intelligent edge. Its mission is to empower every person and every organisation on the planet to achieve more.

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Arrow Electronics guides innovation forward for over 200,000 leading technology manufacturers and service providers. With 2018 sales of $30 billion, Arrow develops technology solutions that improve business and daily life.

A Fortune 500 company and global provider of products, services, and solutions, Arrow aggregates electronic components and enterprise computing solutions for customers and suppliers in industrial and commercial markets.

Arrow shows innovators how they can get their prototypes created and manufactured, enabling growth through IoT connectivity and lifecycle solutions, for example, and reach a mass market.

To support business growth of large enterprises and startups, Arrow offers a range of engineering and supply chain services covering design tools, proof-of-concept review, rapid prototyping, turnkey solution design service, embedded software, cloud software integration, edge computing, sensing technology, advanced connectivity network, power management, data analytics and production, among others.

In 2016, Arrow and Indiegogo, the global platform for entrepreneurs to bring their ideas from concept to market, launched a groundbreaking crowdfund-to-production service, which is aimed at accelerating the pace of innovation for technology and internet of things (IoT) entrepreneurs. Entrepreneurs can apply for Arrow certification on the Indiegogo platform. Arrow Electronics' engineers will then analyse the design and manufacturability of each application.

In 2019, Arrow and Freelancer.com launched ArrowPlus powered by Freelancer. The new platform allows Fortune 500 companies and innovative technology creators to design and build hardware products through access to over half a million skilled electronic and electrical engineers. Arrow brings to the collaboration a large volume of high-quality, high-value projects, from established companies with a real demand for innovation and talent. Businesses that need technology help from concept to scale can leverage ArrowPlus powered by Freelancer to find highly qualified experts, utilize Arrow technology concierge services that ensure project success, and go to market faster and more cost effectively.

Learn more at **fiveyearsout.com**

Arrow's online tools: **arrow.com/en/uk**

SONY

UK Technology Centre

Sony UK Technology Centre is the global brand's only manufacturing facility in Europe, and it is based in Pencoed, South Wales. At the core of the business lies the production of the latest high-end broadcast equipment the brand has to offer, including the industry-leading 4K technology for distribution globally.

The facility offers its services to established businesses, as well as startups and scaleups, and has a track record of successful collaborations, including the manufacture of the UK's best-selling computer, the Raspberry Pi.

Thanks to the centre's unique value proposition, Sony UK TEC's expert team can take your product at any stage of its development and guide you, the creator, through the full process outlined in this paper - from prototype to production.

Collaborating with Sony UK TEC gives access to expert advice at each step of the product journey, from concept, prototype, production and after sales stages.

In the early stages of product development, the facility offers design support, including design for manufacturing (DFM) and design for test (DFT). In addition, they can assist with finalising the PCB layout and the process of selecting the components and suppliers best suited for your product.

At prototype stage you can get access to the vast Sony network of organisations and solution provides, as well as the UK TEC inhouse expertise, such as rapid tooling, 3D printing, fast turnaround, electromagnetic compatibility (EMC) testing, safety testing, drop and vibration, packaging solutions, and compliance advice and support.

At mass production stage, the Sony team will provide total quality management, complete traceability, continuous improvement and innovation, and dedicated customer service and support.

Finally, UK TEC's offering includes aftersales care solutions, including access to the in-house customer technical support call centre, the repairs and service centre, and returns management authorisation.

The Sony UK TEC team understand the challenges that startups and scaleups often face including accuracy of planning, shortage of funding at key stages in development, selection of components or simply the choice of a manufacturing partner to name a few.

The team's unique offering has enabled them to build a bespoke solutions service that can be tailored to your specific business needs.

At Sony UK TEC communication and collaboration are crucial to success, so the team always strives to connect with customers and fully understand the goals and aspirations to ensure they can offer the best advice for any business.

To get in touch visit
www.sonypencoed.co.uk/manufacturing
or email the team at uktec.enquiries@sony.com

CATAPULT Digital

Digital Catapult is the UK's leading advanced digital technology innovation centre, driving early adoption of technologies to make UK businesses more competitive and productive to grow the country's economy.

We connect large established companies, startup and scaleup businesses and researchers to discover new ways to solve big challenges in the manufacturing and creative industries. Through this collaboration businesses are supported to develop the right technologies to solve problems, increase productivity and open up new markets faster.

Digital Catapult provides physical and digital facilities for experimentation and testing that would otherwise not be accessible for smaller companies.

As well as breaking down barriers to technology adoption for startups and scaleup, our work de-risks innovation for large enterprises and uncovers new commercial applications in immersive, future networks, and artificial intelligence technologies.

For more info please visit **www.digicatapult.org.uk**

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