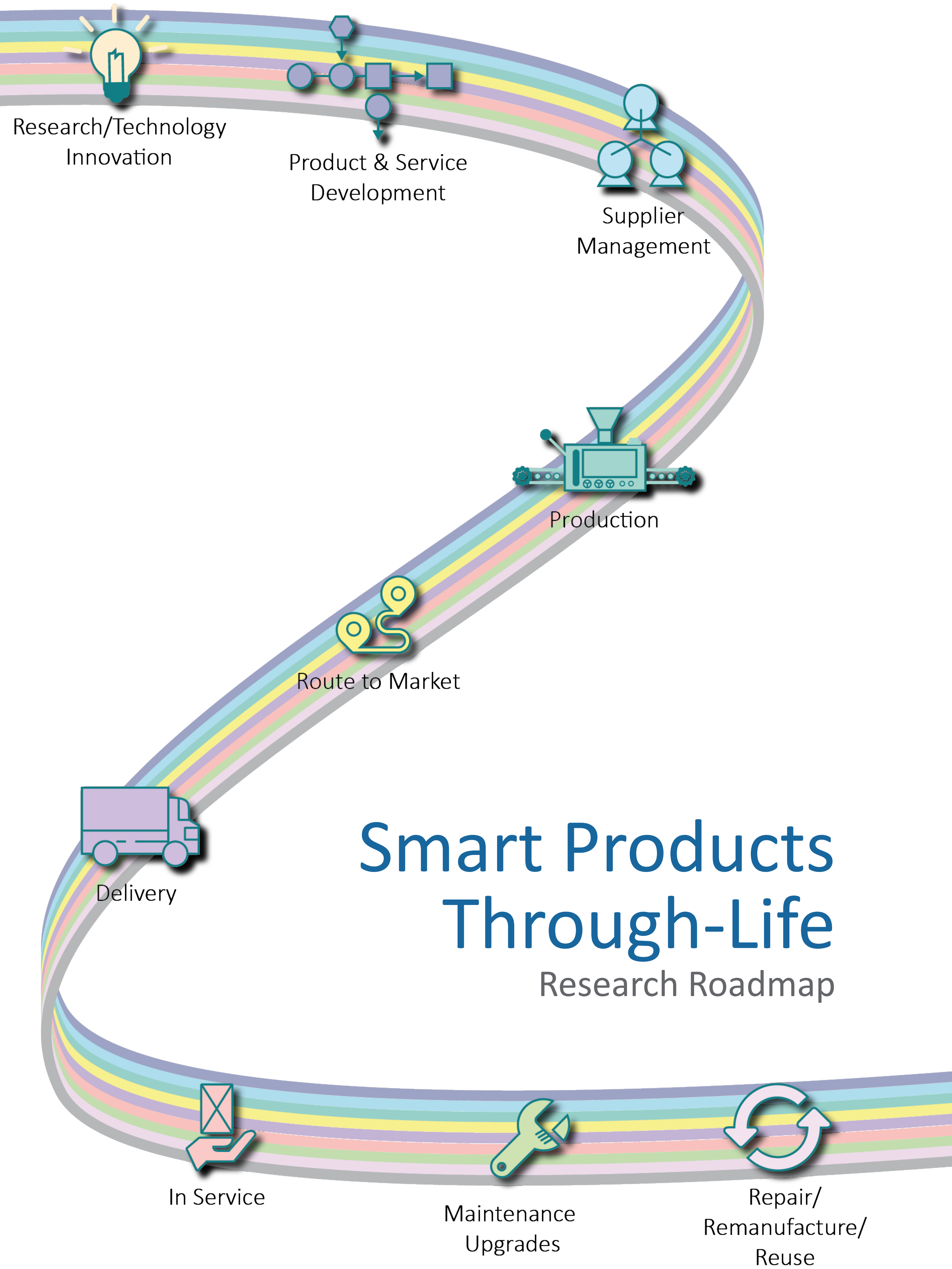
Smart Products Through-Life

Research Roadmap



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THIS REPORT IS INTENDED FOR:
Professionals and researchers interested in design, manufacturing, remanufacturing, cyber physical system and internet of things, policy makers, and legislators.

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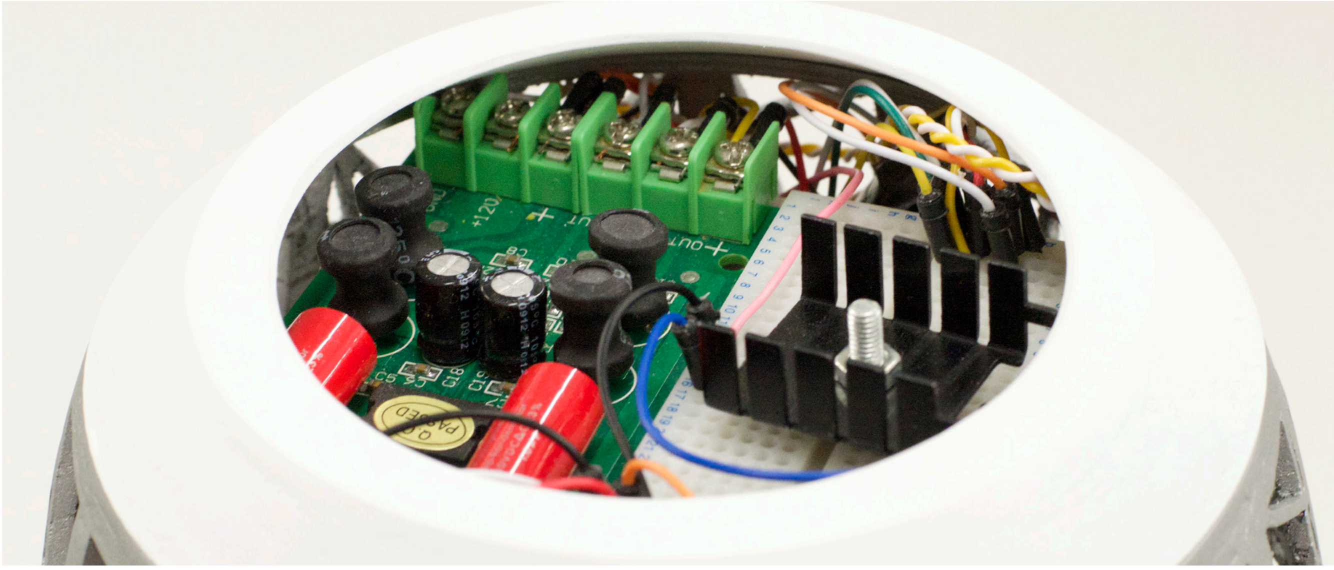
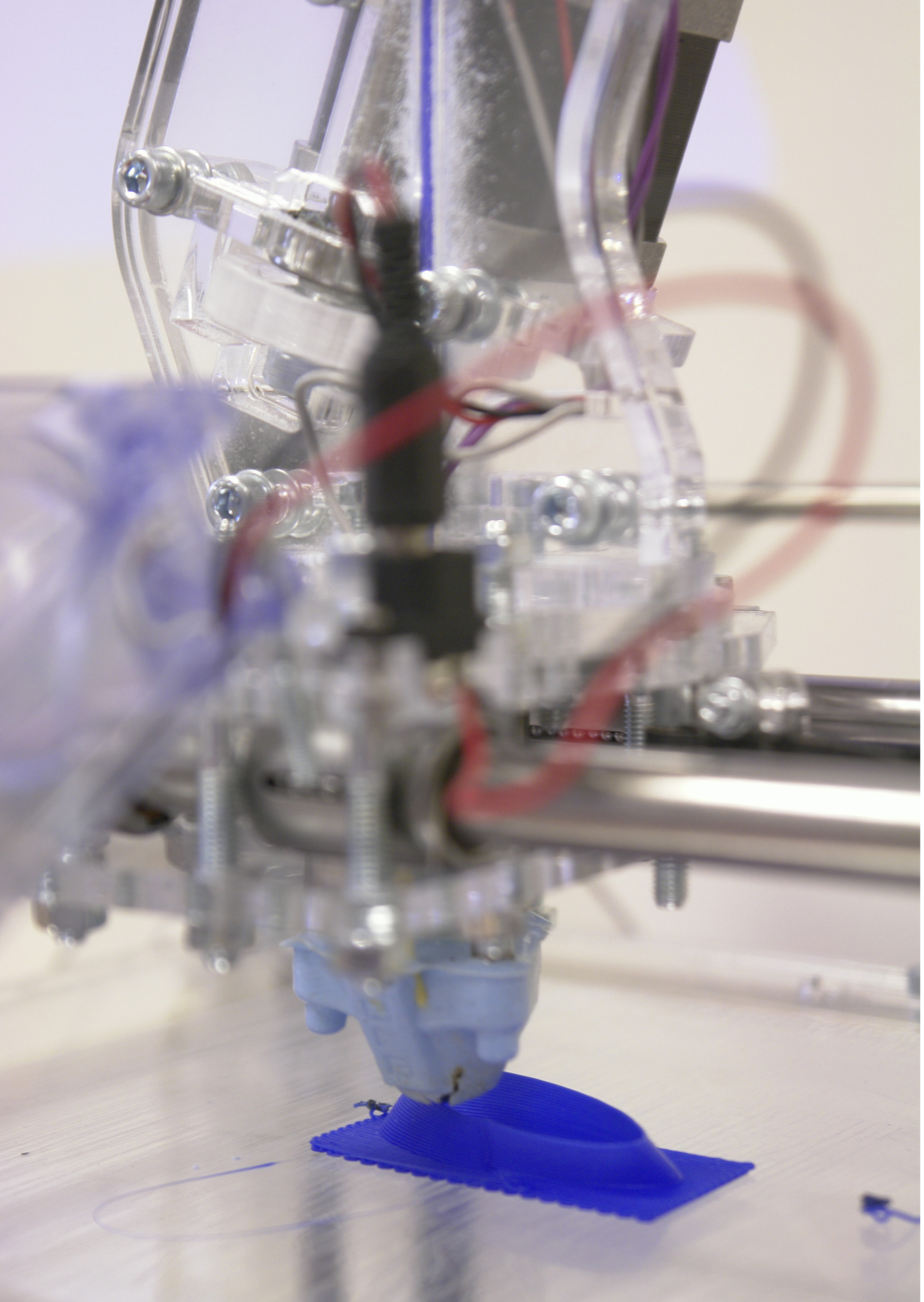
Executive summary

Supported by the EPSRC[1] institutional sponsorship, three workshops were held in order to create a roadmap for future research in the field of smart products through-life. During the workshops a variety of different activities were undertaken by participants from 13 UK universities with expertise in various fields to explore the requirements and challenges relating to smart products-through life. These disciplines included: artificial intelligence, control engineering, knowledge management, manufacturing engineering, material sciences, smart product design, and the supply chain.
Future research should transform manufacturing from analogue to digital, making it faster, more responsive and more easily controlled, which will represent a transformational framework upon which manufacturing can aspire to achieve. The research vision behind these workshops was to integrate through-life product intelligence within smart products, with intelligent manufacturing systems to optimise the manufacturing value chain. The integration between the smart product and smart manufacturing life-phase systems will support a reduction in raw material use through an improved intelligent matching with individual manufacturing processes such as near net shape, with a resulting reduction in energy utilisation and an increase in competitive advantage.
The workshops have confirmed that to successfully develop smart products through-life a multidisciplinary team is required. The roadmap presented in this document details the outcomes of the workshops through trends and drivers underpinning the research, key challenges that need to be addressed in order to achieve the vision, and the resources required in this process.



[1] EPSRC - "The Engineering and Physical Sciences Research Council (EPSRC) is the UK's main agency for funding research in engineering and the physical sciences. EPSRC invests around £800 million a year in research and postgraduate training, to help the nation handle the next generation of technological change."

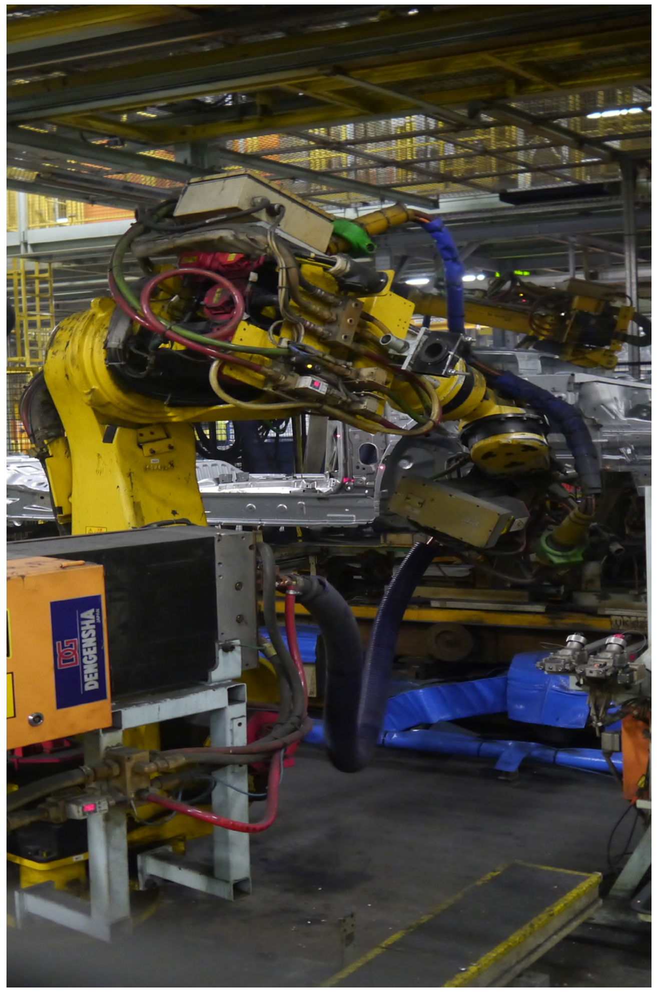


Background

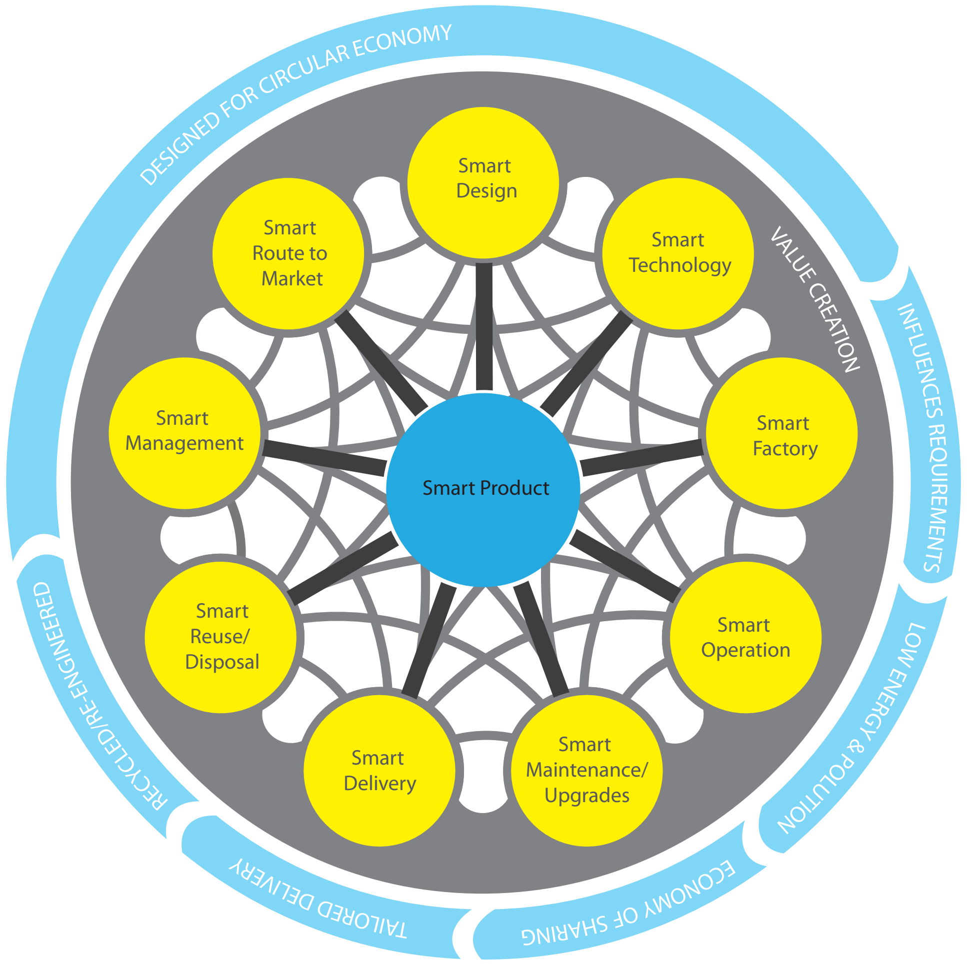
Future manufacturing within the UK needs to enhance adaptability and agility to rapidly reconfigure its manufacturing systems in response to the changing demands of both global and local markets. Smart products will deliver value creation for end users, who will benefit from greater control of the customisation of their products, within the UK supply chain. Manufacturing will benefit from greater efficiencies within their processes, integration within the supply chain, and onshoring of smart manufacturing capability, to the final delivery of high-quality products[2]. Integration between the smart product and smart life-phase systems will support the development of new business models through a more intelligent creation, integration and operation with all stakeholders and supply chains allowing a greater degree of product customisation.

The vision

The research vision is to integrate through-life product intelligence within smart products, with intelligent manufacturing systems to optimise the UK manufacturing value chain. Existing equivalent initiatives focus upon the enabling life-phase systems, for example production and assembly. The novelty of this transformative research is in integrating intelligence within the product/system through life, and managing its interaction within life phase system. The concept of smart products conventionally provokes perceptions of products that possess intelligence within their operational life-phase, to achieve operational performance objectives, and results with a perceived increase in value to the end user. This intelligence, encapsulated within a smart product, does not currently exist in a physical or virtual sense within any of the product's other life phases, and therefore constrains product performance and wider value creation through life. The product performance is conventionally defined in terms of technical operational characteristics, that are measured and used by the product to make smart decisions, but which do not incorporate characteristics of the overall value creation throughout the product's lifecycle. Increasing emphasis is placed upon impact and value



[2] The term product is refered to here to include an engineered system.



potential of the inclusion and embedding of intelligence within the manufacturing life phase system as well as the product to be manufactured. The research roadmap presented in this report will transform manufacturing by introducing the concept of smart products throughout the manufacturing value chain, incorporating through-life intelligence both into the product and throughout the life-phase systems, e.g. research, product and service development, supplier management, production, route to market, and delivery life phase systems, as well as operational, maintenance, re-engineering and recycling, ensuring value creation is achieved through life. It has been stated that “the risks of separating design and manufacturing are enormous”[3] . This research will develop this argument further by emphasising this risk of separation, asserting that the most viable mitigation of this risk is smart product research across the complete life phase value chain, which subsequently presents a unique value proposition to all stakeholders, and represents a “significant source of future competitive advantage”[4] . To fully leverage this benefit will require the adoption of a system-based approach for the integration of this intelligence between the smart product and each of the smart life-phase through life systems. Not only will the result be the digitisation, integration and networking of the manufacturing value chain, but also the digitisation, integration and networking of the products at all stages, life phases within this value chain, resulting in a level of awareness, communication and coordination between the manufacturing systems and the products being manufactured. That is, materials, products and systems will be contextually aware through life and will respond accordingly.

[3] Foresight (2013), The Future of Manufacturing: A new era of opportunity and challenge for the UK; Summary Report, The Government Office for Science, London.
[4] Foresight (2013), The factory of the future, UK Government Foresight Future of Manufacturing Project.

The value chain

The full benefit cannot be leveraged from the manufacturing value chain by adding this intelligence to the manufacturing life phase systems in isolation; the full benefit will be achieved for the first time by extending the manufacturing system to integrate with smart products. This systemic manufacturing intelligence will provide the opportunity to improve manufacturing efficiency through streamlining value chain operations by providing manufacturing intelligence at every stage. This increased efficiency will in turn help to reduce the relatively high UK manufacturing costs and contribute to UK economic efficiency. UK manufacturing effectiveness will take a transformative step to enabling more flexible and adaptive manufacturing through intelligent manufacturing capability awareness, improve product quality by integrating intelligent specifications throughout the value chain by linking life phase systems, e.g. design and production, more closely, and improve UK competency related to the digital economy sector through the creation of a new research area and industrial impact. It is anticipated that the research would indirectly circumvent low-cost overseas labour, by continuing the technological advantage of UK industry and provide the basis for managing fragmented value chains and distributed manufacturing to support high value manufacturing (HVM). The challenges related to achieving these benefits are systemic, require a holistic consideration of the manufacturing value chain, and needs to be approached through the use of manufacturing systems thinking and systems engineering. It will exploit a wide range of emerging and significant science and technology including: advanced and autonomous robotics; customisation; systems modelling and integrated design/simulation; intelligent systems and embedded electronics; integration of new materials with new manufacturing technology; advanced communications software and protocols; artificially intelligent products/systems; data processing and storage; big data analytics; and, smart hybrid and multiple materials.

UK need

Future manufacturing within the UK is characterised by adaptability and agility in rapidly reconfiguring its manufacturing systems in response to the changing demands of both global and local markets; by increased efficiency within energy and resource use through-life consideration of the complete manufacturing value chain; and achieved using big data analytics incorporated within the entire manufacturing system to inform the manufacture of high value products.
Smart Product Research will transform value creation for end users, who will benefit from greater control of the customisation of their products;
within the UK supply chain who will benefit from

High Value Manufacturing [5]
“High value manufacturing (HVM) is the application of leading edge technical knowledge and expertise to the creation of products, production processes, and associated services which have strong potential to bring sustainable growth and high economic value to the UK. Activities may stretch from R&D at one end to recycling at the other. Related products, processes and services accounted for 35% of all UK exports in 2010. That contributed £151 billion to the UK balance of payments.”

[5] High Value Manufacturing Strategy 2012-2015, Innovate UK, 2014

greater efficiencies within their manufacturing processes, integration within the supply chain, and onshoring of smart manufacturing capability; to the final delivery of high-quality products. Integration between the smart product and smart life-phase systems will support the creation of new business models through a more intelligent creation, integration and operation with all stakeholders and supply chains allowing a greater degree of product customisation. The research can transform UK manufacturing from analogue to digital, making it faster, more responsive and more easily controlled, and represents a transformational framework upon which all UK manufacturing can aspire to achieve.

The integration between smart product and smart manufacturing life-phase systems would support a reduction in raw material use through an improved intelligent matching with individual manufacturing processes such as near net shape, with a resulting reduction in energy utilisation and an increase in competitive advantage (efficiency and effectiveness). This integration would extend to the smart supply chain that would benefit from the digital connectivity, building competitiveness within the UK SME base, enhance UK skillsets, and overcoming the "disaggregation of OEM procurement" by onshoring to UK smart supply chain.

Stakeholders in the context of Smart Products Through-Life are:

- Clients
- Designers
- Engineers
- Factories
- Government
- Large enterprises
- Logistics providers
- Maintenance providers
- Managers
- Manufacturers
- OEMs
- Operators
- SMEs
- Users

Internet of Things (IoT) "The further miniaturization and cost reduction of electronic devices makes it possible to expand the Internet into a new dimension: to smart objects, i.e., everyday physical things that are enhanced by a small electronic device to provide local intelligence and connectivity to the cyberspace established by the Internet. The small electronic device, a computational component that is attached to a physical thing, bridges the gap between the physical world and the information world. A smart object is thus a cyber-physical system or an embedded system, consisting of a thing (the physical entity) and a component (the computer) that processes the sensor data and supports a wireless communication link to the Internet."[6] "It is a novel paradigm that aims at bridging the gap between the physical world and its representation within the digital world. The idea is to integrate the state of the 'things' that form the world into software applications, making them benefit from the world's context information."[7]

[6] Kopetz, Hermann. "Internet of things." In Real-time systems, pp. 307-323. Springer US, 2011.
[7] Zhang, Yongheng Wang Xiaoming. "Internet of Things." (2011).

Other Initiatives

Digital Thread - http://dmdii.uilabs.org/

Factory 2050 - http://www.amrc.co.uk/about/factory-2050/

Future of Manufacturing - Foresight (2013). The Future of Manufacturing: A new era of opportunity and challenge for the UK, Project Report, The Government Office for Science, London https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/255922/13-809-future-manufacturing-project-report.pdf

Industry/Industrie 4.0 - https://www.gtai.de/GTAI/Navigation/EN/Invest/Industries/Smarter-business/smart-products-industrie-4.0,t=industrie-40,did=589872.html
http://www.gtai.de/GTAI/Content/EN/Invest/_SharedDocs/Downloads/GTAI/Brochures/Industries/industrie4.0-smart-manufacturing-for-the-future-en.pdf

Smart manufacturing leadership coalition - https://www.smartmanufacturingcoalition.org/

International initiatives

A number of other significant government sponsored international initiatives are focussing on future manufacturing and specifically aspects relating to automation, digitisation, robotics, and rapid reconfigurability:

- Industry/Industrie 4.0[8] – Germany – up to €200m – aims to digitise the manufacturing industry focusing on concepts such as cyber-physical systems and the "internet of things" to achieve adaptability, resource efficiency, and the integration of stakeholders within the value creation process.
- Factory 2050[9] – UK – £43m – aims to combine a range of technologies, including advanced robotics, flexible automation, unmanned workspace, off-line printing in virtual environments linked to plug-and-play robotics, 3D printing from flexible automated systems, man-machine interfaces, and new programming and training tools.
- Smart Manufacturing Leadership Coalition/ Advanced Manufacturing[10] – USA – $70m specifically for Digital Manufacturing and Design Innovation Institute – aims to digitise design, engineering, manufacturing and maintenance systems within a "networked supply chain".

These initiatives principally focus on adding intelligence within manufacturing to achieve the factory of the future, where it is anticipated that "in factory and process environments, virtually everything is expected to be connected via central networks", which strongly links to the concept of the "internet of things". The focus is almost exclusively on adding intelligence to the factory and the specific production life phase, with no consideration of adding equivalent intelligence to the products progressing through the manufacturing processes. This disconnect significantly reduces the associated value creation potential within the manufacturing system, and all but removes the full potential through the following life phases. Similar initiatives are planned and briefly discussed within the Foresight "Future of Manufacturing Project: Evidence Paper 29", within China, Japan, Singapore, and South Korea.

[8] Kagermann, Henning, Johannes Helbig, Ariane Hellinger, and Wolfgang Wahlster. Recommendations for Implementing the Strategic Initiative INDUSTRIE 4.0: Securing the Future of German Manufacturing Industry; Final Report of the Industrie 4.0 Working Group. Forschungsunion, 2013.
[9] http://www.amrc.co.uk/about/factory-2050/
[10] https://www.smartmanufacturingcoalition.org/

Workshops

Three workshops were organised by the University of Strathclyde aiming to develop a research road map for smart products through-life. The roadmap captures the envisioned future research requirements and it will act as a foundation for a potential future research proposal development. A second aim of the workshops was to establish the connections between the participating institutions and scope possibilities for future research collaboration.

Representatives from 13 UK universities attended the workshops:

- Bournemouth University
- Cardiff University
- Cranfield University
- DeMontford University
- Glasgow Caledonian University
- Loughborough University
- Northumbria University
- University of Bath
- University of Bristol
- University of Cambridge
- University of Edinburgh
- University of Glasgow
- University of Strathclyde

Biographies of the atendees are in Appendix.

W1: Sharing the vision

Workshop 1 took place at University of Strathclyde on the 29th October 2015. It was an introductory workshop aiming to establish collaboration and outline the research roadmap and responsibilities in developing it. The key elements influencing the smart products through-life were then identified, along with the dependencies between them and placed in a matrix categorising them under one of the four aspects:

- Lifephase
- Management
- Systems
- Techniques.

W2: Identifying challenges

Workshop 2 was held at Cambridge University on the 28th January 2016, and focused on further elaborating the requirements, challenges and resources required for the future smart products through-life research. It comprised of a further exploration of dependencies between different elements. A 6-3-5 brainstorming session was used, to focus on specific products that could be developed to be smart through-life, the requirements needed to fulfil to do so, and key challenges those requirements pose. The workshop was finalised with a session in which challenges to smart products through-life were placed in the corresponding life phase of a product.

W3: Creating the roadmap

Workshop 3 was held at University of Strathclyde on the 24th March 2016, and aimed to finalise the roadmap consolidate in from the findings. The roadmap was technically developed by drawing on the knowledge about the trends, challenges and resources required for smart products through life research, and consideration of the timescales attached to them. The justification for smart products through-life research was addressed, then what needs to be done to progress the research in terms of key challenges to achieve the vision, and finally how each challenge could be approached was considered. A roadmap was created as an output.

In the interval between workshops 2 and 3, work on definitions of standard elements discussed within smart products through-life was performed by a number of participating universities, within the context of Smart Products Through-Life.

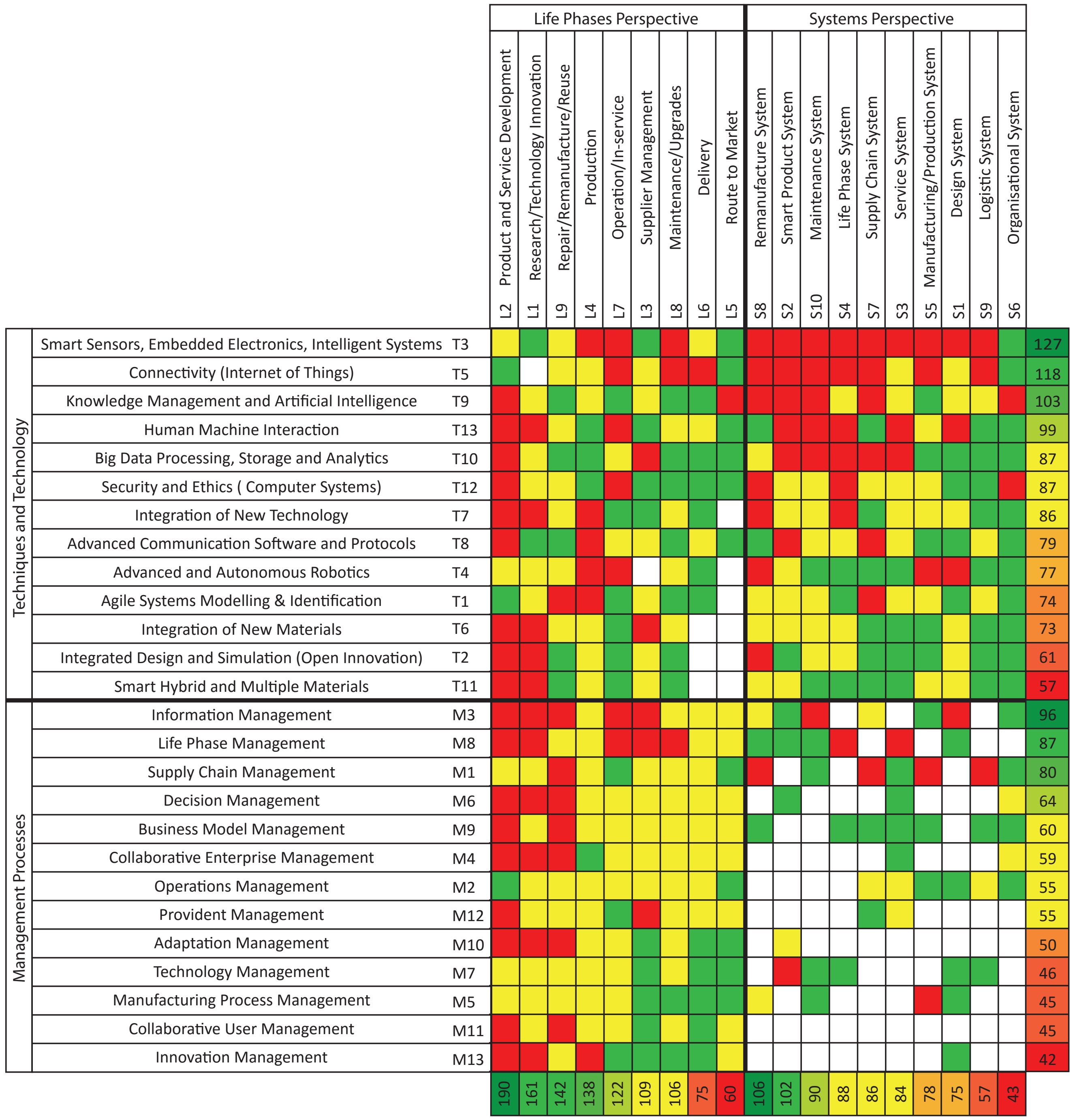
Multidisciplinarity

It was realised early within the conceptualisation of Smart Products Through Life that the research required is multidisciplinary and touches on different aspects of the research field. New techniques and technologies are required, the complete coverage of the life phases that need to be considered introduce further complexity, ways to manage the process need to be taken into account, and due to the complexities involved, and multidisciplinary systems, different aspects are highly interrelated. In order to understand the multidisciplinary nature and the associated relationships between and across disciplines and domains N2[11] diagrams were used to map between life phases, systems, technology and management. N2 diagrams are used within systems engineering in order to capture and model complexity. The specific elements required for lifephase, management, systems and techniques were identified, and their dependencies were explored. Green boxes indicate low dependency, yellow boxes indicate medium dependency and red boxes indicate high dependency. First the dependencies between different aspects were defined (page 14), and then the dependencies within the single aspects (e.g. Technology aspects dependency on other technology aspects, page 15).

Definitions of the specific elements within the four aspects, in the context of Smart Products through life, are given on pages 16 through 19.

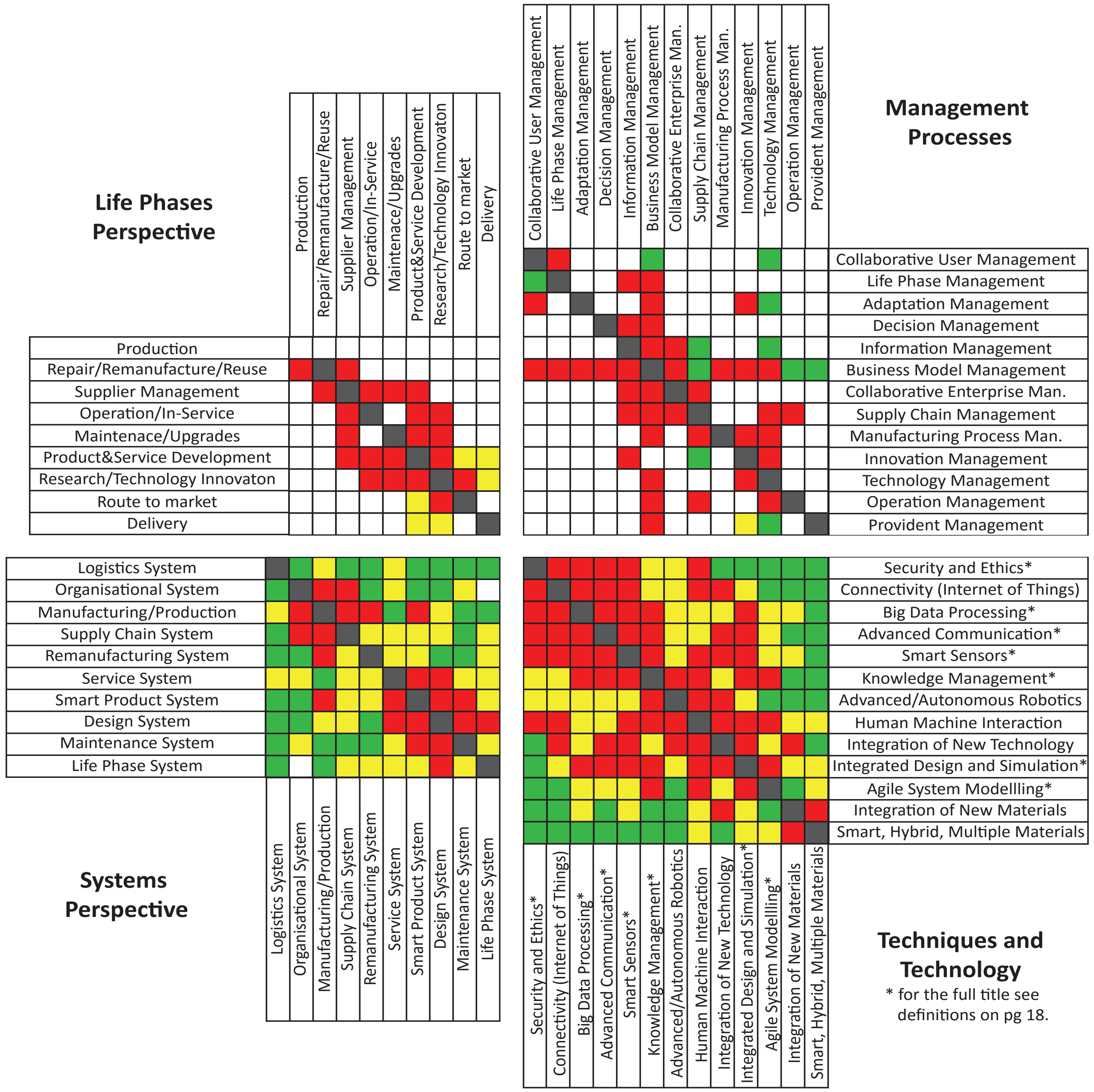
[11] N2 diagrams are used to represent the logical data flow for a system or system segment, often n development of software or hardware interfaces (Shishko, R. and Aster, R., 1995. NASA systems engineering handbook. NASA Special Publication, 6105.)

Dependencies between different aspects



While some type of dependecies exists between most aspects, the higher dependencies are grouped in the top right quadrant, between the Systems Perspectives and Techniques and Technologies, and in the first three columns linking the Life Phase Perspectives (Product and Service Development, Research/Technology Innovation, Repare/Remanufacture/Reuse) to the Techniques and Technologies and Management Processes. The far right column, and the bottom row of the table display the summarised dependencies, respecitvely, for the rows and columns. These were used to sort the elements of the perspectives and help represent the dependencies. They are sorted in a descending order for each of the four perspectives. The order is also indicated by the shading of the boxes with a gradient, from green for high dependency, through yellow for medium dependency, to red for low dependency.

Dependencies within different aspects



The dependencies between the elements within the four aspects have been weighted and clustered. While specific dependencies can be observed in the figure above, there were a number of overall conclusions that arised during the discussions:

- Type of intelligence and inputs required for different stages need to be known, e.g. material could have information about itself, but system could have information on how to use the material.
- Business management is of high importance.
- Design affects everything, particularly due to its position in the lifecycle (it is hard to retrofit smartness).
- The timing (urgency) of the relationship can affect the strength of it.

LIFE PHASE DEFINITIONS

To enable value creation through life, life phases of a smart product were considered. Characteristics of the life phases and the ways they could be observed in the context of Smart Products Through-Life are given below.

L1 Research/technology innovation - The smart product specification reflects a set of smart through-life requirements which can be heavily customised on demand by end user needs, and are autonomously capable of selecting candidate smart manufacturing technology and smart materials and interacting with designers on the basis of their form and functional characteristics.

L2 Product service development - The translation of smart requirements into smart components that possess knowledge of their function, behaviour and structure and interact with other components of the product. These smart requirements will exploit within the production stage the latest smart manufacturing technology (smart products) for efficient near net production. The intelligence within the smart requirements will be embedded within the smart components allowing the smart product to create value through life. It includes design for X (X=reliability, safety, quality, manufacture, assembly, logistics, modularity, serviceability, maintainability, remanufacture, recycling, users, lifestyle).

L3 Supplier management - The smart sourcing of suppliers through facilitating the smart components within a smart product to autonomously interact with and select a supplier and integrate into the life phase systems. These smart supply chains will allow the delivery of components, assemblies and systems in a manner that allows them to be perfectly integrated and assembled.

L4 Production - The delivery of smart raw materials, which are self-aware of their material properties, potential use, innovation potential, and manufacturing processes. Using smart manufacturing technology that knows how to autonomously choose materials and autonomously reconfigure itself to create the components that satisfy the smart requirements. Smart production lines and assembly will automatically reconfigure themselves in response to customised smart requirements and interact with production engineers. The smart manufacturing technology will interact with other smart life phase systems in terms of providing performance feedback for smart manufacturing requirements for example. Smart production process could include autonomous systems and could be production or reproduction.

L5 Route to market - Should be a consideration at the start of the process. It is closely linked to the business model planning, and will define how the product is sold. New business models are expected to arise to support the smart products and sales planning and customer requirements, involvement and satisfaction are parameters to consider.

L6 Delivery - Ensures the delivery of high-quality, high-value and customised smart products which interacts with a smart logistical system for efficient delivery. It must cover delivery and reuse, and the back to the manufacturer or other entities for remanufacture. Smart delivery can:

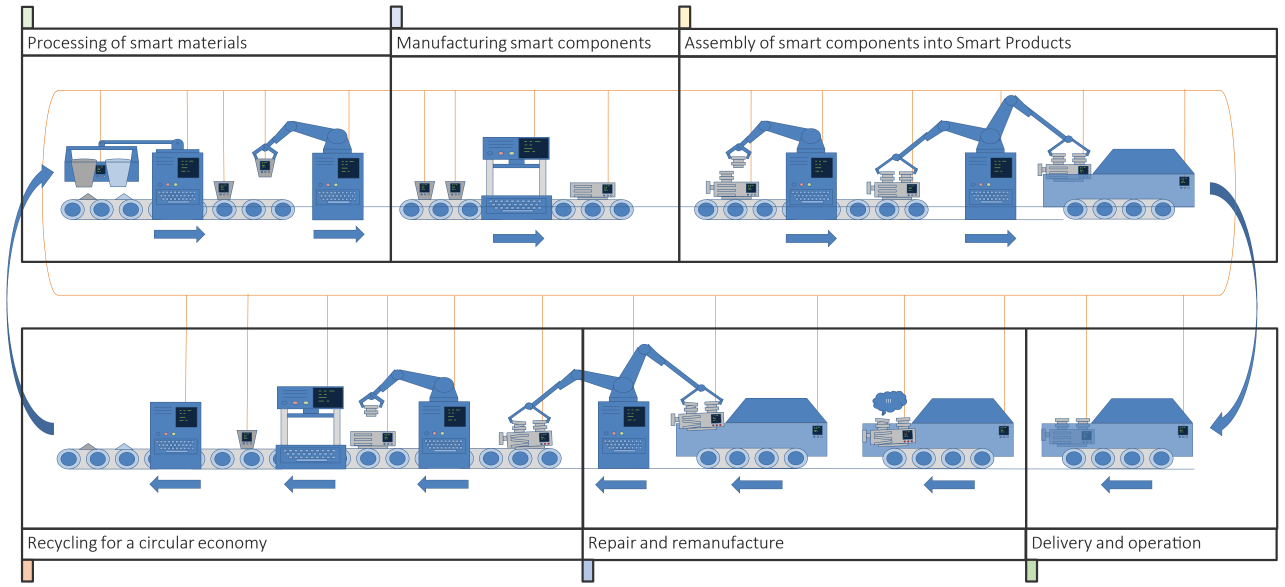
- Be centralised or distributed
- Reduce pollution or increase efficiency

It also poses some security issues to consider, and reliability issues, particularly if humans are involved.
Finally, if the transportation rises, it should be ensured the amount of packaging does not.

L7 Operation/in-service - Smart products will autonomously interact with end users and other smart products to achieve value creation with respect to performance, resource utilisation, and safety for example. Smart products will also interact with other smart life phase systems and products, to provide value creation information for the manufacture of the next generation of smart products, as well as to refine a smart reengineering strategy. Use of the product should include maintenance.
"Use" covers the customer perspective. Different customers will require different uses. "In service" covers the business perspectives.
Smart Support is an important consideration. If a customer is not using a product can a business take that product and repurpose for another customer, e.g. Airplane engines attached on another plane.

L8 Maintenance/upgrade - Health monitoring will allow smart products to adapt their maintenance regime and present themselves in a timely manner to minimise downtime. Maintenance or upgrades will be triggered by the product itself. In later phases of smart product development the product may gain the capabilities for self maintenance.

L9 Repair/remanufacture/reuse - The smart product will interact with smart remanufacturing and recycling systems and present itself in a manner that allows for the most efficient and effective value creation at the end of its life. This may consist for example of either remanufacturing part or all of the smart product to extend operational value creation, or recycling the smart materials using smart disassembly systems to maximum resource value creation. These smart reengineering systems will add the required intelligence for a truly circular economy. This phase should include disposal for parts that cannot be reused.



SYSTEMS DEFINITIONS

Smart products require multidisciplinary involvement and different perspectives that will have to be accounted for at different times of product development and in different subject areas. This introduces complexity that can be managed by different systems involved in the smart product development throughout its lifecycle.

S1 Design system - Collates and considers all of the design aspects, processes information from other life stages influencing the design, and optimises the design to comply with the product requirements.

S2 Smart product system - Explores product development aspects of the smart product focusing on its systems perspective.

S3 Service system - Smart products are likely to require maintenance or, in the case of modular product, upgrades. Service system considers the requirements and approaches to managing support for smart products through life, for different business models.

S4 Life phase system - While other systems defined in this section will explore influences other systems have on the life phase they focus on from their own perspective, an overall system tracking the requirements from a life phase perspective is also required. This is due to smart product being highly multidisciplinary and high dependencies between different life phases. A communications system protocol may be required as stages need to communicate to know each other's state. Smart interface needed between products might be a solution, depending on the product and its application?

S5 Manufacturing/production system - Manufacturing/production system – Considering systems aspects of the manufacturing process.

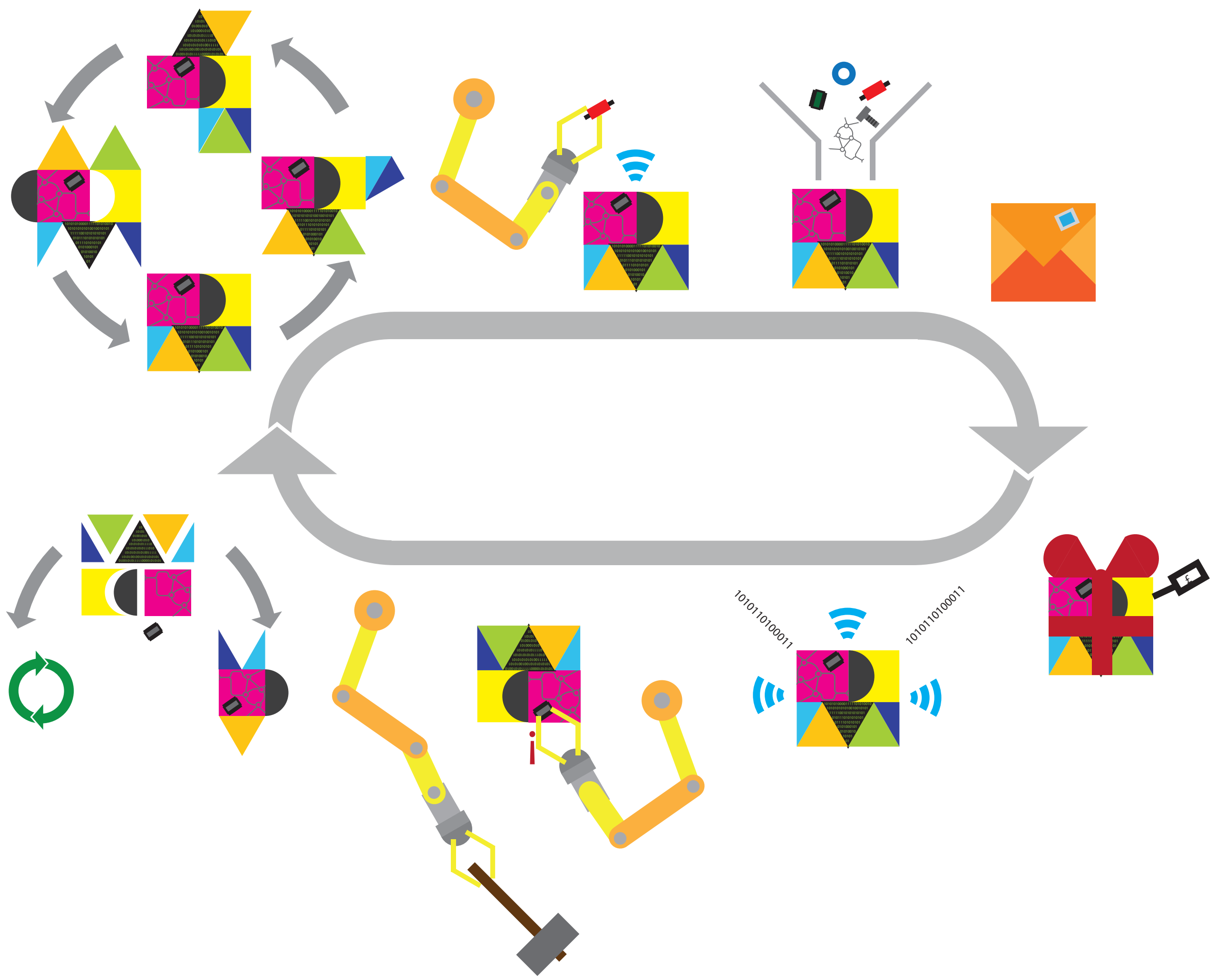
S6 Organisational system- System tracking and description of how the smart product is used is required. Could the system understand when the product is being misused? Could the product differentiate between misuse and genuine accidental damage?
Decision management dimension exists. How do products make autonomous decisions? Who makes decisions? Product, engineer or customer? How efficient is mass production with customisation?
Communications system protocol required - stages need to communicate to know each other's state.

S7 Supply chain system - Provides system focus for the parts delivery during production and any other supply chain challenges before the smart product is finalised.

S8 Remanufacture system - Smart products or parts of smart products may be remanufactured at the end of their life. Remanufacture system explores the challenges, information flows, requirements and activities that need to be undertaken to ensure the right parts are remanufactured for the fitting purposes.

S9 Logistic system - Provides systems focus for the smart product delivery to the customers. This system is particularly meaningful if the business models change and economy of ownership shifts to economy of sharing for certain products.

S10 Maintenance system - Smart products could be maintained in many different ways depending on the business model they follow, and a maintenance system is required to concatenate all the dependencies involved in the maintenance process



TECHNOLOGY DEFINITIONS

The pace and efficiency of Smart Products Through-Life development is highly dependant on the pace of technology development and the efficiency of its implementation in the context of smart products.

T1 Agile systems modelling and identification - Agile Modeling (AM) is a practice-based methodology for effective modeling and documentation of software-based systems. Simply put, AM is a collection of values, principles, and practices for modeling software that can be applied on a software development project in an effective and light-weight manner. The five values of AM are communication, simplicity, feedback, courage and humility. Agile systems engineering focuses on flexibility and speed in the upstream process of conceiving, designing and implementing products and systems. A generic "agile" product development process can be characterized as being:

- nimble, dexterous and swift
- adaptive and response to new, sometimes unexpected, information that becomes available (how does design change with new information?)
- during product/system development
- opposite to the traditional belief in engineering design that requirements and design solutions should be frozen as early as possible.[12]

T2 Integrated design and simulation (open innovation) - Open innovation is the use of purposive inflows and outflows of knowledge to accelerate internal innovation, and expand the markets for external use of innovation, respectively. [This paradigm] assumes that firms can and should use external ideas as well as internal ideas, and internal and external paths to market, as they look to advance their technology[13]. Open innovation is a distributed innovation process based on purposively managed knowledge flows across organizational boundaries, using pecuniary and non-pecuniary mechanisms in line with each organization's business model[14].
Are there new ways to simulate modelling and manufacture through-life:

- Production simulation?
- Manufacture simulation?
- Line simulation?

T3 Smart sensors, embedded electronics, intelligent systems - An embedded system is a computer system with a dedicated function within a larger mechanical or electrical system, often with real-time computing constraints[15][16]. It is embedded as part of a complete device often including hardware and mechanical parts. Embedded systems control many devices in common use today[17]. A smart sensor is a device that takes input from the physical environment and uses built-in compute resources to perform predefined functions upon detection of specific input and then process data before passing it on. Smart sensors are defined by the IEEE 1451 standard as sensors with small memory and standardized physical connection to enable the communication with processor and data network.

T4 Advanced and autonomous robotics - Sensor-based robots that attempt to mimic human intelligence. An autonomous robot is a robot capable of performing behaviors or tasks independent of external control. A working definition by Thrishantha Nanayakkara states "a robot is autonomous if it has the computational resources - both in terms of hardware and software - other than real-time interference from a human agent, to estimate how it is physically embedded in the environment to compute best possible actions bounded by some constraints to perceive and move if needed, to achieve a set of goals."

T5 Connectivity (internet of things) - A global infrastructure for the information society, enabling advanced services by interconnecting (physical and virtual) things based on existing and evolving interoperable information and communication technologies. Through the exploitation of identification, data capture, processing and communication capabilities, the IoT makes full use of things to offer services to all kinds of applications, whilst ensuring that security and privacy requirements are fulfilled. A "thing" in IoT is an object of the physical world (physical things) or the information world (virtual things), which is capable of being identified and integrated into communication networks[18].

T6 Integration of new materials - New materials and the ways they interact with the rest of the smart product, and the implications their use has on the smart product system needs to be taken into account.

T7 Integration of new technology - Similarly to the integration of new materials, integration of new technology needs to be observed concerning their effect on the smart product through life.

T8 Advanced communications software and protocols - Communication software and protocol for connectivity and collaboration required are missing to support:

- Open innovation/collaboration
- Between businesses
- Open source?
- Cloud computing that represents the practicalities of collaborative needs?

Computer systems UI (User Interface) requires development and interaction research, followed by the training for users.

T9 Knowledge management and artificial intelligence/products and systems - Data turned into information turned into knowledge about all of the elements of a smart product, and all of their lifecycles needs to be efficiently managed. Almost all other aspects of the smart products are dependent on a timely and accurate knowledge about the elements of the system.

T10 Big data processing, storage and analytics - Big data is a term that describes large volumes of high velocity, complex and variable data that require advanced techniques and technologies to enable the capture, storage, distribution, management, and analysis of the information[19]. Volume refers to the magnitude of data. Variety refers to the structural heterogeneity in a dataset. Velocity refers to the rate at which data are generated and the speed at which it should be analyzed and acted upon.

T11 Smart hybrid and multiple materials - A smart material is one which reacts to its environment all by itself. The change is inherent to the material and not a result of some electronics. The reaction may exhibit itself as a change in volume, a change in colour or a change in viscosity and this may occur in response to a change in temperature, stress, electrical current, or magnetic field. (Institute for Materials, Mineral and Mining).

T12 Security and ethics (computer systems) - Security of computer systems refers to three terms: confidentiality, integrity, and authentication or availability. Confidentiality means that information cannot be accessed by unauthorized parties. Confidentiality is also known as secrecy or privacy; breaches of confidentiality range from the embarrassing to the disastrous. Integrity means that information is protected against unauthorized changes that are not detectable to authorized users; many incidents of hacking compromise the integrity of databases and other resources. Authentication means that users are who they claim to be. Availability means that resources are accessible by authorized parties; "denial of service" attacks, which are sometimes the topic of national news, are attacks against availability.
Ethics in computer systems relate to Privacy (encryption, web privacy, database privacy), intellectual property (Software privacy, copyright laws, electronic copyright), computer abuse(hacking, virus), speech issues (spam, mass email, email privacy, risks (software reliability, network security), social (access).

T13 Human Machine Interaction - Human machine interface deals with the design and application/use of computer technology on the interfaces between people and computers.

[12] Haberfellner, Reinhard, and Olivier Weck. "10.1. 3 Agile SYSTEMS ENGINEERING versus AGILE SYSTEMS engineering." In INCOSE International Symposium, vol. 15, no. 1, pp. 1449-1465. 2005.
[13]Chesbrough, Henry William. Open innovation: The new imperative for creating and profiting from technology. Harvard Business Press, 2006. *cont.on page 19*

MANAGEMENT DEFINITIONS

Technology and systems need to be appropriately managed throughout all the phases of a smart product life cycle.

M1 Supply chain management - Supply chain management involves the management of flow of materials, information, and finances as they move between different actors in the supply chain, upstream or downstream. Its aim is to efficiently integrate all the actors involved in the realisation of a smart product so that it is produced and delivered at the right quantities, to the right locations and the right time, in order to minimise system wide costs while satisfying the service level requirements. It also involves the collaboration between the supply chain actors to ensure the 'smart' aspects of the product are embedded in the most efficient way and the information flows related to the product manufacturing and operation are fed into the appropriate supply chain actors. Finally, it includes managing the information coming from the smart product itself in order to direct the product during its manufacturing stage to the appropriate supply chain actor to customise it and produce it in the most efficient manner. Each step of this process should add value.

M2 Operations management - Operations management is the activity of managing all the resources which are devoted to the production and delivery of smart products, as well as the respective services.

M3 Information management (IM) - IM intends to provide each and every entity involved in the Smart Product Systems a platform to capture, search, retrieve, use, re-use, and share information to enable them to achieve their functional requirements effectively. Smart intelligent IM could have features of information verification, filtration, categorization, synthesis, adapt to revision/reversion, understand information value, secure, contextualize, delete unimportant information, predict and supply information at the right time, and potentially provide valuable feedback. This will help with the integration of the required systems, as different companies without links to each other will need to use the same information throughout the life- cycle. Intellectual property issues need to be considered- how much information you need to share with each entity to ensure the product can be managed well, e.g. broken product – does it go back to the seller? Or manufacturer? Or the recycling plant?

M4 Collaborative enterprise management -Due to multidisciplinary nature of the field collaboration between different entities will be required throughout the smart product life cycle and the ways to manage it best need to be addressed.

M5 Manufacturing process management - Manufacturing process management is the identification of the most appropriate combination of technologies and methods that should be used to manufacture a smart product, in order to provide final products with the expected level of quality and the desired 'smart' characteristics. It also involves integrating in the manufacturing process the requirement for information exchanges between the smart product and the manufacturing system.

M6 Decision management - Decision management is the management of the decision-making processes during the smart product design, production and operation phases. These can be decisions made by the manufacturing system or the supply chain for the smart product, or decisions made by the smart product itself for the manufacturing or supply chain system. The link between the two decision-making systems needs to be explicitly defined and any potential for conflicting decisions needs to be eliminated.

M7 Technology management - Different technologies involved in the smart product development might require different management approaches to optimise their use within the larger system.

M8 Life phase management is covering mixed processes. They are not necessarily sequential, as each stage in a life cycle might theoretically have input to all the other stages, not only those following it.

M9 Business model management (BMM) - BMM models and supports managing value proposition (i.e. offerings to the market e.g. TotalCareTM), quantifying end users' needs and relationships, monitors communication and distribution channels to reach clients, perceives resource utilization, track activities in the Smart Product Systems, nurture co-creation among stakeholders, rationalize the cost and revenue streams. It helps business sustainability to support smart product to deliver through life functionality.
It should answer the questions of:

- Are you selling the design?
- Are you selling the product?
- Are you self-manufacturing? (and how do you part test self-manufactured or self-remanufactured?)

Example of what business model defines – e.g. modular phones – whose responsibility is it to decide which modules you need, yours or the providers? Who decides if you need a new processor? Depending on who does the maintenance (customer or manufacturer) you would design the product differently.

M10 Adaptation management - How will new additions to the systems be managed? How could system accommodate change?

M11 Collaborative user management - Customer requirements need to be supplied, and a decision needs to be made on the extent of their involvement in the smart manufacturing process. This is, among other things, dependent on their knowledge of the processes involved. Should there be shared used mass production? Individual users need to be managed, and collectives need to be managed, and a collection of needs should be managed. How do users come to an agreement and how do systems know what they want?

M12 Provident management - what happens to the product if futures materialise (manage known/unknown knowns)?

M13 Innovation management (InM) - InM purpose is to collect opportunities/problems in the Smart Product Systems environment, and facilitate iterative process of generation, evaluation and selection of innovative ideas through accumulation of knowledge from various sources (i.e. irrespective of organizational boundaries). It also maps and supports processes involved in converting selected idea to successful implementation. It structures process of fusing collective intelligence from network of stakeholders, encouraging innovation, and forecast potential technology development. Depending on the position of the product in the life cycle the management model may need to change.

cont.from page 18
[14] Chesbrough, Henry and Bogers, Marcel, Explicating Open Innovation: Clarifying an Emerging Paradigm for Understanding Innovation (April 15, 2014).
[15]Barr, Michael. "Embedded systems glossary." Neutrino Technical Library (2007).
[16]Heath, Steve. "Embedded systems design. EDN series for design engineers . Newnes." ISBN 1110122468 (2003): 2.
[17]Barr, Michael, and Anthony Massa. Programming embedded systems: with C and GNU development tools. " O'Reilly Media, Inc.", 2006.
[18]Recommendation ITU-T Y.2060, Overview of the Internet of things, 06/2012
[19]Mills, Steve, Steve Lucas, L. Irakliotis, Michael Rappa, T. Carlson, and B. Perlowitz. Demystifying big data: a practical guide to transforming the business of government. Technical report. http://www. ibm. com/software/data/demystifying-big-data, 2012.

Challenges for smart products through life

Two approaches were taken to identification of challenges:

1. Considering key challenges with regards to the life phase of a product they might materialise in.
2. Observing specific products and extracting key challenges identified for them that could be common for a wider variety of products.

In the first activity challenges were considered and mapped onto the life phase they belonged to. Different challenges are present in different life phases, and while some might be limited to a single life phase, others could span different life phases or perhaps all life phases.

In a separate activity specific focus was on what would be required in order to make a chosen smart product integrated through life with all appropriate smart life phase systems, in order to support a circular economy and enhance value creation (see page 22).

Life phase specific challenges

Research/Technology Innovation

- Assessing whether value created through life is cost effective
- Changing legislation
- Convincing industry – where to start?
- Correct levels of autonomy
- Designing a smart product might require research in areas a company might have no expertise on. How do you get this knowledge?
- Does smart always require electronics/computation?
- Flexibility and customisation
- How to convince a user that their product should make decisions for them without daily mail getting involved
- How to make a product smart? What makes it smart?
- Identifying target markets
- IP ownership + security of IP when shared across life phases
- Link with customer driven demand via predictive prototyping
- Managing short product life cycle vs longevity vs customer expectation vs technology changes
- Manufacturing components: customisation
- Open-collaborative innovation
- Predicting what smartness is useful?
- Research/TI: 1. System-level model and intelligence; 2. Product-level optimisation/intelligence
- Risks from depending on new/novel technology
- Standardisation
- Standardised identifiers for tracking (replaceable)
- What are market needs for smart production and manufacturing services

Product & Service Development

- 1. Automatic design; 2. User-driven design; 3. Optimised design
- 1. How to design, develop and evaluate smart product; 2. What are new tools/.methods required
- Business process modelling
- Cost of equipment to make a product smart vs cost of product
- Deliverables on the roadmap along the way
- Design within the context of an integrated life phase systems – which comes first
- Effect of replaced part on the functionality of the product
- How can a product be 'for life': trends, fashion, legislation
- How to develop a flexible services business environment
- How to do open innovation
- How to make users/maintainers centric smartness in the product development
- Modularity for different uses
- More smarts = higher cost?
- Ownership - Through life ownership – who owns the intelligent materials (production, use, recycle)
- Privacy/data sharing/security (cyber attack)
- Smart components assembly: Standards e.g. communication, interfacing to start with
- Smartness @ different levels of system hierarchy – material, component, system
- Standardisation
- Standardised identifiers for tracking (replaceable)
- Through life business process model
- What are associated system innovation and new business models?
- What is close to marker now and what is in the blue sky
- What materials to use? What technology to use? How to decide?

Supplier Management

- Design change and adaptation to parts
- Incentives for supplier to build/manufacture a smart product
- Integrated with complete visibility
- Need to connect with suppliers e.g. in electronics
- Parts obsolescence
- Smart materials: New processes
- Unforeseen circumstances that affect availability
- Unpredictability in what components + materials will be used for
- What information is required and how to make them available for supplier management

Production

- Assembly: 1. Sequencing/ordering; 2. Flexibility according to relevant/different products
- Combining data into a single product
- Compatibility with existing systems. Production lines can be pretty hard to change
- Design for through life
- Distributed manufacturing
- Effect of production processes on product elements(if integrated)
- Flexibility, multi-agents
- How to add process information/manufacturing methods/parameters to the produced parts/assembly
- Integrating intelligence into materials
- Intelligent resource, smart factory
- Logistics within a smart product production system
- Manufacturing components: 1. Scheduling/planning; 2. Optimise multi-objectives
- Processing of smart materials: Mapping material with functions & cost
- Product driven production, high level customisation
- Re-configurable, Self organising production
- Routing the product through factory (production facility)
- Traceability of components
- Traceability of subsystems
- What does this highly dynamic factory look like?

Route to Market

- 1. What are best supply chain to deliver a final product to a customer; 2. How to do viral marketing
- Convince customers to pay extra to get a smart version of a product
- From idea to product – making this appealing to everyone
- People don't know what is useful until they have it
- Prove/show economic benefit for different stakeholders
- Service/ownership?
- Type of smartness – marketing
- Understanding business risks from Smart Products

Delivery

- Delivery + Operation: Data analysis, predictive projection
- Delivery/operation: 1. User-driven delivery (in time in place etc.); 2. Personalised operation settings/conditions
- Environment impact – distributed systems
- How to model and understand the whole system to support optimal delivery service?
- Information sharing among organisations
- Logistics tracking
- Smart delivery services
- Smart products or smart containers/packages/pallets etc.
- Warranty, deadlines, cost of time for delivery

In Service

- 'Smart' in function should still be easy to use. Don't over-complicate
- Dealing with in-life adaptation
- Every product will need its own form of 'smart. How do we generalise?
- How to collect and where to store information during the operation
- How to support problem detecting? DIY repair, part exchange, and sharing?
- In-life monitoring
- Learning and adapting
- Measuring wear & need for replacement for different parts taking into account assembly/disassembly process
- More complex means more to go wrong
- Ownership
- Responsibility
- Self-diagnose/Self repairs
- Standardised sensors/performance data?

Maintenance upgrades

- Access historical information that will help you repair or maintain a product accordingly
- Cost of repair vs cost of replacement? (business case)
- Disassembly
- How do we ensure smartness will recognise and be capable?
- How do we know what upgrades are needed? (when designing?)
- How to provide UX based maintenance and upgrading services?
- Human/machine interface
- Identifying optimal time to begin re-man process
- Prediction of failures/condition based maintenance
- Proactively predicting failures and taking action
- Self diagnosis of repair/maintenance

Repair/Remanufacture/Reuse

- Autonomous disassembly
- Business model for customers + manufacturers to be willing to do it
- How to maximise resource reuse whilst reducing energy use
- Human/machine interface
- Identify residual value of components
- Optimal location of recycling facilities – and knowing what is best disposed of
- Optimising re-use options
- Recycling: 1. recording information of function level (e.g. degree of reusability)
- Recycling: Design inclusiveness, design for the future
- Repair/remanufacturing: 1. working status info for repair/remanufacturing; 2. cost – whether worthy to repair/remanufacture
- Repair: smart sensing, smart diagnosis
- Supplier ownership for re-use/re-cycling?
- Testing for defects post disassembly
- What are best modular design and manufacturing for reuse/repair/remanufacturing

Everything

- Biggest Challenge – simulation of the full life supply chain, support chain, virtual tests + virtual prototyping for 1st right manufacture
- Business case for stakeholders
- Business model for all supply chain partners in a 'smart' supply chain/product
- Coping with unpredictability
- Cost
- Design for 'X' (x=through life, manufacture, remanufacturing, disassembly, production)
- Licensing
- Ownership
- Policy change
- Public opinion and buy-in
- Responding to change
- Security of IOT
- Standards
- Traceability
- When does 'smart' begin? (+ when might it be a bad thing)
- Who pays for it

Smart product oriented challenges

Higher priority

- Have a business case for all stakeholders
- Human machine interface
- Moving from data to info to decision making
- Collection and storage and sharing of info/data
- Ability to make distributed decisions
- Modularity - can hinder design innovation
- Cost of data storage. Who will pay for it?
- Open standards
- Ease of dissasembly
- Economic benefit
- Design products that are smart from the beginning
- Life phase system
- Interaction between designers, manufacturers and users
- And what needs to be smart? Product or cloud?
- Marketing and advertising
- Re-use/multi-function
- Or tell people what to want
- Optimise all components throughout the supply chain so as to keep the cost down
- What new standards needed?
- Setting up the supply chain
- Flexible design - do 'people' know what they want?
- The product could be designed for remanufacture
- Managing changing fashions
- Knowing history of the product - manufacture and make

Lower priority

- Security of information on user/manufacturer
- Common information sharing interfaces/ languages
- Decision making and learning
- Product and service development
- Communication between new - old generations of products
- Integrated production/supply chain
- Human-product interface design
- Design for maintenance
- Upgrades being standardised across PLM
- Safe use/easy to dispose materials (WEEE)
- Knowledge to integrate smart products with other environments
- Research in new materials/technology
- Pay for data by manufacturer?
- Collection and storage of information and data
- Ethical material/technology use
- Validation and verification
- Modular design/manufacturing/supply
- New research
- New production and manufacturing capabilities
- Product and service innovation and design
- Privacy issues about collecting data
- Service free
- Smart design
- Flexible remanufacture to respond to future worker needs
- Adoption processes based on gathered data
- Fitting components to manufacture or vice versa
- Flexible function/materials
- Marketing
- Knowing component residual value for recycling
- Use cheap/flexible material
- Capture and monitor added value
- Though- life simulations before manufacture

Both types of challenges were further discussed and used to populate the roadmaps.

Roadmap

The goal of the third workshop was to build a roadmap for Smart Products Through-Life by consolidating the outputs from workshops 1 and 2 into the 3 main streams:

- Trends and drivers – e.g. social, technological, environmental, economic, infrastructural, political drivers. Aiming to answer the question of why smart products through life should be the focus of the research.
- Key challenges to achieve vision – focus on what needs to be done for smart products through-life to become a reality. It covers functions, features and performance of the products throughout their evolution (from the current state to the final vision), development of services, infrastructure, and mechanisms used to integrate technology, capabilities, knowledge and resources.
- "Resources required" - explore how the challenges can be achieved, and defines what are the knowledge based resources (technology, skills, competences) and other resources (finance, partnerships and facilities) required to do this[20].

These three streams were developed for three stages: current situation, short term (5-10 years), and long term (up to 30 years). A consideration was made of expanding the road map further to include the medium term and a final vision, however it was deemed that the focus on current, short and long term are more appropriate for the current phase of research.

The road map is not specific to any type of smart product, it is instead an inclusive road map aiming to cover the key elements common to a wide range of smart products, residing in different industries.

Potential future activity to further enrich roadmaps would be to assess the impact each challenge would have on the Smart Product Through-Life development. While the roadmaps, in their current state, do indicate the time line of challenges, thus indirectly placing higher impact considering the timing of challenges, further work should be done on the assessment of the technical, societal and economic impact.

[20] Phaal, R. and Muller, G., 2009. An architectural framework for roadmapping: Towards visual strategy. Technological Forecasting and Social Change, 76(1), pp.39-49.

Why?

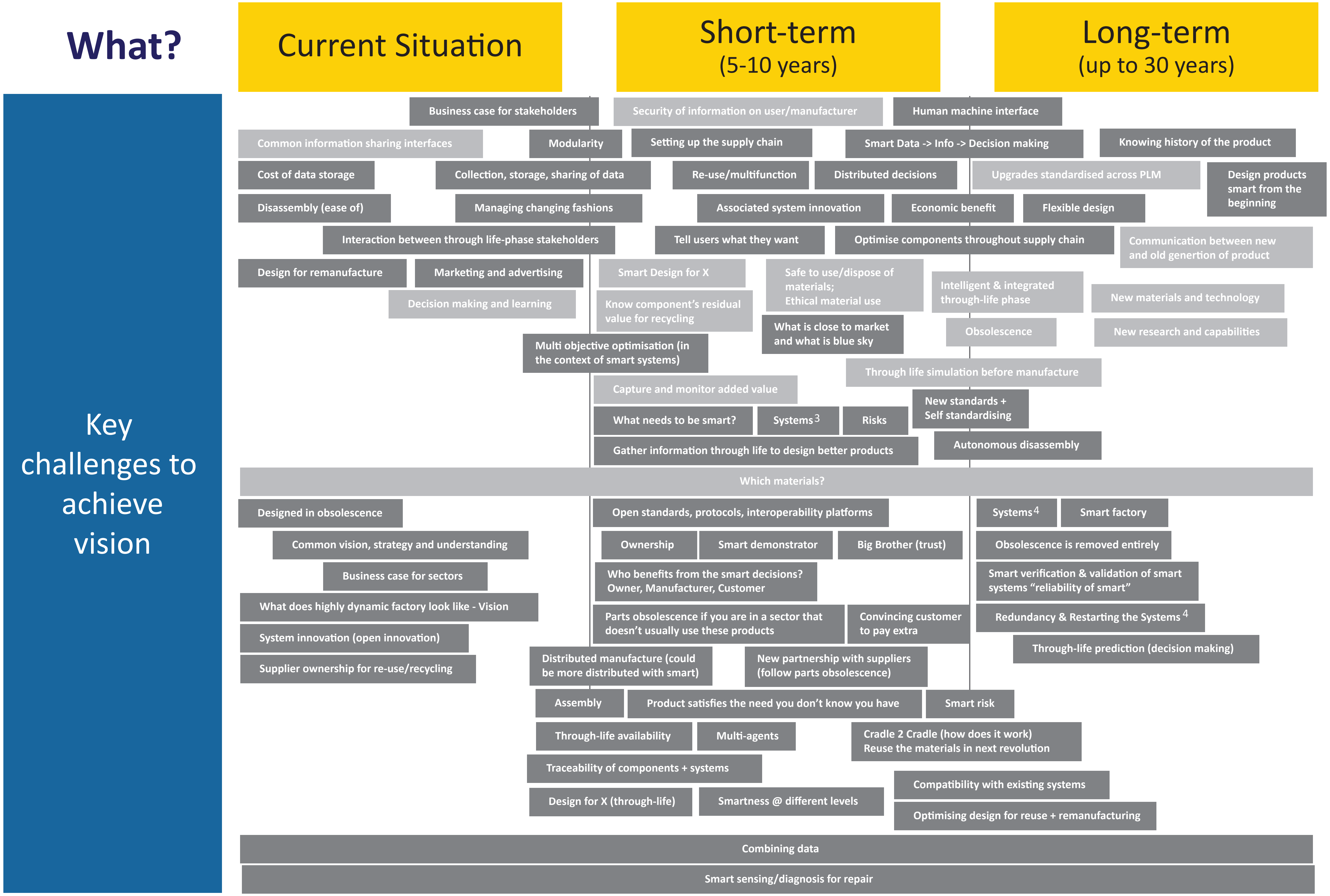
Trends and drivers

Current Situation	Short-term (5-10 years)	Long-term (up to 30 years)
Design aspects overlooked Segmented, do not have the tools; Self manufacturing, user prototyping, additive	Value from changing the way industry operates	Smart support for repurposing
Large, multidisciplinary effort	Mass customisation	Smart reusing of materials; 100% availability; Self-X *100years
Segmented; Big data analytics and data processing	New business models; New consumerism models	Through Life
Solve things we do not know how to do	New business landscapes	
Smart human interface; Optimise UK manufacturing value chain		Intelligent creation, integration and stakeholder operation
Remanufacturing; Virtual manufacturing	Reduction in energy utilisation	
Cyber security; New levels of forward thinking	Increase in competitive advantage	Plug and play products
Open Innovation/Source	Autonomous Manufacturing - trend	Shared use mass production
Cloud computing; Smart sensors	Smart delivery services	Cyber-physical manufacturing
Intelligent systems; Smart services	Personalised delivery; Design centric economy	Zero net resource use
Cloud manufacturing; Whole life-phase virtual modelling	Use the smart product idea to improve visibility between suppliers	User centred design economy
Value added through-life		
Systems of systems; Self diagnosis	New ownership models; Systems[3]; Self healing	Systems[4]
Lack of through-life design and evolutionary approach for smart products		
Throw away culture/energy/material		
Self adaptation; Smart textiles, smart materials		
Isolated islands; Less customised products		

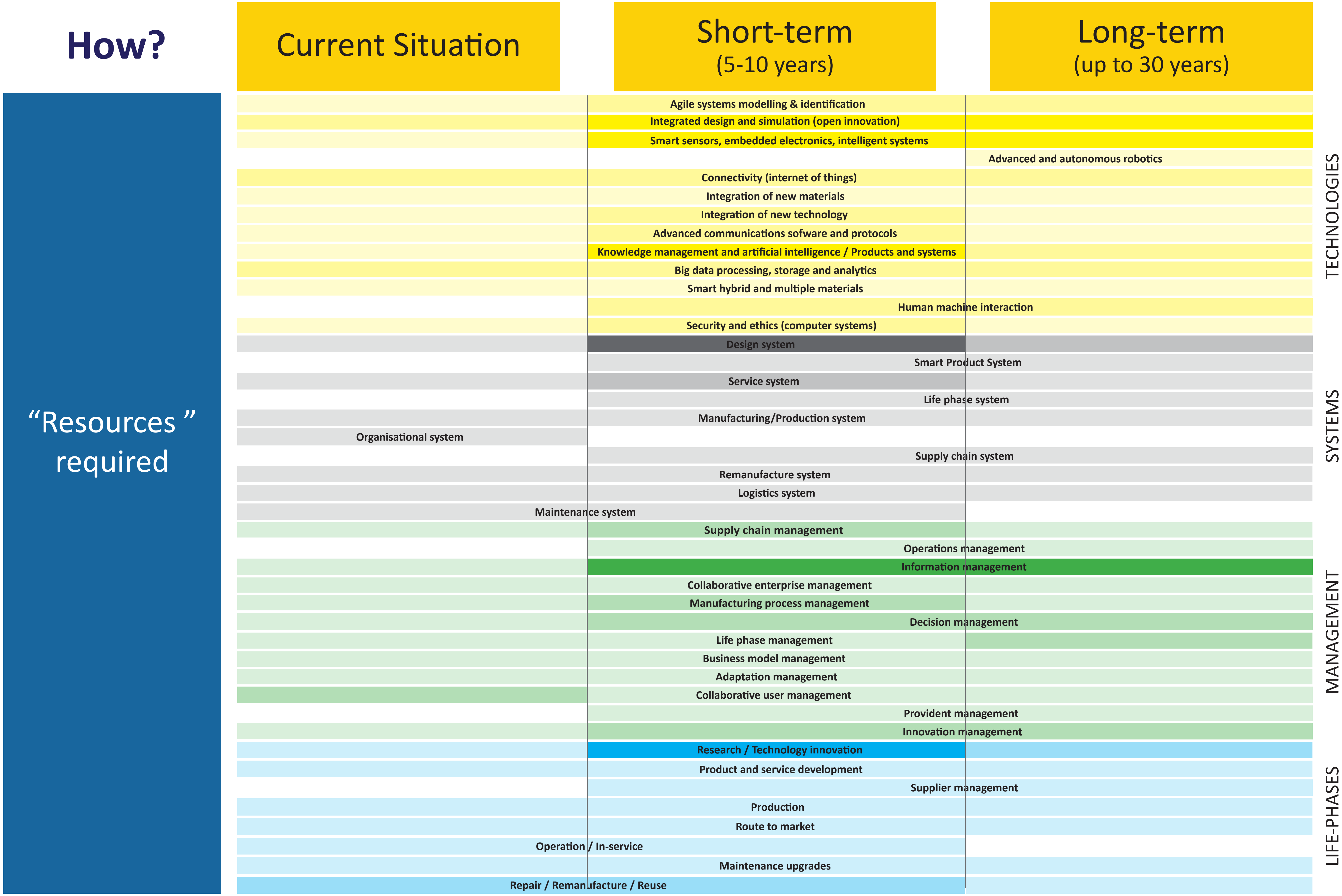
Systems[3] - Systems of systems of systems

Systems[4] - Systems of systems of systems that can validate themselves (e.g. a system that is able to perform checks regarding whether the information it receives about its state is accurate and if it requires maintenance, that it could perform itself)

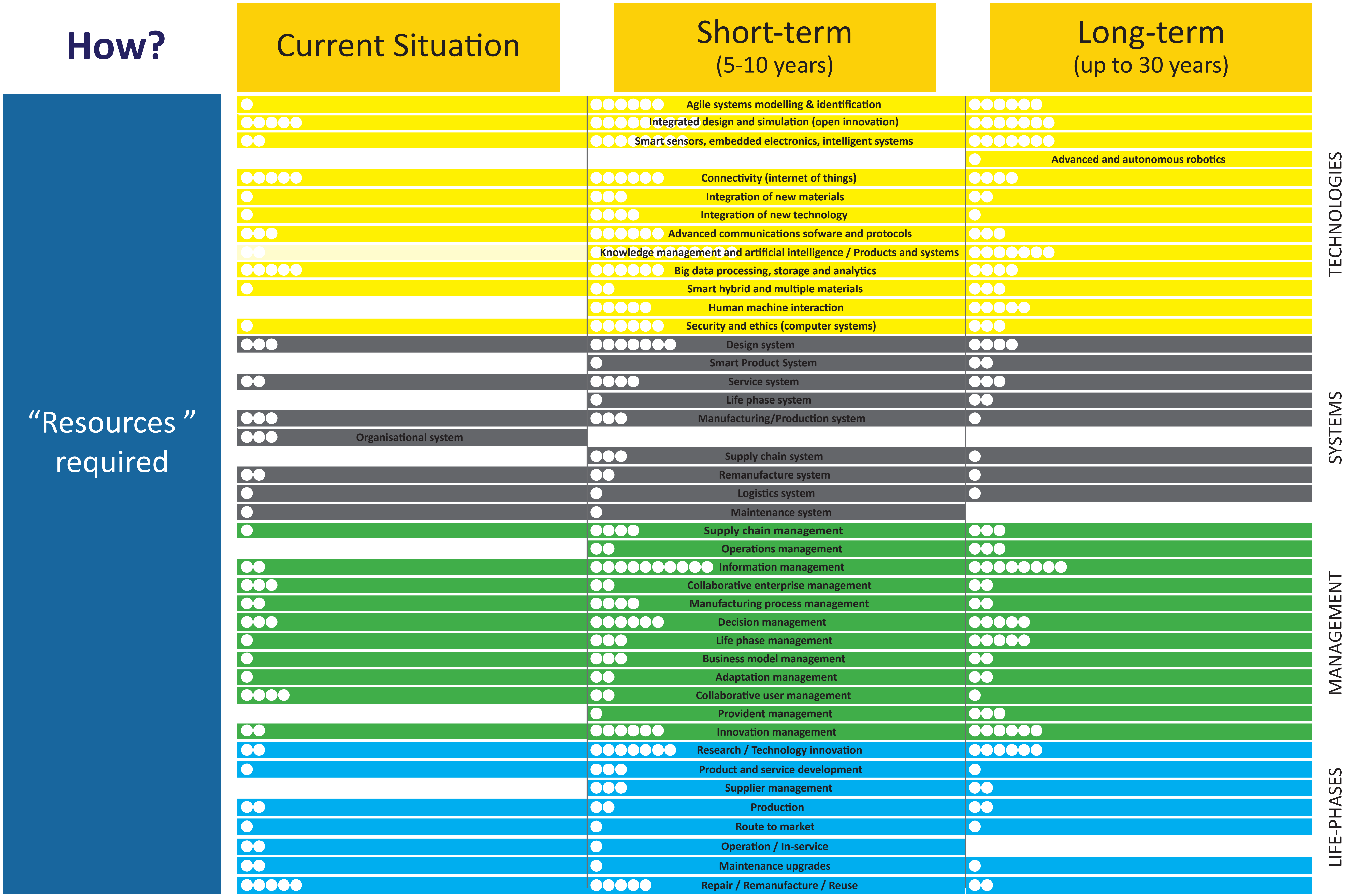
The "Why" roadmap shows trends and drivers contributing to the need for Smart Products Through-Life development. The elements of the roadmap are placed in the current, short-term or long-term column, based on when the need for a specific element would become most prominent. However, for all four roadmaps, the specific placement of an element within the column does not necessarily indicate the order importance considering time (e.g. cloud computing does not need to be developed before smart sensors are). The placement of more than one element in the same row was done due to space limitations.



Challenges found in the roadmap were identified through workshop activities observing the life phase specific challenges and smart product oriented challenges (specific products were observed and then challenges were generalised). Then in the final workshop these challenges were combined and placed in the roadmap, which instigated a discussion and lead to the identification of further challenges. The challenges are not specific to any field, industry or a product.



The “How” roadmap given here and on pages 30 and 31 are displaying the same data in two visually different ways. Here, shade of the colour per aspect signifies the necessity for the resource. Specific elements of resources within the four perspectives (life-cycle, management, system, technology) were mapped considering the support they would offer for specific challenges given in the “What” roadmap.



The roadmap shown here contains the same data as the roadmap on pages 28 and 29, but it shows the number of occurrences specific resources were identified as required, in each of the time based columns, to address different challenges given in the "What" roadmap. Number of occurrences is indicated by the number of white dots.

Conclusion

Strong dependencies between different aspects are required for smart-products through life. e.g. autonomous manufacturing, servicing, disposal and products cannot be considered independently as they are strongly interdependent.

In the similar initiatives, such as Industrie 4.0 and The Digital Thread, Design for X (where X stands for integration with smart through life systems) aspects are overlooked, and discussions so far show that it is one of the key aspects of the smart products through-life.

A well-developed business case for a smart product is the key to successful implementation. It has to take into account all the interdependencies, link design to manufacturing, in-service use and disposal, and demonstrate to the industry how changing the ways they operate can bring considerable benefits to the process and value creation through life.

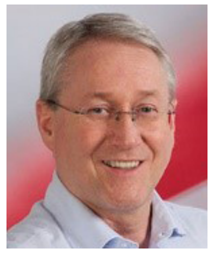
Impact should perhaps be added to the current roadmaps in the future incarnations, in order to better illustrate the benefits to the lifecycle of a product. Additionally case studies focusing on specific industries and specific products would help develop the concept further.

This is a large, multidisciplinary initiative requiring expertise in a variety of vastly different fields, and requiring long-term dedication and research over a number of different stages. It would be characterised by a long time scale, varied areas of expertise, through-life development focus and appropriate funding levels to support this vision. The current and long term sections of the roadmap illustrate the difference on where the industry currently is and where it needs to be. The right people in the UK need to be engaged, academic, industry policy makers etc.

Finally, the majority of workshop participants were interested in some form of future collaboration, and the connections established during the workshops between the Bath University, Cambridge University, Cardiff University, Cranfield University, DeMontford University, Loughborough University, Northumbria University, University of Bristol and University of Strathclyde are intended to be built on in the future.

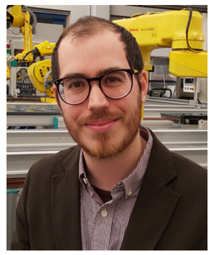
Appendix
Biographies of the workshop participants

Dr Alexandra Brintrup, University of Cambridge
Alexandra Brintrup is a senior research fellow at the Distributed Information & Automation Laboratory within the Institute for Manufacturing, University of Cambridge. She carries out research in the complexity of manufacturing systems, which aims to model, analyze and control dynamical and functional properties of emergent industrial systems. She develops intelligent systems to help organizations navigate through complexity. Her broader work in this area includes smart products and systems for traceability and automated product lifecycle management, using artificial intelligence and data analytics. After obtaining her PhD from Cranfield, she held postdoctoral, fellowship and lectureship appointments with the University of Cambridge, University of Oxford, and Cranfield University.



Prof Alex Duffy, University of Strathclyde
Alex Duffy is Professor of Systems Design and currently Head of Department of Design Manufacture and Engineering Management, at the University of Strathclyde. He is the editor of the Journal of Engineering Design, an Associate Editor of Design Science, a Strategic Advisory Board member for the International Journal of Design Creativity and Innovation, and on the editorial boards of the journals of Research in Engineering Design, Artificial Intelligence in Engineering Design Analysis and Manufacture, and the International Journal of Engineering Management and Economics. His research focusses on the application and development of artificial intelligence and cognitive based design, knowledge modelling and re-use, performance and process optimisation, integrated systems design, and design co-ordination. He has championed and co-ordinated an FP5 EU technology platform project (VRShips-ROPAX 2000) in distributed life-cycle management, worth 12M€, with 36 European partners, from 13 European countries. He was one of five leaders on VIRTUE, an 18M€ EU project with 23 European partners working on Integrated Computational Fluid Dynamics, one of four leaders on NECTISE (Network Enabled Capability Through Innovative Systems Engineering) an £8.4M joint EPSRC and BAE Systems project involving 10 UK university partners, and was a partner in SAFEDOR an 18M€ EU project on integrated Risk-Based design with 52 European partners. He is currently PI on a £1.1m EPSRC project studying cognitive based design.

Dr Michael Farnsworth, Cranfield University
Dr Michael Farnsworth is a Research Fellow at the Manufacturing Informatics Centre at Cranfield University. After completing his PhD in Computer Science from Cranfield University in 2013, he took up a research fellowship with the Through-life Engineering Services (TES) centre at Cranfield University. Covering research across artificial intelligence and robotics to self-healing autonomous systems he moved to the Manufacturing Informatics Centre to continue his research in artificial intelligence and optimisation of composite recycling processes.Michael has participated in national and international conferences, and contributed to several research projects during his academic career. His main research interests have been focused on computer science, artificial intelligence, self-healing, robotics and embedded systems.
At Cranfield University, his work is characterised by strong industrial collaboration, having worked with companies such as Rolls-Royce, BAE Systems, MoD, Bombardier Transportation, EnginSoft, and this is supported by excellent links with universities and research organizations worldwide.



Dr Vaggelis Giannikas, University of Cambridge
Vaggelis Giannikas is a research associate at the Institute of Manufacturing, University of Cambridge and the associate director of the Cambridge Auto-ID Lab. He holds a PhD in operations management from the University of Cambridge and a BSc in management science and technology from the Athens University of Economics and Business. In the past, he has been an editor and regular author for XRDS, the ACM magazine for students, and OR/MS Tomorrow, the INFORMS student magazine. His research work is focused in the areas of digital manufacturing, product intelligence, data analytics, supply chain management and logistics.

Dr Yee Mey Goh, Loughborough University
Dr Yee Mey Goh is a Senior Lecturer in Wolfson School of Mechanical and Manufacturing Engineering. She has 15 years of research expertise in through-life information management, uncertainty analysis/modelling and intelligent automation. Her research focusses on the development of data and knowledge-driven models and methods to support the design of product-service systems and advanced manufacturing technology. She has worked with the aerospace, defence, energy and automotive sectors. Her previous research income of over £7M is from IeMRC, EPSRC Centre for Innovative Manufacturing in Intelligent Automation, Impact Acceleration Account and industry. She has graduated 3 PhD students, published 21 journal papers and 36 conference papers. She is a Member of the Design Society and has served on the Scientific Committee for international conferences and journals, including the International Conference on Engineering Design (ICED), ASME IDETC/CIE, DESIGN and Engineering & Product Design Education Conference (E&PDE). She chairs the 14th International Conference on Manufacturing Research and is a committee member of The Consortium of UK University Manufacturing and Engineering for the Engineering Professors' Council.

Prof Bill Ion, University of Strathclyde
Prof. William Ion is currently Director of Research and Knowledge Exchange in the Department of Design, Manufacture and Engineering Management (DMEM) and was Head of Department from 2002 to 2008. He is also Projects Director within the Department's Advanced Forming Research Centre, a part of the High Value Manufacturing Catapult. His research interests include: knowledge information management; collaborative design environments; rapid and virtual prototyping; design for manufacture, advanced manufacturing and engineering design education. He has been an investigator on research and development projects totalling over £20m including the following: the JISC/NSF funded project with Stanford University "Distributed Innovative Design, Education and Teamworking" (DIDET); the EPSRC Grand Challenge project "Knowledge and Information Management Through Life' led by University of Bath IMRC; SAMULET (Strategic Affordable Manufacturing in the UK through leading Environmental Technologies) and over 20 Knowledge Transfer Partnerships since 1995. In recognition of his contribution to KTP he was given the 2013 UK Academic Ambassador award by the Technology Strategy Board. He is also Director of the EPSRC supported Industrial Doctorate Centre in Advanced Forming and Forging and a member of the The Design Society Advisory Board.

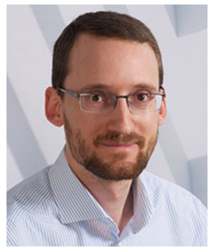
Prof Yun Li, University of Glasgow
Yun Li is Professor of Systems Engineering at University of Glasgow. He received his PhD in parallel computing and control from University of Strathclyde in 1990. During 1989 and 1990, he was with National Engineering Laboratory, East Kilbride, and Industrial Systems and Control Ltd, Glasgow. He joined the University of Glasgow as Lecturer in 1991 and served as Founding Director of University of Glasgow Singapore during 2011-2013. Since 1992, he has supervised 30 PhD students in intelligent systems, design for manufacture and evolutionary computation (EC). He developed one of the world's first 30 EC course in 1995 and the popular online interactive courseware GA Demo in 1997. In 1998, he established and chaired both the IEEE Computer-Aided Control System Design Evolutionary Computation Working Group and the European Network of Excellence in Evolutionary Computing (EvoNet) Workgroup on Systems, Control, and Drives for Industry. He has over 200 publications, one of which is elected by Thomson Reuters to "Research Front in Computer Science", one to "Research Front in Engineering", four to "Essential Science Indicators" (ESI), and two have been noted the most popular in IEEE Transactions on Control Systems Technology and the most cited in IEEE Transactions on Systems, Man, and Cybernetics – Part B: Cybernetics since their publications in 2005 and 2009, respectively. Professor Li is a Chartered Engineer in the U.K. and is currently an Associated Editor of IEEE Transactions on Evolutionary Computation and Guest Editor of Smart Design, Smart Manufacture and Industry 4.0 Special Issue for Energies.

Prof Duncan McFarlane, University of Cambridge
Duncan McFarlane is Professor of Industrial Information Engineering at the Cambridge University Engineering Department, and head of the Distributed Information & Automation Laboratory within the Institute for Manufacturing. He has been involved in the design and operation of industrial automation and information systems for twenty five years. His research work is focused in the areas of distributed intelligent automation, product intelligence, reconfigurable industrial systems, RFID integration, track and trace systems and valuing industrial information. Most recently he has been examining the role of automation and information solutions in supporting industrial services and infrastructure. Professor McFarlane is also Co-Founder and Chairman of RedBite Solutions Ltd - an industrial RFID and track & trace solutions company. He was Professor of Service and Support Engineering from 2006 to 2011 which was supported by both Royal Academy of Engineering and BAE Systems. Since 2010 he has been the Cambridge Professor of Industrial Information Engineering and is Co-Investigator in the Cambridge Centre for Smart Infrastructure and Construction.

Dr Aydin Nassehi, Bath University [21]
Dr. Aydin Nassehi is a Senior Lecturer (Associated Professor) at the University of Bath. He received his PhD in Mechanical Engineering from the University of Bath. In 2007, Dr Nassehi was appointed to a Research Council UK Research Fellowship and has gained promotions to Lecturer in 2012, and Senior Lecturer in 2013. He also gained an MSc in Software Engineering with distinction from the University of Oxford in 2013. His expertise is in manufacturing interoperability, computational informatics including energy efficiency modelling and analysis of manufacturing processes, knowledge based CAD/CAM and CAx systems. He has represented Bath on two FP7 programmes namely DEMAT and as the leader of the FP7 programme STEPMAN. He has published over 80 refereed papers and been on technical & scientific committees of a number of international conferences. He is a CIRP Associate Member, the convener of ISO standards group in charge of developing ISO14649 for physical device control (ISO TC184/SC1/wg7) and the Managing Editor of the International Journal of Computer Integrated Manufacturing

Dr Michael Packianather, Cardiff University
Michael Packianather obtained his BSc (Hons) in Electrical and Electronics Engineering in 1991 and MSc in Artificial Intelligence (AI) with Engineering Applications in 1992 from Cardiff University where he also completed his PhD in AI in 1997. Currently he is working as a Senior Lecturer at Cardiff University where he also runs the MSc course in Manufacturing Engineering, Innovation and Management. His research interest, among others, is in the development and application of AI in Smart Manufacturing. He was one of the investigators on the EPSRC-"Pipeline Logistics Improvement Programme (PLIP)", EC-TEMPUS MEDA "Academic Curriculum Development in Manufacturing Engineering (ACME)" and "Innovative Production Machines and Systems NoE". His recent project was funded by Innovate UK to investigate and research into Lean Manufacturing Process for an SME and provide technology transfer to improve production capacity, reduce waste and achieve energy efficiency. He is an External Examiner at the University of Gloucestershire for the BEng Integrated Engineering course, and at Coventry University for the BEng/BSc courses in Computer, Electronics, Telecommunications, Wireless Networks and Data Communications. He is an expert reviewer for EPSRC. His professional membership includes CEng and MIET. He is an active member of the IET South Wales Manufacturing & Management Technical Section and a Peer Review Associate College.

Prof Sheng-feng Qin, Northumbria University
Dr Sheng-feng Qin is Professor of Design at Northumbria University with an extensive career in design academia. Before he joined Northumbria University in 2014, he was a Lecturer and then a Senior Lecturer and Head of the CAD research group, in Department of Design at Brunel University from 2001 to 2013. Prior to this, he was a Postdoc Research Associate in the Manufacturing Systems Integration Research Institute (MSI), Loughborough University.
Professor Qin obtained his BSc and MSc degrees in China and his PhD degree in Digital Design Technology in the UK. His research interests include: computer-aided conceptual design, interaction and emotional design, crowdsourcing based product development platform, simulation driven design, smart product development, design for X and integrated digital design methods and tools.
Professor Qin has published more than 150 papers in peer-reviewed journals and conferences.



Dr Athanasios Rentzelas , University of Strathclyde
Athanasios Rentzelas, PhD, MSc, MEng, FHEA is a Lecturer in Operations and Engineering Management at the University of Strathclyde. His main areas of interest include Operations Management, Production Management, Supply Chain Management and Quality Management. More specifically, his research interests include modelling and optimisation of supply chain design, logistics and reverse logistics, sustainability assessment of supply chains, decision support systems and techno-economic analyses. The areas of application are primarily energy supply chains, including the biomass, waste and oil & gas supply chains. He has over 25 publications in academic journals and book chapters. His research has been supported by European and nationally funded projects.

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Dr Raj Srinivasan, University of Cambridge
Rengarajan Srinivasan received the Ph.D. degree in engineering from Cambridge University, Cambridge, U.K., examining the impact of information availability on maintenance decisions. He is currently working as a Research Associate with the Engineering Department, Cambridge University, Cambridge, U.K. He is based at the Institute for Manufacturing, where he is a part of the Distributed Information and Automation Laboratory. Currently, he is also working on developing whole life asset management decision making based value rather than cost. His research interests are in understanding the value of information for maintenance decision making, and managing disruptions in manufacturing operations.

Dr Gokula Annamalai Vasantha, University of Strathclyde
Dr. Annamalai Vasantha is a research associate in the Design Manufacture and Engineering management department, University of Strathclyde, UK. His research interests span across modelling and management of engineering processes, information and knowledge management, collaborative product development, product-service systems design, crowdsourcing, patent informatics, and rural development. He has published over 40 journal and conference papers in these research areas. He is an awardee of 'Young Researcher Award' from the committee of International Product-Service Systems, Tokyo, Japan, 2013.

Ms Tijana Vuletic, University of Strathclyde
Tijana Vuletic is a reseach assistant in the Design Manufacture and Engineering Management department, University of Strathclyde, UK. Her research interests include CAED supported engineering design, specifically CAD systems encompassing different design stages, from conceptual design to manufacturing, their integration in the lifecycle of a product and the effect they have on the final design. She is currently working on a project exploring systems engineering in the context of engineering design, particularly information exchange, tools supporting it, and ways to use them to best serve a complex system engineering design project.

Dr Ian Whitfield, University of Strathclyde
Dr Robert Ian Whitfield BEng PhD CEng MIED has a Systems Engineering background and research interests in collaborative design, decision support, design coordination, distributed design and working, knowledge management, lifecycle management, process design, risk engineering, and systems integration. He has written and coordinated the system integration work packages for EU and EPSRC research proposals with a total value of approximately £40M. These projects related to the development of collaborative design support, lifecycle management, and decision support for industry in the design of Engineering to Order products. Within the FP5,6,7 projects Dr Whitfield collaborated with a wide range of European shipbuilding industry as an expert in systems integration and collaborative design.

Dr Erfu Yang, University of Strathclyde
Dr Erfu Yang is a Lecturer in the DMEM. His main research interests include robotics, autonomous systems, mechatronics, manufacturing automation, computer vision, image/signal processing, nonlinear control, process modelling and simulation, condition monitoring, fault diagnosis, multi-objective optimizations, and applications of machine learning and artificial intelligence including multi-agent reinforcement learning, fuzzy logic, neural networks, bio-inspired algorithms, and cognitive computation, etc. He has over 60 publications in these areas, including more than 30 journal papers and 5 book chapters. He has been awarded 7 research grants as PI (principal investigator) or CI (co-investigator) from UK, China and Japan.
Dr Yang has been a Scientific/Technical Programme Committee member or organizer for a series of international conferences and workshops. He has also served for many international journals and conferences as a scientific reviewer or a guest editor. He was a Literature Surveyor for the leading International Journal of Adaptive Control and Signal Processing (published by Wiley). He is now an associate editor for the Cognitive Computation journal published by Springer.

Prof Shengxiang Yang, De Montfort University
Shengxiang Yang is a Professor of Computational Intelligence (CI) and the Director of the Centre for Computational Intelligence, School of Computer Science and Informatics, De Montfort University, Leicester, U.K. He has worked for 20 years in the areas of CI methods (e.g., evolutionary computation, swarm intelligence, meta-heuristics, and artificial neural networks) and their applications for real-world problems (e.g., data mining and analysis, production scheduling, communication and transportation network optimisation problems). Especially, he is a world leading researcher in CI in Dynamic and Uncertain Environments. He has over 210 publications. His research has been supported by EPSRC, Royal Academy of Engineering, Royal Society, EU FP7 and Horizon 2020, Chinese Ministry of Education, and industry (e.g., BT, Honda, Rail Safety and Standard Board (RSSB), and Network Rail), etc., with a total funding of over £1.2M to him as the PI. He serves as an Associate Editor or Editorial Board Member for 7 international journals. He is the Chair of the Task Force on Evolutionary Computation in Dynamic and Uncertain Environments, under the IEEE Computational Intelligence Society (CIS) Evolutionary Computation Technical Committee, and the Founding Chair of the Task Force on Intelligent Network Systems, under IEEE CIS Intelligent Systems Applications Technical Committee.

Prof Hongnian Yu, Bournemouth University
Professor Hongnian Yu has held academic positions at the Universities of Sussex, Liverpool John Moor, Exeter, Bradford, Staffordshire and now Bournemouth in the UK. He is currently Professor in Computing at Bournemouth University. He has extensive research experience in mobile computing, modelling, scheduling, planning, control, and simulations of large discrete event dynamic systems with applications to manufacturing systems, supply chains, transportation networks, computer networks and RFID applications, robotics and mechatronics. He has successfully supervised 16 PhD theses and 18 Master by Research theses, is supervising 8 PhD students, and has examined over 30 PhD/MPhil students' theses as both internal and external examiner. He has trained 11 post-doctoral research fellows. He has published over 200 journal and conference research papers. He has held several research grants worth about five million pounds from the UK EPSRC, the Royal Society, and the European, AWM, as well as from industry. He has managed several international large consortiums as a coordinator.

Other workshop participants

Dr Leo Chen, Glasgow Caledonian
Dr Laura Justham, Loughborough University
Mr Stephen Marshall, University of Strathclyde
Dr Michael Rovatsos, University of Edinburgh
Dr Chris Snider, University of Bristol

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Glossary and Acronyms

AM -Agile Modelling
BMM - Business Model Management
EPSRC - Engineering and Physical Sciences Research Council
HVM - High Value Manufacturing
IM - Information Management
InM - Innovation Management
IP - Intellectual Properties
OEM - Original Equipment Manufacturer
PLM - Product Lifecycle Management
SME - Small and Medium-sized Enterprises
UI - User Interface
WEEE - Waste Electrical and Electronic Equipment

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