REPORT ON
Future of Manufacturing Initiative
# CONTENTS

<table>
<thead>
<tr>
<th>Chapter</th>
<th>Pages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Executive Summary</td>
<td>01</td>
</tr>
<tr>
<td>Chapter 1: The Importance of Manufacturing</td>
<td>03</td>
</tr>
<tr>
<td>Chapter 2: Approach to the Development of the Future of Manufacturing Initiative</td>
<td>09</td>
</tr>
<tr>
<td>Chapter 3: Recommendation 1 – Create Public–Private Partnership Platforms to Drive Technology Innovation, Knowledge Transfer and Adoption</td>
<td>13</td>
</tr>
<tr>
<td>Tech Labs</td>
<td>14</td>
</tr>
<tr>
<td>Tech Access</td>
<td>17</td>
</tr>
<tr>
<td>Tech Depot</td>
<td>17</td>
</tr>
<tr>
<td>Chapter 4: Recommendation 2 – Invest in R&amp;D Programmes that Create Differentiation</td>
<td>19</td>
</tr>
<tr>
<td>Chapter 5: Recommendation 3 – Build and Raise Awareness of Standards in the Future of Manufacturing</td>
<td>23</td>
</tr>
<tr>
<td>Conclusion and Implementation Strategy</td>
<td>25</td>
</tr>
</tbody>
</table>

### ANNEXES

<table>
<thead>
<tr>
<th>Annex</th>
<th>Pages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annex A: Composition of the Committees of the FoM Initiative</td>
<td>27</td>
</tr>
<tr>
<td>Annex B1: Technology Roadmapping Process</td>
<td>30</td>
</tr>
<tr>
<td>Annex B2: Technology Roadmaps for Prioritised Technology</td>
<td>31</td>
</tr>
<tr>
<td>Annex C1: Technology Roadmaps for Electronics Sector</td>
<td>35</td>
</tr>
<tr>
<td>Annex C2: Technology Roadmaps for Chemicals Sector</td>
<td>39</td>
</tr>
<tr>
<td>Annex C3: Technology Roadmaps for Precision Engineering Sector</td>
<td>45</td>
</tr>
<tr>
<td>Annex C4: Technology Roadmaps for Transport Engineering Sector</td>
<td>49</td>
</tr>
</tbody>
</table>
Chapter 1 | The Importance of Manufacturing

Globally, technology trends and industry shifts are emerging and growing in strength that will shape a future of manufacturing and change how products are manufactured and distributed. Demand from customers is driving the shift to mass customisation and manufacturing for eventually a lot size of one. A common understanding of the various opportunities and challenges related to manufacturing has been established. It is one of enhancing operating assets efficiency through data-driven manufacturing, leveraging gains in advanced disruptive manufacturing technologies such as robotics and additive manufacturing. Notably, the increasing pace of digitalisation and the emergence of a digital thread connecting the various parts of the manufacturing value chain opens up new manufacturing business models such as the servitization of manufacturing; from selling physical products to services. In this aspect, the Industrial Internet of Things will serve as a key and important enabler.

I. Manufacturing continues to be a key pillar of Singapore’s economy. Investing in R&D and promoting technology adoption and having a higher skilled workforce with greater productivity are critical to the sustenance of Singapore’s competitiveness in manufacturing. For companies to identify Singapore as a location of choice to set up their manufacturing activities, Singapore would need to:

- Remain attractive as a pilot location for cutting-edge technologies and systems
- Grow new activities to be a thought leader and first mover in growth areas

III. The deliberations of the Future of Manufacturing (FoM) initiative1 focused on the technology aspect of the Future of Manufacturing. This report is envisaged for use as a strategic plan for Singapore’s manufacturing sector in RIE2020. The efforts of the FoM Initiative culminated in the development of a roadmap of capabilities needed to achieve the competencies required in an advanced manufacturing operation, along with recommendations on the standards required for FoM activities in Singapore.

IV. To enable technology co-innovation, knowledge transfer and technology adoption by enterprises, the following near term recommendations involving the establishment of public-private partnership platforms were proposed:

- TECH LABS: Building a network of model factories to bring together the ecosystem of industry end-users, technology providers and research performers to co-innovate and test-bed advanced manufacturing technologies in a pilot production setup
- TECH ACCESS: Providing technology access to advanced manufacturing equipment and facilities for industry
- TECH DEPOT: Establishing a Tech Depot to create a suite of plug-and-play technologies that are easy to use

V. The development of R&D programmes was also identified as a critical thrust in creating differentiation. These programmes were guided by the areas identified in the conducted technology roadmapping exercise and prioritised in consultation with the economic agencies. Details of the technology areas are articulated in the main report.

VI. A*STAR will work in partnership with other economic agencies (EDB and SPRING) and Trade Association and Chambers (TACs), to lead the implementation of these recommendations in RIE2020.

1 A*STAR’s FoM Initiative was developed over an eight-month period from January to August 2016. The exercise involved extensive engagement and consultation of multiple stakeholders, including various industry clusters, Trade Association and Chambers (TACs), the Ministry of Trade and Industry (MTI), economic agencies (A*STAR, EDB and SPRING) and Institutes of Higher Learning (IHLS). A total of 104 representatives participated in the strategy development and technology roadmapping exercise, where the roadmaps were validated through industry roundtable discussions and one-to-one engagements with 58 companies from the eight Advanced Manufacturing and Engineering (AME) industry clusters.
CHAPTER 1  | The Importance of Manufacturing

Global Advanced Manufacturing Landscape


2. In the United States, former President Obama called for the establishment of a National Network of Manufacturing Innovation Institutes (NNMI) to scale up advanced manufacturing technologies/processes, which included the Digital Manufacturing & Design (DMDII) and the Lightweight, Modern Metals & Advanced Composites Manufacturing Innovation Institutes launched in 2014/2015. The Industrial Internet Consortium (IIC) was also set up in 2014 to accelerate the growth of the Industrial Internet by coordinating ecosystem initiatives. These included the connection and integration of objects with people, processes and data using common architectures, interoperability and open standards which would lead to transformational business outcomes.

3. In May 2015, China unveiled its “Made in China 2025” masterplan with a budget of US$1.3B over 10 years to increase its manufacturing competitiveness. Major projects such as the setting up of a manufacturing innovation centre and boosting of intelligent manufacturing were revealed. Key target sectors included Aerospace, New Materials and Robotics.

4. A year later in May 2016, Japan’s Industrial Competitiveness Council approved the Japan Revitalisation Strategy 2016, chaired by Prime Minister Shinzo Abe. The Strategy involved establishing a public–private council as the government control tower and promoting “smart factories” and the use of big data. The Robot Revolution Initiative Council was also set up with the aim to double the use of robotics in manufacturing, and increase the robotics use by twenty-fold in other sectors, including services.

5. Indeed, a common international understanding of how manufacturing activities will change in the future has been established. The increasing pace of digitalisation with the emergence of a digital thread connecting the various parts of the manufacturing value chain, mass customisation and manufacturing in lot size of 1, and the advancement of disruptive advanced manufacturing technologies such as robotics and additive manufacturing are clear drivers for new activities and manufacturing business models. To support these future activities, it would be important to ensure that the manufacturing workforce is enabled to adapt to the new advanced manufacturing concepts. Learning environment platforms will be required to allow workers to have an immersive experience. The ongoing global initiatives in manufacturing create a strong impetus for Singapore to stay relevant and be thoroughly equipped to compete on the international stage.
Manufacturing as a Key Driver of Growth in Singapore

6. Manufacturing has played a major role as a key growth engine for Singapore’s economy over the last 50 years. As depicted in Figure 1, Singapore’s manufacturing gross domestic product (GDP) contribution stood at around 20% from 2008 to 2015. The Committee for the Future Economy (CFE), whose report was released in early 2017, recommended that Singapore must retain a globally competitive manufacturing sector, with further value-added from manufacturing related services.

7. In 2016, the contribution of manufacturing to Singapore’s GDP stood at 19.6% (Figure 2a). For the whole of 2016, the manufacturing sector grew by 3.6%, a reversal from the 5.1% contraction in the previous year.

8. From 2006 to 2016, manufacturing output and value added (VA) grew at a compounded annual growth rate (CAGR) of 1.1% and 2.3%, respectively. In addition, the manufacturing sector had generated strong spillovers. A recent study showed that in 2005, every S$1 of manufacturing VA created S$0.25 of additional VA to the rest of the economy. By 2012, this had risen to S$0.34 as the sector strengthened its linkages with other sectors, particularly with business services and wholesale trade. The breakdown of VA according to the various manufacturing industry clusters in 2016 is shown in Figure 2b.

9. A relatively stable manufacturing workforce of 530,000, which formed 13.6% of total employment in Singapore in 2016, had supported the growth of the sector since 2009.

10. Moving forward, the rapid pace and pervasive nature of digitalisation, and disruptive technologies such as robotics and additive manufacturing will shift the nature of manufacturing and create new business models. The emergence of the ASEAN region, in both production capacity and consumption needs, presents an opportunity to fuel the growth of the manufacturing sector. To address our land constraints and slower workforce growth rate of between 1% and 2% up to 2020 as outlined in the Population White Paper, it is also to Singapore’s benefit to be a manufacturing innovation hub as a means to enable the sector to be more competitive, and have a higher skilled workforce with greater productivity.

---

1 Source: Department of Statistics (DOS).
2 Source: Report of the Committee of Future Economy, 2017. The Committee on the Future Economy (CFE) is a 30-member committee comprising members from different industries that operate in both global and domestic markets, as well as enterprises both large and small. It is chaired by Minister for Finance Heng Swee Keat and Minister for Trade and Industry S Iswaran. The CFE aims to keep the Singapore economy competitive by helping to position Singapore for the future, as well as identify areas of growth with regard to regional and global developments. To do this, the CFE will build on and update the 2010 Report of the Economic Strategies Committee (ESC), whose recommendations have enabled us to keep our economy competitive. But rapid changes in the global environment, technological change, and a slower labour force growth has presented us with new challenges and opportunities. Thus, it is timely for us to review what we are doing and to see how we can position ourselves better for the future.
3 Source: National Population and Talent Division (NPTD).
4 Source: Ministry of Manpower (MOM). Manufacturing workforce refers to all the employees of companies in the manufacturing sector. These members of the workforce would cover all the job functions in a typical manufacturing company, including non-production roles.
11. In the Research, Innovation and Enterprise 2020 Plan (RIE2020) announced by Prime Minister Lee Hsien Loong on 8 January 2016, eight AME industry clusters were identified to grow Singapore’s manufacturing sector based on various factors, including the extent of contribution to Singapore’s economy, industry outlook and potential in which Singapore could be a global leader. The eight industry clusters are:

- Aerospace
- Biologics & Pharmaceutical Manufacturing
- Chemicals
- Electronics
- Machinery & Systems
- Marine & Offshore
- MedTech Manufacturing
- Precision Modules & Components

Of these identified industry clusters in the AME domain, Singapore has attained strong global recognition, for example, in the Aerospace industry cluster, where we commanded close to a 25% share of the Asia-Pacific MRO (maintenance, repair and overhaul) market. In the Electronics industry cluster, Singapore produced in the past nearly 40% of global hard disc drive (HDD) media.

12. To position the Singapore economy for the future, the Government launched the development of the Industry Transformation Maps (ITMs) for over 20 industry clusters, including those in manufacturing such as Electronics, Chemicals and Precision Engineering. It is envisaged that the ITMs will serve as integrated plans for the Government to work with industry and through agencies such as TACs to support sector and company-level efforts in growth, productivity improvement, skills development, technology and innovation as well as internationalisation.

13. Growth and transformation of existing manufacturing industry clusters will be key to achieving our 2020 aim of maintaining the manufacturing sector’s 20% contribution to the country’s GDP, with only incremental growth in the manufacturing workforce in certain industries. Transformation of the installed base of companies within each industry cluster would be an area of focus, so as to boost the overall productivity and competencies of the industry cluster. The availability and accessibility of domestic R&D and technology capabilities will play a critical enabling role in supporting our vision of transforming the local manufacturing base from simply being a competitive manufacturing site to a global lead manufacturing hub.

14. Beyond targeting growth within existing manufacturing industry clusters, growth can also be captured by leveraging existing pockets of capabilities and adjacent expertise to seed new niches. One example is the development of a Food and Nutrition industry sub-cluster by capitalising on Singapore’s current capabilities in discovery and production of high-value ingredients and an installed base of related multi-national corporations (MNCs) and small and medium-sized enterprises (SMEs).

8 Source: Economic Development Board (EDB).

* Industry Transformation Maps (ITMs) were announced by Finance Minister Mr Heng Swee Keat at Budget 2016 as part of the Industry Transformation Programme. The aim is to review and sharpen the value proposition of Singapore’s companies so that they are the best that they can be, and are relevant to the global economy. A total of 23 ITMs have been identified, including AME-related industry clusters such as Precision Engineering, Electronics, Aerospace and Chemicals.
Key Players in the Development of the FoM Initiative

15. The various players spearheading the development of the FoM Initiative are illustrated in Figure 3. A Steering Committee comprising Institutes of Higher Learning (IHLs), economic agencies and industry leaders was set up to establish the vision and desired outcomes for the FoM for Singapore. Four sub-committees were also convened and their respective scopes are detailed as follows:

- **INDUSTRY:**
  Evaluation of Singapore’s manufacturing sector landscape

- **ADVANCING CURRENT MANUFACTURING:**
  Evaluation of conventional manufacturing technologies

- **ENABLING & DISRUPTIVE TECHNOLOGIES:**
  Identification of undergirding capabilities and technologies that enable disruption in manufacturing

- **STANDARDS & POLICY:**
  Evaluation of the impact of standardisation and regulations on FoM

16. The members of all committees are listed in Annex A.

![Organigram of the FoM Initiative](figure3)
Differentiated Approach for Each Enterprise Segment

17. Digitalisation is a thread that pervades the fabric of FoM, linking multiple different players across the ecosystem. Different industries and enterprises are at varying phases in their internal adoption of digital technologies. This requires a convener of partnership platforms to bring together the various players so as to demonstrate and fully realise the potential of FoM and to allow enterprises to learn together as a community. The convening of partnership platforms is a multi-agency effort which would be centrally coordinated by A*STAR.

A*STAR’s envisioned value proposition to the different enterprise segments is as follows:

- **Support for large companies [MNCs and large local enterprises (LLEs)] to raise the efficiency of their locally based manufacturing facilities by providing them access to advanced manufacturing capabilities, test-beds and a conducive ecosystem to develop and co-create FoM solutions with public-sector research organisations**

- **Support for SMEs by developing easy-to-use tools and applications that are scalable and easily adopted. SMEs that are more advanced in their manufacturing processes could partner A*STAR to be the first to implement FoM technologies in Singapore**

Developing the FoM Strategy

18. Fundamentally, the essence of FoM involves increased efficiency and higher productivity. The importance is accentuated in high mix/low-volume operations. Thus, the FoM strategy was developed with the vision to transform Singapore into a technology innovation hub for manufacturing by becoming a pilot location for cutting-edge technology and systems, and to be a thought leader and first mover in growth areas.

19. Technology innovation has always been the driver of manufacturing sector transformation. As outlined in Figure 4, the various Industrial Revolutions throughout modern history have been characterised by distinct technology innovations.

20. Singapore aims to i) continually enhance a base of technologies to advance our current manufacturing methods; and ii) identify and develop leadership in selected disruptive technologies.

21. Realising the potential of the FoM initiative in Singapore will involve three main flanks: i) technology, ii) industry and iii) manpower development. This would serve as a roadmap for companies wishing to adopt FoM practices; and the same process can be used as a template for companies in other sectors.

22. Building on these aspects, the key pillars of the FoM strategy can be distilled as follows:

- **RECOMMENDATION 1:** Create public–private partnership (PPP) platforms to drive technology innovation, knowledge transfer and adoption

- **RECOMMENDATION 2:** Invest in R&D programmes that create capabilities in disruptive technologies

- **RECOMMENDATION 3:** Build and raise awareness on Standards in FoM

---

18 Source: German Research Centre for Artificial Intelligence (DFKI).
CHAPTER 3

Recommendation 1: Create Public–Private Partnership Platforms to Drive Technology Innovation, Knowledge Transfer and Adoption

23. Three new public–private partnership platforms (PPP) platforms will be developed under Recommendation 1, namely Tech Labs, Tech Access and Tech Depot. The scope of each platform is detailed in Figure 5 and accounts for the variations in enterprises (i.e. MNCs, LLEs and SMEs).11

Tech Labs

24. Tech Labs, positioned as “Model Factories @ X”, where X is the location of the aforesaid Model Factory provide a platform for the ecosystem of research performers, end users, technology providers and system integrators to co-innovate, test and demonstrate FoM technologies. Depending on the capabilities required and areas of emphasis, the Model Factories may be located both at public and private sector premises. The Model Factories can be used by engineers and technicians for applied learning experience, which they can quickly implement in their own organisations. The operating model of the Tech Labs is depicted in Figure 6.

A*STAR has developed two Model Factories, namely Model Factory @ SIMTech; and Model Factory @ ARTC, which will be sited at two locations:

SINGAPORE INSTITUTE FOR MANUFACTURING TECHNOLOGY (SIMTECH):
SIMTech develops high-value manufacturing technology and human capital to enhance the competitiveness of Singapore’s manufacturing industry. It collaborates with multinational and local companies in the Electronics, Semiconductor, Precision Engineering, Aerospace, Automotive, Marine, MedTech, Logistics and other industry clusters.

ADVANCED REMANUFACTURING AND TECHNOLOGY CENTRE (ARTC):
ARTC is a platform built upon strong partnerships with the industry across the supply chain complemented by technical support from research institutes and academia and operates as a consortium model. It is modelled after the UK’s Advanced Manufacturing Research Centres (AxRC) consortium model concept. With a purpose-built facility, and world-class research expertise at A*STAR and NTU, ARTC works to rapidly create technology solutions and bring them into industrial production. The current technology focus: Repair & Restoration, Surface Enhancement, Robotics, Product Verification and Additive Manufacturing.

11 These will be in addition to A*STAR’s installed legacy efforts, e.g. industry engagements through various modes in RIs, Centres of Innovation and joint-labs.
The Model Factory @ SIMTech

26. The Model Factory @ SIMTech will encompass a low-cost, digital Learning Factory (LF) platform particularly for companies at the beginning of their FoM journey. LF refers to an actual production environment that would allow for the experimentation and experiential learning of manufacturing system technologies (e.g. production planning and scheduling, overall equipment effectiveness).

27. The target end users are SMEs focused on discrete manufacturing which include processes such as those shown in Figure 7.

The processes and test-bed areas have been specifically selected as areas which are important to a large number of SMEs in the manufacturing sector. SMEs will have the opportunity to experience the impact of FoM to their own businesses through masterclasses, workshops and modules.

The Model Factory @ ARTC

28. The Model Factory @ ARTC will be a Factory of the Future (FoF) platform for companies investing in advanced manufacturing processes with a focus in coupling smart and virtual (i.e. Digital Twin) capabilities. Target end users include larger enterprises and MNCs in heavy engineering such as for the Aerospace industry cluster.

29. Four manufacturing lines will be implemented in the FoF platform, namely

- Advanced discrete manufacturing line
- Additive manufacturing line
- Continuous line
- Virtual showcase

The details of the four lines are illustrated in Figure 9.
Tech Access

30. The “Tech Access” initiative offers access to A*STAR’s installed base of advanced manufacturing facilities and equipment and expertise, thereby mitigating the high upfront cost of investment. It can be provided in various combinations of:

- Access to use of the equipment
- User training
- Consultancy

to optimise equipment effectiveness. From the experience gained and benefits validated with the adoption of such technologies, the SMEs could then opt to scale and acquire their own equipment to capture new business opportunities.

31. The suite of research equipment offered by A*STAR range from inspection tools to advanced equipment such as robotised 3D scanners and high-pressure cold spray for additive manufacturing. The implementation would take into account factors such as liability, equipment training, booking policy and pricing model. To promote the availability of the facilities, publicity and outreach events to potential users would be organised, in conjunction with TACs12 and other relevant organisations.

Tech Depot

32. In cases where public-sector offerings of capabilities and talent may be insufficient for the needs of any particular growth area, SMEs could also come together in private-sector-led initiatives funded by the Singapore Government. An example of such an effort is the consolidation of Additive Manufacturing (AM) projects of six Precision Engineering companies into a single entity – Forefront Additive Manufacturing Pte Ltd. The benefits of such a collaboration include a more focused development of AM applications in Singapore and equipment sharing between amongst the companies to maximise utilisation.

33. The “Tech Depot” initiative will provide readily accessible and deployable technologies for SMEs’ adoption. The implementation of Tech Depot will be overseen by A*STAR’s SME Office. The interactions between Tech Depot and the stakeholders are depicted in Figure 10.

34. Examples of ready-to-go (RTG) and pipeline Tech Depot technology solutions are listed in Table 1.

<p>| TABLE 1: EXAMPLES OF TECH DEPOT TECHNOLOGY SOLUTIONS |
|---------------------------------|---------------------------------|</p>
<table>
<thead>
<tr>
<th>READY TO GO</th>
<th>PIPELINE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inventory Management and Tracking System</td>
<td>Modstore</td>
</tr>
<tr>
<td>Advanced Machining Dynamic Optimiser for High Productivity and Surface Quality</td>
<td>Augmented Reality Platform (provides real-time augmented information for the intelligent workforce)</td>
</tr>
<tr>
<td>Maintenance Operation System (Production Planning and Tracking)</td>
<td>Generic Mobile Workflow and Configurable Mobile Apps for On-the-Go Staff Management</td>
</tr>
<tr>
<td>Shop Floor Machine Effectiveness Monitoring System</td>
<td>Digital Workbench (a system to augment and eliminate errors in the assembly line by digitalising processes of workflow)</td>
</tr>
<tr>
<td>FITPRISE (a web-based Enterprise Management System)</td>
<td>Localisation (tags/sensors to help to track location of workers and/or equipment)</td>
</tr>
<tr>
<td></td>
<td>Health/condition monitoring for machines</td>
</tr>
<tr>
<td></td>
<td>Collection, Delivery and Management System</td>
</tr>
<tr>
<td></td>
<td>RFID based Counting and Tracking System (Gantry system)</td>
</tr>
</tbody>
</table>

12 These include the Singapore Manufacturing Federation (SMF) and Singapore Precision Engineering and Technology Association (SPETA)
CHAPTER 4

Recommendation 2:
Invest in R&D Programmes that Create Differentiation

35. The Technology Roadmapping Methodology encompasses three phases:
   - Survey & Identify
   - Contextualise & Prioritise
   - Implementation

Details of the Technology Roadmapping exercise are attached in Annex B1.

36. The list of prioritised areas are indicated in Figures 11a and 11b. The technology roadmaps of these prioritised areas are attached in Annex B2. The prioritised base of key current manufacturing technologies for advancement as well as disruptive technologies would be developed into R&D programmes. These R&D programmes aim to seed long-term capabilities for future industry readiness, with the potential to transform or disrupt Singapore’s existing manufacturing sector.

37. The technology roadmaps were also developed for the following industry sectors: Electronics, Chemicals, Precision Engineering and Transport Engineering and are attached in Annex C. These roadmaps outline the capabilities needed for different sectors, across various time horizons, to build advanced manufacturing expertise.
FIGURE 11a: PRIORITISED DISRUPTIVE AREAS (PART 1)

Smart Robotics & Intelligent Adaptive Automation
- Human-Robot Collaborative Systems
- Learning Robotic Systems
- Mobile Manipulation
- Adaptive and Reconfigurable Robotics Systems
- Next Generation Robot Design

Big Data Analytics for Manufacturing
- Machine Learning for Active Artificial Intelligence
- Sensing Analytics for Equipment and Product Management
- Cyber-security for Big Data Analytics
- Insight-driven EAM and PLM Platforms
- Big Data Analytics for Personalized Biomedicine
- Tactile Internet for Distributed Remote Manufacturing

3D Additive Manufacturing
- Integrated Design & Simulation platform
- On-Site/in-Situ Direct Manufacturing/Repair
- 3D Biomedical Applications
- Multi-Materials & Micro-Features
- 3D Customized Food Fabrication

Medical Technology and Devices for Aging and Rehabilitation
- Manufacturing of Medical Technology
- Device Designing, Manufacturing, Materials Manufacturing & Integration of Sensors to Wearables

Smart Urban Logistics and SCM
- Open Supply Chain Towards Sharing Economy
- Smart Last Mile Logistics
- Sensing-Driven ANTICIPATORY Demands
- Sustainable Supply Chain towards Circular Economy

Multi-functional materials for FoM
- Smart Materials
- Advanced Composites for packaging and repair
- Functional & adaptive materials
- Digitization of Materials

Legend: Text in orange are prioritized disruptive technologies

FIGURE 11b: PRIORITISED DISRUPTIVE AREAS (PART 2)

Industrial Internet of Things and CPS
- Robust IIoT security system
- Smart Sensors & actuators
- Predictable OS for CPS
- Cognitive wireless network
- Digital twin Unified Platform
- Ultra low power sensor node computing
- Integrated Positioning System for Precise Inventory Tracking

Industriatisation of Personalised Medicine and Synthetic Biology, and Drug Delivery and In vitro Toxicology Systems
- Industriatisation of personalised medicine
- Industrialization of Synthetic Biology Bioproceses
- Formulation and drug delivery systems
- Automation and High-throughput In Vitro Toxicology

Advanced AGVs and UVs
- Deep learning powered Machine Perception
- Smart Power & Charging Infrastructure
- Advanced Navigation & Autonomous technologies
- Secure Advanced AGVs and UVs
- High Precision Sensing for Localization & Tracking
- Materials Light weighting and Reconfigurable Platforms for UVs

Bio-manufacturing of Cell, Tissues and Organs
- Manufacturing Technologies for Cell and Cell-derived Products
- Manufacturing of Tissues and Organs
- Advanced Metrology and Monitoring for Bio-manufacturing

Zero waste manufacturing
- Smart Remanufacturing at large scale
- Manufacturing Waste-to-Resource Conversion
- Industrial Symbiosis

Legend: Text in orange are prioritized disruptive technologies

AGV: Autonomous Guided Vehicle
CPS: Cyber-physical System
EAM: Enterprise Asset Management
OS: Operating System
PLM: Product Lifecycle Management
UV: Unmanned Vehicle
CHAPTER 5

Recommendation 3: Build and Raise Awareness of Standards in the Future of Manufacturing

38. Standards will be integral to the implementation phase of the FoM strategy, to ensure an unbroken digital thread across the whole value chain of manufacturing. In particular, it would be necessary for the entire advanced manufacturing ecosystem to reach a consensus on the types of standards that would be required for connectivity, interoperability and security.

39. SPRING’s Quality and Standards (Q&S) division, which oversees the Q&S process in Singapore, serves as the main link between the Singapore Standards Council (SSC) to international standards bodies such as the ISO, IEC and ITU.

40. Industry-led standards development organisations are emerging, an example of which is the Industrial Internet Consortium (IIC). Launched in March 2014 by five companies (i.e. AT&T, Cisco, GE, IBM and Intel), the IIC is an open, neutral “sandbox” where industry, academia and government met to collaborate, innovate and enable the Industrial Internet.

41. To address the rapid pace of developments of standards in the FoM space, SPRING has convened an Expert Group in Smart Manufacturing, represented by a wide range of public-sector organisations, IHLs and companies, whose role is to evaluate worldwide trends and developments involving standards in FoM. The Expert Group will advise on the scope for Smart Manufacturing standardisation in Singapore, identify and prioritise opportunities and gaps in the standardisation landscape and develop a national standardisation roadmap for Smart Manufacturing.

42. As part of the effort to raise awareness and build capacity for FoM standards development, SPRING and A*STAR will also jointly organise a conference on standards for FoM. The conference will endeavour to bring together both local and international participants from industry, academia and government. A desired output of this conference is a set of guidelines that industry and researchers can adhere to in the implementation of standards for FoM.

13 The Singapore Standards Council (SSC), which is supported by SPRING and oversees several local Standards Committees such as the Manufacturing Standards Committee, the Information Technology Standards Committee and the Chemical Standards Committee, were consulted as part of the standards development process to support the implementation of the FoM strategy.

14 International Organization for Standardization, ISO; International Electrotechnical Commission, IEC; International Telecommunication Union, ITU.

15 The mission of the IIC was to accelerate growth of the Industrial Internet through coordinating ecosystem initiatives in an effort to connect and integrate objects with people, processes and data using common architectures, interoperability and open standards which would ultimately lead to transformational business outcomes. Through its membership in the IIC, A*STAR would be kept updated on the IIC’s efforts in the FoM space.
Conclusion and Implementation Strategy

43. The FoM strategy was developed as a cornerstone of the vision to transform Singapore into a technology innovation hub for manufacturing by becoming a pilot location for cutting-edge technology and systems, and to be a thought leader and first mover in growth areas.

44. The FoM strategy was developed in close consultation with various stakeholders from IHLs, industry and agencies.

45. In summary, the recommendations undergirding the FoM strategy are as follows:

- **RECOMMENDATION 1:** Create public–private partnership (PPP) platforms to drive technology innovation, knowledge transfer and adoption

- **RECOMMENDATION 2:** Invest in R&D programmes that create differentiation

- **RECOMMENDATION 3:** Build and raise awareness on Standards in FoM

46. A*STAR, in partnership with other economic agencies and TACs, would lead the implementation of these recommendations in RIE2020.
## ANNEX A

### Composition of the Committees of the FoM Initiative

#### Steering Committee

<table>
<thead>
<tr>
<th>S/N</th>
<th>NAME</th>
<th>DESIGNATION</th>
<th>ORGANISATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Dr Raj Thampuran (Chair)</td>
<td>MD</td>
<td>A*STAR</td>
</tr>
<tr>
<td>2</td>
<td>Prof Tan Sze Wea</td>
<td>ED SERC</td>
<td>A*STAR</td>
</tr>
<tr>
<td>3</td>
<td>Dr Lim Ser Yong</td>
<td>ED SIMTech</td>
<td>A*STAR</td>
</tr>
<tr>
<td>4</td>
<td>Prof Lam Kong Peng</td>
<td>ED BTI</td>
<td>A*STAR</td>
</tr>
<tr>
<td>5</td>
<td>Prof Lim Lee Kwong</td>
<td>ED PR</td>
<td>A*STAR</td>
</tr>
<tr>
<td>6</td>
<td>Ms Bernadette Fooong</td>
<td>D RED</td>
<td>MTI</td>
</tr>
<tr>
<td>7</td>
<td>Mr Lim Kok Kiang</td>
<td>AMD</td>
<td>EDB</td>
</tr>
<tr>
<td>8</td>
<td>Mr Edwin Chow</td>
<td>GD</td>
<td>SPRING</td>
</tr>
<tr>
<td>9</td>
<td>Mr Lam Joo Khoi</td>
<td>Sec-Gen</td>
<td>SMF</td>
</tr>
<tr>
<td>10</td>
<td>Adj Prof Aziz Merchant</td>
<td>ED</td>
<td>Keppel Offshore &amp; Marine</td>
</tr>
<tr>
<td>11</td>
<td>Dr Joe Liu</td>
<td>VP</td>
<td>3M</td>
</tr>
<tr>
<td>12</td>
<td>Mr Phua Han Tian</td>
<td>Formar VP &amp; GM</td>
<td>HP &amp; KODAK</td>
</tr>
<tr>
<td>13</td>
<td>Prof Chen Tsuhan</td>
<td>Dean of Engineering</td>
<td>NTU</td>
</tr>
<tr>
<td>14</td>
<td>Prof Chua Kee Ching</td>
<td>Dean of Engineering</td>
<td>NUS</td>
</tr>
<tr>
<td>15</td>
<td>Dr Edward Hunter</td>
<td>VP, Product &amp; Supply</td>
<td>P&amp;G</td>
</tr>
<tr>
<td>16</td>
<td>Ms Arleen Paulino</td>
<td>VP, Operations (Singapore)</td>
<td>Amgen</td>
</tr>
</tbody>
</table>

#### Coordinating Committee

<table>
<thead>
<tr>
<th>S/N</th>
<th>NAME</th>
<th>DESIGNATION</th>
<th>ORGANISATION</th>
<th>ADDITIONAL APPOINTMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Dr David Low</td>
<td>CEO ARTC</td>
<td>A*STAR</td>
<td>Chair of sub-committee 3</td>
</tr>
<tr>
<td>2</td>
<td>Mr Ling Kook Tong</td>
<td>D SERC</td>
<td>A*STAR</td>
<td>Member of sub-committee 3</td>
</tr>
<tr>
<td>3</td>
<td>Ms Joanne Mosbergan</td>
<td>DD SERC</td>
<td>A*STAR</td>
<td>-</td>
</tr>
<tr>
<td>4</td>
<td>Ms Audrey Tan</td>
<td>H BMRC</td>
<td>A*STAR</td>
<td>-</td>
</tr>
<tr>
<td>5</td>
<td>Dr Karthik Kumar</td>
<td>H SERC</td>
<td>A*STAR</td>
<td>Secretariat of sub-committee 4</td>
</tr>
</tbody>
</table>

#### Sub-committee 1: Industry

<table>
<thead>
<tr>
<th>S/N</th>
<th>NAME</th>
<th>DESIGNATION</th>
<th>ORGANISATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Mr Ho Yow Wei (Chair)</td>
<td>D IDG</td>
<td>A*STAR</td>
</tr>
<tr>
<td>2</td>
<td>Ms Amy Foo</td>
<td>D IDG HPC</td>
<td>A*STAR</td>
</tr>
<tr>
<td>3</td>
<td>Mr Liu Eng Soon</td>
<td>D SERC</td>
<td>A*STAR</td>
</tr>
<tr>
<td>4</td>
<td>Mr Ravi Varahamurthy</td>
<td>D IDG ICES</td>
<td>A*STAR</td>
</tr>
<tr>
<td>5</td>
<td>Mr Chik Wai Chiew</td>
<td>SVP</td>
<td>ETPL</td>
</tr>
<tr>
<td>6</td>
<td>Mr Lee Eng Wah</td>
<td>DED SIMTech</td>
<td>A*STAR</td>
</tr>
<tr>
<td>7</td>
<td>Ms Seet Qhui</td>
<td>H</td>
<td>BMS IPO</td>
</tr>
<tr>
<td>8</td>
<td>Mr Simon Goh</td>
<td>D BD ARTC</td>
<td>A*STAR</td>
</tr>
<tr>
<td>9</td>
<td>Mr Ralph Foong</td>
<td>D PE</td>
<td>EDB</td>
</tr>
<tr>
<td>10</td>
<td>Ms Kok Wan Ting</td>
<td>H</td>
<td>SPRING</td>
</tr>
<tr>
<td>11</td>
<td>Ms Meanu Sarin</td>
<td>Consultant</td>
<td>A*STAR</td>
</tr>
<tr>
<td>12</td>
<td>Ms Audrey Tan</td>
<td>H BMRC</td>
<td>A*STAR</td>
</tr>
<tr>
<td>13</td>
<td>Ms Felyn Tan (Co-Secretariat)</td>
<td>H ACO</td>
<td>A*STAR</td>
</tr>
<tr>
<td>14</td>
<td>Ms Serene Ng (Co-Secretariat)</td>
<td>AH IDG</td>
<td>DSI</td>
</tr>
</tbody>
</table>

#### Sub-committee 2: Advancing Current Manufacturing

<table>
<thead>
<tr>
<th>S/N</th>
<th>NAME</th>
<th>DESIGNATION</th>
<th>ORGANISATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Dr John Yong (Chair)</td>
<td>D IDG</td>
<td>A*STAR</td>
</tr>
<tr>
<td>2</td>
<td>Dr Navab Singh</td>
<td>Senior Manager IME</td>
<td>A*STAR</td>
</tr>
<tr>
<td>3</td>
<td>Dr Zeng Xianting</td>
<td>D SIMTech</td>
<td>A*STAR</td>
</tr>
<tr>
<td>4</td>
<td>Prof Chen I-Ming</td>
<td>D School of Engineering</td>
<td>A*STAR</td>
</tr>
<tr>
<td>5</td>
<td>Mr Nicholas Yeo</td>
<td>Principal Research Engineer ARTC</td>
<td>A*STAR</td>
</tr>
<tr>
<td>6</td>
<td>Dr May Win Naing</td>
<td>Senior Scientist SIMTech</td>
<td>A*STAR</td>
</tr>
<tr>
<td>7</td>
<td>Dr Desmond Heng</td>
<td>Scientist ICES</td>
<td>NUS</td>
</tr>
<tr>
<td>8</td>
<td>Dr Li Xiaoli</td>
<td>Senior Scientist FR</td>
<td>A*STAR</td>
</tr>
<tr>
<td>9</td>
<td>Ms Lim Jia Wen (Secretariat)</td>
<td>SO SERC</td>
<td>A*STAR</td>
</tr>
</tbody>
</table>
1. As illustrated in Figure 12, the Technology Roadmapping Methodology encompasses three phases:

- **Survey & Identify**
- **Contextualise & Prioritise**
- **Implementation**

2. In the Survey & Identify phase, the sub-committees identified the respective disruptive technologies for the Precision Engineering, Transport Engineering, Electronics and Chemicals industry clusters and developed technology roadmaps for the base of technologies in each industry.

3. The roadmaps and identified disruptive technologies were then validated through a series of three industry roundtable discussions, which were attended by 58 companies from the eight AME industry clusters as well as FoM technology providers.

4. In the Contextualise & Prioritise phase, the technology areas were contextualised to the specific industry needs and capabilities of Singapore, according to the following six criteria. These areas were then ranked through a prioritisation exercise undertaken collectively by A*STAR, EDB, SPRING and MTI.

   - Creation of high-value manufacturing jobs in Singapore;
   - Potential leadership in FoM technology;
   - Impact to productivity;
   - ROI on resource (land and energy);
   - Enhancing global competitiveness of Singapore-based companies;
   - and Leveraging current Singapore R&D strengths.

5. The Implement phase would then see the development of R&D programmes around the prioritised technologies and the dissemination of the technology roadmaps through TACs and the ITMs.

### ANNEX B1 | Technology Roadmapping Process

#### Sub-committee 3: Enabling & Disruptive Technologies

<table>
<thead>
<tr>
<th>S/N</th>
<th>NAME</th>
<th>DESIGNATION</th>
<th>ORGANISATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Dr David Low (Chair)</td>
<td>CEO ARTC</td>
<td>A*STAR</td>
</tr>
<tr>
<td>2</td>
<td>Dr Martin Saebeek</td>
<td>Senior Scientist IHPC</td>
<td>A*STAR</td>
</tr>
<tr>
<td>3</td>
<td>Dr Michael Han</td>
<td>D IME</td>
<td>A*STAR</td>
</tr>
<tr>
<td>4</td>
<td>Ms Meenu Sarin</td>
<td>SERC Consultant</td>
<td>A*STAR</td>
</tr>
<tr>
<td>5</td>
<td>Dr Ng See Kong</td>
<td>D PR</td>
<td>A*STAR</td>
</tr>
<tr>
<td>6</td>
<td>Prof Tay Tong Eam</td>
<td>H Department of Mechanical Engineering</td>
<td>NUS</td>
</tr>
<tr>
<td>7</td>
<td>Dr Karen Chong</td>
<td>Senior Scientist IMRE</td>
<td>A*STAR</td>
</tr>
<tr>
<td>8</td>
<td>Dr Tan Puay Siew</td>
<td>Group Manager SIMTech</td>
<td>A*STAR</td>
</tr>
<tr>
<td>9</td>
<td>Dr Steve Oh</td>
<td>D BTI</td>
<td>A*STAR</td>
</tr>
<tr>
<td>10</td>
<td>Prof Nic Lindley</td>
<td>D BMRC</td>
<td>A*STAR</td>
</tr>
<tr>
<td>11</td>
<td>Ms Tay Shi Ling (Secretariat)</td>
<td>SO SERC</td>
<td>A*STAR</td>
</tr>
<tr>
<td>12</td>
<td>Mr Ivan Khoo (Secretariat)</td>
<td>SO ARTC</td>
<td>A*STAR</td>
</tr>
</tbody>
</table>

#### Sub-committee 4: Standards and Policies

<table>
<thead>
<tr>
<th>S/N</th>
<th>NAME</th>
<th>DESIGNATION</th>
<th>ORGANISATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Dr Ng Wai Kiong (Chair)</td>
<td>Programme Manager ICES</td>
<td>A*STAR</td>
</tr>
<tr>
<td>2</td>
<td>Dr Zhang Ying</td>
<td>D SIMTech</td>
<td>A*STAR</td>
</tr>
<tr>
<td>3</td>
<td>Dr Wallyn Thong</td>
<td>D PR</td>
<td>A*STAR</td>
</tr>
<tr>
<td>4</td>
<td>Mr Loh Wai Mun</td>
<td>D SERC</td>
<td>A*STAR</td>
</tr>
<tr>
<td>5</td>
<td>Mr Lee Han Boon</td>
<td>SVP</td>
<td>ETPL</td>
</tr>
<tr>
<td>6</td>
<td>Mr Choong Tak Leong</td>
<td>D</td>
<td>SPRING</td>
</tr>
<tr>
<td>7</td>
<td>Dr Karthik Kumar (Co-Secretariat)</td>
<td>H SERC</td>
<td>A*STAR</td>
</tr>
<tr>
<td>8</td>
<td>Dr Benjamin Tan (Co-Secretariat)</td>
<td>Scientist I ICES</td>
<td>A*STAR</td>
</tr>
</tbody>
</table>
### ANNEX B2-1

**Advanced Manufacturing Processes – Technology Roadmap**

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1. Design &amp; Process Simulation Tools for Additive Manufacturing</strong></td>
<td>Robust and efficient simulation tools positioning Singapore at the forefront of Digital Manufacturing</td>
<td>Computations framework for add process to minimise surface roughness and porosity to optimise microstructures</td>
<td>Fast parts scale simulation models to determine distortion and residual stress</td>
<td>Design tools for tunable optimised multi-functional optimised architectures</td>
<td></td>
</tr>
<tr>
<td><strong>2. On-Site/On-Site Direct Manufacturing/Repair with Additive Manufacturing</strong></td>
<td>Mobile 3D hybrid manufacturing system</td>
<td>Eliminates transportation of large part or structure to workshop for repair One-stop solution for on-site repair with assured quality Quick turn-around time for repair</td>
<td>Mobile 3D hybrid manufacturing system</td>
<td>Closed-loop feedback control for additive repair</td>
<td></td>
</tr>
<tr>
<td><strong>3. Hybrid Manufacturing Processes</strong></td>
<td>Leveraging upon existing expertise in SS and AMSTAR to create - High-rate, high-volume manufacturing processes for efficient manufacturing of commercially viable products and nanoproducts.</td>
<td>Nanomanufacturing processes</td>
<td>Integration of manufacturing processes</td>
<td>High-rate, high volume manufacturing processes</td>
<td></td>
</tr>
</tbody>
</table>

### ANNEX B2-2

**Robotics and Automation – Technology Roadmap**

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1. Human-Robot Collaboration</strong></td>
<td>To augment worker’s capabilities by 3D sense of usage and 2D robotic intelligence decision making thus increasing workers’ productivities and extending their employability</td>
<td>Intuitive Software Platform</td>
<td>High Performance Collaborative Robot</td>
<td>Human-robot systems with shared autonomy</td>
<td></td>
</tr>
<tr>
<td><strong>2. Learning Robotic Systems</strong></td>
<td>Productivity and efficiency improvements through heightened robotic capabilities and to target industries where manual human labour is required but considered undesirable working conditions</td>
<td>Human Skin Learning</td>
<td>Industrial Robot Artificial Intelligence</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>3. Advanced Autonomous Systems</strong></td>
<td>Plug and play system allowing for more flexible configuration and greater manufacturability for ease of integration into factories</td>
<td>Mobile Manipulation</td>
<td>Adaptive and Reconfigurable Robotics Systems</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Agile Remanufacturing and Repair</td>
<td></td>
</tr>
</tbody>
</table>
## ANNEX B2-3
### Smart Manufacturing – Technology Roadmap

|----------|----------------|----------------------|-------------|-------------|
| 1. Connectivity on the shop floor | - Secure machine-to-machine (M2M) communications  
- Integrated positioning system  
- In-vehicle autonomous flight/ navigation with collision avoidance | Robust low-delay 2-way industry wireless control supporting 3D devices | High precision localization & tracking | Route planning & collision avoidance of autonomous & drone devices |
| 2. Connectivity in supply chain | - SC Operations Management tools/platform with cloud-based support to include timely sensed data, online optimisation and executive of logistics operations  
- Large scale cyber-physical model for optimised design of shipping networks, ports & corridors and closed-loop supply chains  
- Cloud-based platform for resource co-sharing & delivery consolidation | Highly effective and efficient supply chain | Sensing-driven optimisation & demand forecasting | Smart Less Mile Logistics (LMM)  
Sustainable Supply Chain towards Circular Economy |
| 3. Smarts of Factors | - Relational models with production output  
- Intelligent decision support and integration of historical pattern and real-time data stream  
- Sentiment analytics | Company to respond faster and better to demand changes | Mining manufacturing key parameters to improve the accuracy, quality and yield | Data-driven simulation for decisions in green operations  
Demand forecasting |
| 4. Predict Future Failures or Defects | - Supply chain cooperative models  
- Advanced machine learning integration with economic factors  
- Sentiment analytics  
- Rapid detection and quantification methods for continuous defect or contaminant monitoring | Machines with built-in sensory systems for in-line and real-time monitoring can reduce failures and increase profits | In-line monitoring  
Real-time edge analytics | Self and continuous built pattern learning  
Cyber-physical modeling  
Feedback based prioritization |
Advanced Materials & Processes - Technology roadmaps for the Electronics sector

Flexible Automation - Technology roadmaps for the Electronics sector
ANNEX C1-3

Industry 4.0 – Technology roadmaps for the Electronics sector

ANNEX C1-4

Metrology Roadmap – Technology roadmaps for the Electronics sector
ANNEX C2-1

Advanced Materials and Processes –
Technology roadmaps for the Chemicals sector

ANNEX C2-2

Flexible Automation –
Technology roadmaps for the Chemicals sector
ANNEX C2-5
Metrology Roadmap - Technology roadmaps for the Chemicals sector

Harsh environment & sustainability
- Robust sensors that can operate under chlorine-rich environments, strong electromagnetic background radiation, high temperatures or long-term process monitoring
- Precise carbon footprint measurement methodology and tools
- Characterisation through 3D non-destructive/non-contact techniques
- Adaptive sensors (incorporation of suitable conditions in measurement systems) for monitoring parameters in harsh remote areas and to conform to regulatory requirements
- Accurate lifespan prediction of sensors in harsh environments

Quality control & safety
- Developing measurement methods to conform to packaging biodegradability standards
- From rapid detection to rapid quantification novel methods for food and therapeutic microbiological and pathogen analysis, known and unknown contaminants analysis, and product fidelity and quality assessments
- Measuring migration of nanomaterials from packaging into food, therapeutic and personal care products
- Detection of impurities and harmful species: Establishing toxicity effects, traceability limits, measurement tools and uncertainties in measurements
- Food, therapeutic and personal care authentication: component forensics & fingerprinting
- Real-time food and therapeutic integrity measurement

ANNEX C2-6
Metrology Roadmap - Technology roadmaps for the Chemicals sector

Metrology
- Continuous monitoring of in-line processes to reduce regulatory issues via proof of quality control throughout process
- Establishing methods to measure production cell line variability to enable higher product quality and yields
- Developing new measurement standards for new materials
- Establishing calibration standards (e.g., mass spectrometry) for complex biomolecules (e.g., virus-like particles, proteins, small molecular weight metabolites)
- Monitoring sensor parameters to ensure product consistency
- Process analytical technology-based advanced process control and optimization
- Developing novel in-line biosensors for biomanufacturing process monitoring
- Yield measurement of chemical processes during reaction (without opening reactor or stopping reaction)
- Achieving high level characterization with reduced test volumes
## Industry 4.0 – Technology roadmaps for the Precision Engineering sector

### Data Analytics
- Predictive maintenance
- Self and continuous fault pattern learning
- Concurrent learning from data, experts and human knowledge
- Distributed real time algorithms
- Cyber physical modeling in the cloud for fleet based optimization
- Real time edge analytics
- Efficient production without stopping production line
- Modeling fluid under ambiented machine learning
- Real time simulation and distributed optimization
- Mixing manufacturing key parameters to improve the accuracy, quality and yield
- In-situ monitoring & adaptive machine learning
- Multimodal decision making
- Predictive analytics in supply chain management
- Predictive risk management in supply chain
- Anticipatory logistics (data from external sources, e.g. social media)

### Manufacturing Data Management
- Storage design and data selection for manufacturing
- Metadata Management

### Smartness of Factory
- Data-driven simulation for design in smart factories
- Hybrid hide by simulation and optimization
- Real time decision making for production and maintenance scheduling
- Robust VFM communication
- Low delay, safe communication
- Human Machine Interface management
- Industry wireless communications
- Human machine interface planning & collision avoidance
- Communication supports a list of devices
- Secure cyber physical system
- 5G network & connectivity
- High precision localization & tracking

### Efficient Connectivity Between Shop Floor and Supply Chain
- Industry 4.0 – Technology roadmaps for the Precision Engineering sector

## Metrology - Technology roadmaps for the Precision Engineering sector

### New sensors / tools
- Measuring the internal dimensions (e.g. holes) of 3D printed parts
- Accurate lifetime prediction of sensors in harsh environments

### Harsh Environment & Sustainability
- Precise carbon footprint measurement methodology and tools

### Quality Control
- Development of biometric sensor technologies to monitor recovery progress based on activity levels
- Characterization through 3D non-destructive non-contact techniques
- Development of high speed imaging for inspection of finished product
- Continuous monitoring of in line processes to reduce regulatory issues via proof of quality control throughout process
- Tools for more precise measurement of fatigue properties

### Connectivity & Efficiency
- Methodology and tools for assessing manufacturing efficiency
- Establishing optical 3D metrology with Augmented Reality glasses
### Annex C4-1

**Advanced Materials and Processes** – Technology roadmaps for the Transport Engineering sector

<table>
<thead>
<tr>
<th>Advanced Materials and Processes</th>
<th>2 Years</th>
<th>3 Years</th>
<th>4 Years</th>
<th>5 Years</th>
<th>6 Years</th>
<th>8 Years</th>
<th>10 Years</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Advanced Manipulation &amp; Actuation</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soft manipulation &amp; flexible maneuvering with spray painting materials</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Adaptive workpiece control</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Connectivity</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shop floor connectivity on robotics system</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Multi-robots management in a distributed system</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Human Robot Collaboration</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Safety system for HBC</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Communication with humans in a multi-robots environment</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Learning Robotic System</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Adaptive sensing &amp; perception in unstructured environments</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Distributed intelligence through cloud computing</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Flexible Automation</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flexible &amp; mobility robotic system</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reconfigurable / Modular system</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Advance Robotic System</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Large structure manipulation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flexible Robot cells for Remanufacturing</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Safe &amp; reliable drones &amp; robotic system for inspection</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bio-inspired robots for operations</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Advanced Manipulation & Actuation
- Soft manipulation & flexible maneuvering with spray painting materials
- Adaptive workpiece control

- Connectivity
  - Shop floor connectivity on robotics system
  - Multi-robots management in a distributed system

- Human Robot Collaboration
  - Safety system for HBC
  - Communication with humans in a multi-robots environment

- Learning Robotic System
  - Adaptive sensing & perception in unstructured environments
  - Distributed intelligence through cloud computing

- Flexible Automation
  - Flexible & mobility robotic system
  - Reconfigurable / Modular system

- Advance Robotic System
  - Large structure manipulation
  - Flexible Robot cells for Remanufacturing
  - Safe & reliable drones & robotic system for inspection
  - Bio-inspired robots for operations

---

**Annex C4-2**

**Flexible Automation** – Technology roadmaps for the Transport Engineering sector

**Annex C4-1** and **Annex C4-2** are part of the Technology Roadmaps for the Transport Engineering sector. These roadmaps outline the advancements and technologies expected to be developed over the next decade to enhance the transport engineering sector.
ANNEX C4-3

Industry 4.0 – Technology roadmaps for the Transport Engineering sector

ANNEX C4-4

Metrology Roadmap – Technology roadmaps for the Transport Engineering sector