Deliverable 2.1

Report on scientific and technological challenges

<table>
<thead>
<tr>
<th>DISSEMINATION LEVEL</th>
<th>PU</th>
<th>CO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Public</td>
<td></td>
<td>Confidential, only for members of the consortium (including the Commission Services)</td>
</tr>
</tbody>
</table>
The Road2CPS project is co-funded by the European Community's Horizon 2020 Programme under grant agreement no 644164.

The author is solely responsible for its content, it does not represent the opinion of the European Community and the Community is not responsible for any use that might be made of data appearing therein.

---

1 R=Report, DEC= Websites, patents filling, etc., O=Other

2 PU=Public, CO=Confidential, only for members of the consortium (including the Commission Services)

©Road2CPS Consortium
Change Control

Document History

<table>
<thead>
<tr>
<th>Version</th>
<th>Date</th>
<th>Change History</th>
<th>Author(s)</th>
<th>Organization(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>2015-06-12</td>
<td>Document instantiated</td>
<td>M.A. Sinclair</td>
<td>LU</td>
</tr>
<tr>
<td>0.2</td>
<td>2015-06-20</td>
<td>Content added from all partners</td>
<td>M.A. Sinclair, all</td>
<td>LU, all partners</td>
</tr>
<tr>
<td>0.3</td>
<td>2015-06-30</td>
<td>More content added from all partners</td>
<td>M.A. Sinclair, all</td>
<td>LU, all partners</td>
</tr>
<tr>
<td>0.4</td>
<td>2015-07-03</td>
<td>More content added from all partners</td>
<td>M.A. Sinclair, all</td>
<td>LU, all partners</td>
</tr>
<tr>
<td>0.5</td>
<td>2015-07-09</td>
<td>More content added from all partners</td>
<td>M.A. Sinclair, all</td>
<td>LU, all partners</td>
</tr>
<tr>
<td>0.6</td>
<td>2015-07-16</td>
<td>More content added from all partners</td>
<td>M.A. Sinclair, C.E. Siemieniuch</td>
<td>LU, LU</td>
</tr>
<tr>
<td>0.7</td>
<td>2015-07-23</td>
<td>Proof-reading copy</td>
<td>M.A. Sinclair, C.E. Siemieniuch</td>
<td>LU, LU</td>
</tr>
<tr>
<td>0.9</td>
<td>2015-07-28</td>
<td>Final version</td>
<td>M.A. Sinclair, C.E. Siemieniuch</td>
<td>LU, LU</td>
</tr>
<tr>
<td>1.0</td>
<td>2015-07-30</td>
<td>Final revision by Coordinator</td>
<td>M. Reimann</td>
<td>SEZ</td>
</tr>
</tbody>
</table>

Distribution List

<table>
<thead>
<tr>
<th>Date</th>
<th>Issue</th>
<th>Group</th>
</tr>
</thead>
<tbody>
<tr>
<td>2015-06-12</td>
<td>Instantiated document</td>
<td>Project consortium</td>
</tr>
<tr>
<td>2015-06-20</td>
<td>Revision</td>
<td>Project consortium</td>
</tr>
<tr>
<td>2015-06-30</td>
<td>Revision</td>
<td>Project consortium</td>
</tr>
<tr>
<td>2015-07-03</td>
<td>Revision</td>
<td>Project consortium</td>
</tr>
<tr>
<td>2015-07-09</td>
<td>Revision</td>
<td>Project consortium</td>
</tr>
<tr>
<td>2015-07-16</td>
<td>Revision</td>
<td>Project consortium</td>
</tr>
<tr>
<td>2015-07-23</td>
<td>Penultimate revision</td>
<td>Project consortium</td>
</tr>
<tr>
<td>2015-07-31</td>
<td>Submission</td>
<td>EC</td>
</tr>
</tbody>
</table>
Consortium Information

<table>
<thead>
<tr>
<th>Name (and contact data)</th>
<th>Institution (incl. address)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M. Reimann <a href="mailto:reimann@steinbeis-europa.de">reimann@steinbeis-europa.de</a></td>
<td>Steinbeis-Europa-Zentrum  Erbprinzenstrasse 4-12, Karlsruhe, DE</td>
</tr>
<tr>
<td>M.J.D. Henshaw <a href="mailto:M.J.d.Henshaw@lboro.ac.uk">M.J.d.Henshaw@lboro.ac.uk</a></td>
<td>Loughborough University Ashby Road, Loughborough, UK</td>
</tr>
<tr>
<td>J. Fitzgerald <a href="mailto:john.fitzgerald@ncl.ac.uk">john.fitzgerald@ncl.ac.uk</a></td>
<td>University of Newcastle King’s Road, Newcastle upon Tyne, UK</td>
</tr>
<tr>
<td>David Servat <a href="mailto:David.SERVAT@cea.fr">David.SERVAT@cea.fr</a></td>
<td>Commissariat à l’énergie atomique et aux energies alternatives Paris 15, 75015, FR</td>
</tr>
<tr>
<td>U. Rauschecker <a href="mailto:Ursula.rauschecker@ipa.fraunhofer.de">Ursula.rauschecker@ipa.fraunhofer.de</a></td>
<td>Fraunhofer IPA 70569 Stuttgart, DE</td>
</tr>
<tr>
<td>D. Ordóñez <a href="mailto:dom@anysolution.eu">dom@anysolution.eu</a></td>
<td>Anysolution SL 07010 Palma de Mallorca, ES</td>
</tr>
<tr>
<td>N. de Lama <a href="mailto:nuria.delama@atos.net">nuria.delama@atos.net</a></td>
<td>Atos España SA Madrid 28037, ES</td>
</tr>
</tbody>
</table>

Authors

<table>
<thead>
<tr>
<th>Name</th>
<th>Institution</th>
<th>Contact</th>
</tr>
</thead>
<tbody>
<tr>
<td>M.A. Sinclair</td>
<td>Loughborough University</td>
<td><a href="mailto:m.a.sinclair@lboro.ac.uk">m.a.sinclair@lboro.ac.uk</a></td>
</tr>
<tr>
<td>C.E. Siemieniuch</td>
<td>Loughborough University</td>
<td><a href="mailto:c.e.siemieniuch@lboro.ac.uk">c.e.siemieniuch@lboro.ac.uk</a></td>
</tr>
<tr>
<td>P.J. Palmer</td>
<td>Loughborough University</td>
<td><a href="mailto:p.j.palmer@lboro.ac.uk">p.j.palmer@lboro.ac.uk</a></td>
</tr>
<tr>
<td>M. Reimann</td>
<td>Steinbeis-Europa-Zentrum</td>
<td><a href="mailto:reimann@steinbeis-europa.de">reimann@steinbeis-europa.de</a></td>
</tr>
<tr>
<td>C. Rückriegel</td>
<td>Steinbeis-Europa-Zentrum</td>
<td><a href="mailto:rueckriegel@steinbeis-europa.de">rueckriegel@steinbeis-europa.de</a></td>
</tr>
<tr>
<td>U. Rauschecker</td>
<td>Fraunhofer IPA</td>
<td><a href="mailto:ursula.rauschecker@ipa.fraunhofer.de">ursula.rauschecker@ipa.fraunhofer.de</a></td>
</tr>
<tr>
<td>D. Stock</td>
<td>Fraunhofer IPA</td>
<td><a href="mailto:daniel.stock@ipa.fraunhofer.de">daniel.stock@ipa.fraunhofer.de</a></td>
</tr>
<tr>
<td>C. Ingram</td>
<td>Newcastle University</td>
<td><a href="mailto:claire.ingram@newcastle.ac.uk">claire.ingram@newcastle.ac.uk</a></td>
</tr>
<tr>
<td>Z. Andrews</td>
<td>Newcastle University</td>
<td><a href="mailto:zoe.andrews@newcastle.ac.uk">zoe.andrews@newcastle.ac.uk</a></td>
</tr>
<tr>
<td>J. Rico</td>
<td>Atos España SA</td>
<td><a href="mailto:juan.rico@atos.net">juan.rico@atos.net</a></td>
</tr>
</tbody>
</table>
# Table of Contents

1  Introduction................................................................................................................. 14
   1.1  Aim of this report................................................................................................. 14
   1.2  A definition of Cyber-Physical Systems, as used in this report ....................... 14
   1.3  ‘Technology push’, defined for this Deliverable ................................................ 15
   1.4  Research approach adopted .............................................................................. 15
   1.5  Links to other Deliverables ............................................................................. 16
   1.6  Structure of the Deliverable.............................................................................. 16
2  Global sustainability and the role of CPS in achieving this goal ......................... 18
   2.1  An outline of the Global Drivers that affect sustainability, and the role of CPS in
       mitigating the effects...................................................................................... 18
   2.2  Science and technology issues arising from global drivers............................ 23
3  Generic challenges to layers of the CPS................................................................. 25
   3.1  Connecting devices to the IoT ............................................................................ 25
       3.1.1  Scientific and technological challenges at the device level .................... 26
   3.2  Interconnecting devices...................................................................................... 26
       3.2.1  General aspects of interconnection............................................................. 26
       3.2.2  Scientific and Technological challenges arising from general aspects .... 26
       3.2.3  Aspects of mobile interconnection............................................................... 27
       3.2.4  Scientific and technological challenges for mobile interconnection ....... 28
   3.3  Managing, controlling and maintaining functions............................................. 28
       3.3.1  Architectural considerations......................................................................... 28
       3.3.2  Scientific and technological challenges for the control of interconnection .. 29
       3.3.3  Autonomy and learning in CPS................................................................. 29
       3.3.4  Scientific and technological challenges in autonomy and learning for CPS .. 31
       3.3.5  ‘Big Data’ in CPS....................................................................................... 32
       3.3.6  Scientific and technological challenges for Big Data............................. 33
3.3.7 Verification and Validation for CPS .................................................................33
3.3.8 Scientific and technological challenges for CPS V&V ........................................34
3.3.9 Modelling, simulation and control ........................................................................34
3.3.10 Scientific and Technological challenges for modelling, simulation and control ....36
3.4 Strategy, co-operation and regulation ....................................................................36
3.4.1 Supervision and regulation of CPS ........................................................................36
3.4.2 Scientific and technological challenges for a supervisory regime .........................37
4 Challenges for CPS in 8 domains ........................................................................38
4.1 IT&C and mobility of devices ....................................................................................38
4.1.1 Scientific and technological challenges for IT&C ...................................................38
4.2 Energy generation, distribution and use ...................................................................39
4.2.1 Energy generation and distribution ......................................................................39
4.2.2 Energy use ..............................................................................................................40
4.2.3 Scientific and technological challenges for Energy generation, distribution and use .41
4.3 Manufacturing ........................................................................................................42
4.3.1 Extraction and utilisation of minerals .....................................................................43
4.3.2 Landfill ....................................................................................................................44
4.3.3 Enterprise effects from the ‘circular economy’ .........................................................44
4.3.4 Manufacturing processes .......................................................................................44
4.3.5 Scientific and technological challenges for CPS in manufacturing .......................47
4.4 Security .....................................................................................................................49
4.4.1 Scientific and technological challenges for security ................................................49
4.5 Transport ..................................................................................................................50
4.5.1 Transport at sea .......................................................................................................51
4.5.2 Transport in the air ...............................................................................................51
4.5.3 Transport on the roads ..........................................................................................52
4.5.4 Transport on the railways .....................................................................................53
4.5.5 Urban mobility .......................................................................................................54
4.5.6 Scientific and technological challenges for transport .............................................55
4.5.7 Health care ............................................................................................................56
4.5.8 Scientific and technological challenges in health care........................................57
4.6 Smart communities................................................................................................58
4.6.1 Scientific and technological challenges for the Smart Community ...............59
4.7 Environment & Agriculture..................................................................................60
4.7.1 Agriculture........................................................................................................60
4.7.2 Water ................................................................................................................61
4.7.3 Environment.......................................................................................................61
4.7.4 Scientific and technological challenges for environment and agriculture........62
5 Society and CPS.......................................................................................................63
5.1 CPS and consumers..............................................................................................63
5.1.1 Some legal and governance considerations..........................................................63
5.1.2 The requirement for ethical behaviour by CPS....................................................65
5.2 CPS and co-workers.............................................................................................65
5.2.1 Keeping the CPS in operation.............................................................................66
5.2.2 Co-working within the CPS................................................................................67
5.3 Management of CPS............................................................................................67
5.4 Autonomous CPS operating in society.................................................................69
5.4.1 Autonomy..........................................................................................................69
5.4.2 Learning................................................................................................................71
6 Combining and conflating CPS technologies..........................................................72
6.1 Mapping of projects in Table 6.1 to show technology outputs and coverage.......72
6.2 Technologies organized by interoperability level....................................................79
7 Conclusions.............................................................................................................84
References..................................................................................................................87
List of figures

Figure 2.1   Interactions between the global drivers; Figure 2.1b Mitigation activities........22
Figure 4.1   Intended reductions for greenhouse gas emissions for the EU28 as outlined in EC Communication COM(2011) 112......................................................... 40
Figure 4.2   Illustration of ‘Circular Manufacturing’, as an instance of the ‘Circular Economy. ................................................................. 43
Figure 4.3   Illustration of the Internet of Things from a manufacturing perspective, omitting most of the complexities such as standards, interconnection protocols, interoperability contracts, co-operation and co-ordination and network security arrangements.................................................................................. 46
Figure 4.4   Illustration of a network to deliver health and social care to an individual at home................................................................. 56
Figure 6.1   The Road2CPS cube, from D1.1, with the Domain access compressed. It shows the 4 main areas expressed by 53 projects. ........................................... 75
Figure 6.2   The cube, with some explanation of the contents of the 4 areas. .................... 76
Figure 6.3   The cube, with the 53 projects superimposed, classifying their various outputs for Infrastructure and Interoperability. Gaps in coverage exist........ 77
Figure 6.4   The cube, with technology contributions from the 53 projects combined. ....... 78

List of tables

Table 2.1   An outline of the Global Drivers, their likely effects and characteristics, together with mitigation possibilities, and further reading........................................ 21
Table 6.1   List of 53 projects for assessment in Road2CPS............................................. 72
Table 6.2   Interoperability levels and technologies associated with each one. Technologies named in this report, which are based on the findings of the 53 projects....... 84
Executive Summary

This Deliverable is an output of the Road2CPS Co-ordination and Support Action (CSA), Grant Agreement number 644164. It forms one of three simultaneous Deliverables: D1.1 ‘State of the Art and Impact’, D2.1 ‘Scientific and technological challenges’ and D2.2 ‘Market requirements and socio-economic needs’. Together, they form a coherent perspective on the state of research projects in Cyber-Physical Systems (CPS) funded by the European Commission in recent years.

An established definition of CPS is the following (acatech-pos 2011):

“Cyber-physical systems are systems with embedded soft-ware (as part of devices, buildings, means of transport, transport routes, production systems, medical processes, logistic processes, coordination processes and management processes), which:

• directly record physical data using sensors and affect physical processes using actuators;
• evaluate and save recorded data, and actively or re-actively interact both with the physical and digital world;
• are connected with one another and in global networks via digital communication facilities (wireless and/or wired, local and/or global);
• use globally available data and services;
• have a series of dedicated, multimodal human-machine interfaces. “

One part of the requirements for this CSA was to explore the contributions made by 53 projects in the CPS domain. These three Deliverables address this requirement. The 53 projects, covering a very wide range of topics, are listed below:

<table>
<thead>
<tr>
<th>ADVANCE</th>
<th>ENOYSYS</th>
</tr>
</thead>
<tbody>
<tr>
<td>AGILE</td>
<td>EOT</td>
</tr>
<tr>
<td>AMADEOS</td>
<td>ERA</td>
</tr>
<tr>
<td>AXIOM</td>
<td>EUROCP</td>
</tr>
<tr>
<td>CLAM</td>
<td>GENESI</td>
</tr>
<tr>
<td>COMPASS</td>
<td>GreenerBuildings</td>
</tr>
<tr>
<td>CONSERN</td>
<td>HYCON2</td>
</tr>
<tr>
<td>CPSELABS</td>
<td>HYDROBIOS</td>
</tr>
<tr>
<td>CPSoS</td>
<td>IMC-AESOP</td>
</tr>
<tr>
<td>CyPhERS</td>
<td>IMMORTAL</td>
</tr>
<tr>
<td>DANSE</td>
<td>INTO-CPS</td>
</tr>
<tr>
<td>DYMASOS</td>
<td>Karyon</td>
</tr>
<tr>
<td>EC-SAFEMOBIL</td>
<td>Local4Global</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The aim of D2.1 is as follows:
to take a panoptic view reaching forwards to 2050 of the likely position and function of Cyber-Physical Systems (CPS), together with the overlapping concept of the Internet of Things (IoT), necessarily including within that timeframe a perspective on sustainability, and then to identify in levels of finer granularity what the scientific and technological challenges might be.

The focus, then, has been on ‘Technology push’. This term has different meanings to different professions, and to individuals within those professions. For some, this means ‘where could we utilise the technology that we have developed?’, summarised as ‘solutions in search of applications’. For others, it means ‘What else is needed to make this developed technology useful in society?’, summarised as ‘fitting technology to the needs of society’. For still others, it means ‘How do we push competitors out of the market?’, summarised as ‘entrepreneurs at work’.

In this report, we have adopted the second meaning; ‘What else is needed to make this developed technology useful in society?’ In addressing this question, necessarily we have also addressed the first, to establish a baseline to determine what else is needed.

Consequently, as said earlier, this Deliverable has made much use of D1.1 ‘State of the Art and Impact’. For convenience, summary charts from D1.1 are included in Section 6.1 to show the current State of the Art at the commencement of the Road2CPS project in February 2015.

This document covers much of the same ground as other road-mapping projects such as CPSoS\(^3\), CyPHERS\(^4\) and Road4FAME\(^5\) and of the major contribution to CPS, the acatech study, ‘Living in a networked world’\(^6\). For this reason, the focus of D2.1 has been slightly different; while covering the same ground it presents a longer-term, more socio-technical perspective, that, because it is longer-term, necessarily addresses sustainability. Thereby, it complements and elaborates these other projects. In addressing sustainability, D2.1 makes the strong point that manufacturing, and CPS in particular, are fundamental to achieving sustainability.

The conclusions are given in Section 7, and for convenience are repeated below.

1. While the diagrams in section 6.1 above show that there are gaps in the coverage of technological and social considerations of CPS in the EU, there is a picture of across-the-board technical competence that provides a basis for EU leadership in the development and application of CPS.

2. There are overlaps in the research as indicated in the diagrams in section 6.1, but not much sign of a common reference framework. It is important that this is developed so that future projects can contribute more directly to composable technology.

3. In terms of interoperability, the lower, more detailed levels of operability have received wide attention; sufficient to show some important gaps at higher levels that

---

\(^3\) http://www(cpsos.eu

\(^4\) http://www.cyphers.eu

\(^5\) http://road4fame.eu

\(^6\) http://www.acatech.de/uk

©Road2CPS Consortium
need to be addressed in future to make sure that the technology can be adopted and interfaced without extended effort.

4. Societal aspects of CPS should be addressed to a greater extent; for example, the current delays in the deployment of autonomous vehicles are largely due to these aspects that are often described as ‘non-functional’. Societal aspects are not non-functional; they are functional requirements for the political, legal and social support systems that are necessary for acceptance of CPS into society.

5. While accepting that there is no common reference framework and an accompanying lack of standards, there is more complementarity in the technology than perhaps was expected. While domain-specific projects may be necessary to tease out details of CPS (c.f. the German proverb, “The Devil is in the details”), perhaps projects in future should be directed at a minimum of two domains with strong requirement for adoption of technology from earlier projects that has reached NASA TRL 5 or 6.

6. There is a clear and pressing need to address the interoperability issues between different CPS system components; hybrid models, simulations, languages, tools, methods, frameworks, trade spaces, etc. Given the elision between design and operation that is recognised as fundamental for CPS, there is a danger of undue delays in the adoption of CPS technology.

7. Given that in the future many Cyber-Physical Systems will be expected to operate in an ‘always on’ mode (i.e. cannot be stopped), but will still be subjected to upgrades (both planned and unexpected), and to ‘normal accidents’ (Perrow 1999) and other emergent phenomena, it will be necessary to develop certified processes and standards for maintaining the integrity of the CPS during the ever-changing states and configurations over its lifecycle.

8. The technology for engineering autonomous systems requires further development, to address trustworthiness and the impact of autonomous learning. This is particularly important given the demographics of the EU28 as we head towards 2050, and an inevitable increase in the numbers of vulnerable people. This is also important from the perspective of people as co-workers with such systems.

9. The ever-growing role of smartphones and other wearable devices in turning people into mobile, networked cyborgs indicates a strong requirement for very extensive, high-capacity networks based on secure, ‘plug and play’ technology. The technology for this is becoming available, but will need more development for the full exploitation of CPS.

10. As the uptake of the IoT increases with ever-more devices being attached, the requirement for high-speed, low-latency, guaranteed secure communications (M2M) will grow. The technical base for this requires further attention.

11. There is a requirement that CPS behave ethically when they interact with people, both as individuals and in organised groups, if they are to be trusted and accepted. The
technology to accomplish this is almost non-existent, and this represents a potential barrier to their deployment in society that needs to be addressed very soon.

12. It seems clear that skills and knowledge shortages in designing, operating, and maintaining CPS will hamper the adoption of CPS in the EU28 unless a systemic effort is made to impart the necessary skills across the EU at all levels from individuals through organisations and into governments.

13. Given that the skills are available within the workforce, there is still the problem of applying these skills to CPS. This is an important area of enterprise system design to deploy skills into roles that are meaningful for the people who possess these skills, and then ensuring that the people have the interfaces into the CPS to exercise those skills appropriately. Given the likely extent and complexity of CPS in the future, a current analogy to the kind of interface that might be required in the aircraft cockpit, in which the pilot operates more as the manager of a suite of interconnected cyber-physical systems of significant complexity. But the situation for CPS may be even more complex; for the pilot, the systems do not change until a major overhaul period arrives. In the CPS world, given their reach and complexity, it is possible that a CPS will be in a near-constant state of change, as exemplified by examples in this report. Designing a cost-effective human-CPS interface for this situation represents a difficult problem beyond the current state of the art, and yet it is a necessary part of operational CPS. This is a potential barrier for the deployment of future CPS.

14. CPS technologies are likely to be encumbered with IPRs, confidentiality clauses and other legal considerations. For their effective deployments into CPS, there is likely to be a need for standard contract forms to enable the equitable creation of CPS in relatively quick real time. For some CPS operating in fast-changing environments (mobile is an example) it may be necessary to allow component systems in CPS to engage in contracts autonomously. This will require standard contracts.

15. From a sustainability perspective, the situation seems to be encouraging. There is a general awareness of the need for economies in materials, energy and emissions, and almost all of the technologies explored within the 53 projects are of evident value in bringing about these economies. However, combining them into CPS that will deliver these economies is still a big issue. Nevertheless, we are in a technological position to consider projects to develop real-world pilot systems in the near future.

16. The move from an end-to-end economy in the EU28 to a circular economy will be aided greatly by CPS and their technologies. Attaining a state of ‘no more landfill’ in the EU28 may be an achievable goal; what will help even more is the mining of landfill for materials. This role for CPS is underdeveloped, although many of the technical developments that have already taken place would make this a possibility to explore.

17. The need for a common reference framework, for composable technology to create CPS, for standards (including standard contract forms), and for bringing together the wide range of disciplines necessary to create and operate acceptable CPS indicates a requirement for a wide-ranging constituency of people and organisations to deliver
such CPS. It is likely that a Joint Undertaking as exemplified by ARTEMIS and ECSEL will be necessary to create this constituency.
1 Introduction

1.1 Aim of this report

This Deliverable forms one part of three Deliverables for Road2CPS all due on the same date and which should be seen as a collected set. The first deliverable, D1.1 ‘State of the Art and Impact’ looks at a set of 53 recent EU projects all exploring the world of Cyber-Physical systems (CPS); this formed a basis for the other two Deliverables, D2.1 ‘Report on scientific and technological challenges’ and D2.2 ‘Report on Market Requirements and Socio-economical needs’.

Based on the analysis of the 53 projects in Deliverable D1.1 ‘State of the Art and Impact’, and on current progress and roadmaps elsewhere in the EU and other developed countries, an assessment has been made to produce this Deliverable D2.1.

The aim has been:

- to take a panoptic view reaching forwards to 2050 of the likely position and function of Cyber-Physical Systems (CPS), together with the overlapping concept of the Internet of Things (IoT), necessarily including within that timeframe a perspective on sustainability, and then to identify in levels of finer granularity what the scientific and technological challenges might be.

In other words, the aim is to produce a top-down assessment of the scientific and technological challenges over that period, with attention to sustainability. This aim was chosen to provide a long-term perspective, including some global aspects, to augment other reports that have taken a shorter, more market-focused, perspective.

Because neither science nor technology exists in a vacuum, the report contains some discussion of social and political considerations. However, these are considered in much more detail in the third Deliverable, D2.2 ‘Market requirements and Socio-economic needs’.

1.2 A definition of Cyber-Physical Systems, as used in this report

An established definition (acatech-pos 2011) is:

“Cyber-physical systems are systems with embedded software (as part of devices, buildings, means of transport, transport routes, production systems, medical processes, logistic processes, coordination processes and management processes), which:

- directly record physical data using sensors and affect physical processes using actuators;
- evaluate and save recorded data, and actively or re-actively interact both with the physical and digital world;
- are connected with one another and in global networks via digital communication facilities (wireless and/or wired, local and/or global);
• use globally available data and services;
• have a series of dedicated, multimodal human-machine interfaces. “

In this Deliverable, because of the focus on the implementation of CPS, we include within this definition the people who are stakeholders in CPS; customers, incidental bystanders affected by CPS, workers and managers within CPS; all of the people who come into contact with the human-machine interfaces mentioned above, many of whom will be legally responsible for the operations and actions of the CPS.

1.3 ‘Technology push’, defined for this Deliverable

One of the functions of this report is to address ‘technology push’, as stated in the proposal. This term has different meanings to different professions, and to individuals within those professions. For some, this means ‘where could we utilise the technology that we have developed?’, summarised as ‘solutions in search of applications’. For others, it means ‘What else is needed to make this developed technology useful in society?’; summarised as ‘fitting technology to the needs of society’. For still others, it means ‘How do we push competitors out of the market?’, summarised as ‘entrepreneurs at work’.

In this report, we have adopted the second meaning; ‘What else is needed to make this developed technology useful in society?’ In addressing this question, necessarily we have also addressed the first, to establish a baseline to determine what else is needed.

Consequently, as said earlier, this Deliverable has made much use of D1.1 ‘State of the Art and Impact’. Summary diagrams from D1.1 are included in Section 6 to show the current SoA at the commencement of the Road2CPS project in February 2015.

1.4 Research approach adopted

The research approach that was adopted, leading to this Deliverable, was based mainly on literature reviews, supplemented by attendances at many workshops and other functions both within the project and those run by other organisations where discussions with Subject Matter Experts could be undertaken.

A core part of the literature review was based on the 53 EU-funded CPS projects listed in D1.1 ‘State of the Art: advances and impacts’, that provided a detailed picture of current developments and issues in CPS. This was supplemented by other documents from outside this resource pool, including EC Directives and Communications, reports from professional bodies such as the IEEE, acatech, CNRS, IDC and the UK Royal Society, and from industry-facing bodies such as ARTEMIS, ECSEL, ISO, the ILO and the ICTU, and many others.

This large, unstructured body of information was then reduced into this document by an iterative process of compilation, conflation and discussion on several draft copies with Subject Matter Experts within Road2CPS and from other domains until this report finally emerged.
1.5 Links to other Deliverables

The links between this document and D1.1 and D2.2 have been outlines above; the three deliverables form a complementary set and a full picture is gained by reading all three.

Looking forwards in time, D2.1 will provide a basis for D1.5 ‘Programme achievements, exploitation opportunities & impact multiplication activities’ and for D2.3 ‘Intermediate and final technology and application roadmap’ (intermediate/ final technology and application roadmaps, accompanied by D2.4 ‘Strategic roadmap’. It will also contribute to D4.1 ‘Recommendations for research priorities, business opportunities and innovation strategies’.

1.6 Structure of the Deliverable

The scientific and technological challenges to the development and utilisation of CPS that are discussed in this Deliverable are those of importance that can be foreseen in the time period up to 2050. This has been chosen partly to reflect a common time horizon assumed in many planning documents produced by the European Commission and partly to acknowledge a time milestone in many of the documents discussing sustainability developed in many other parts of the world such as those emanating from the International Panel on Climate Change (IPCC). This date is also convenient in consequence of the arguments below in Section 2, discussing global sustainability from the point of view of eight interoperating Global Drivers, the vital role of CPS in addressing these, as well as maintaining the functioning of our societies.

Given that this document is linear, and therefore outlining the challenges in sequence, whereas the real-world challenges discussed necessarily are inter-related to address the inter-related nature of the global drivers, it is necessary to indicate how the document is constructed.

Section 2 introduces a more global, longer-term perspective of the roles of CPS in a world that is changing under the effects of eight identified Global Drivers.

Section 3 addresses the general architectural challenges facing the development of CPS, at the levels of interconnection, orchestration of effects, management and strategy. Given that these topics are explored in detail in many other documents (particularly by documents from acatech (acatech-pos 2011, Geisberger and Broy 2015) and ARTEMIS JU (Gide 2013)), this section presents a less detailed synopsis of current issues.

Section 4 moves on to discuss CPS challenges in relation to 8 domains, corresponding to those identified in the ARTEMIS JU documents, ranging from health care to energy.

Section 5 then discusses the role of humans, both as external agents interacting in some way with CPS as citizens, consumers and casual bystanders, and as agents within CPS as operators, controllers and managers. The first class addresses the role of CPS within society; the second class addresses the role of humans within the CPS as legally-responsible agents of authority over the operations of the CPS, as sources of wisdom and experience, and of capabilities such as problem solving, delivering resilience and agility to the CPS as these operate in an evolving environment. This discussion is of some length, complementing and extending the sections in both the acatech and ARTEMIS document mentioned above.
For each of these sections, scientific and technological challenges, and possible mitigation pathways, are identified at the end of each of the sub-sections within the sections above.

Section 6 collates and condenses the technologies, utilising several diagrams from D1.1 State of the Art and some implications for interoperability likely to be faced by organisations involving themselves in CPS.

Finally, section 7 draws some conclusions from the report, and also indicating progress towards the longer-term goal of sustainability, as indicated in the aim in section 1.1 above.
2 Global sustainability and the role of CPS in achieving this goal

2.1 An outline of the Global Drivers that affect sustainability, and the role of CPS in mitigating the effects

To provide some purchase on the notion of global drivers, we present a list of these drivers, and a table to indicate their potential effects on our societies and the world. Comments in this section are based on forecasts and strategy documents of governments and other national and international organisations, referenced in the last column of Table 2.1 on the next page.

Global drivers as identified in the Sulston report (Sulston 2012) and the Working Group 5th Assessment Reports of the IPCC (IPCC-WGI 2013, IPCC-Synth-Rep 2014, IPCC-WGII 2014, IPCC-WGIII 2014) are considered mostly from a longer-term perspective; the trends are extrapolated to about 2050 in most of the documents.

Based on this perspective, and focusing on the EU28 as a significant global entity, the following inter-related global drivers can be identified:

- Population demographics, including lifestyles, growth and aging
- Food security
- Energy security
- Resource depletion
- Emissions and global climate
- Community security and safety
- Transportation
- Globalisation of economic and social activity

A brief outline of the effects of the global drivers on the EU28 follows, in Table 2.1, adapted from (Siemieniuch, Sinclair et al. 2015).
<table>
<thead>
<tr>
<th>Driver</th>
<th>Characteristics</th>
<th>Likely effects</th>
<th>Sustainability issues</th>
<th>Sources</th>
</tr>
</thead>
</table>
| Population demographics     | • World population, 7 billion currently, expected to reach 9-11 billion by 2050 (28-57% increase)  
• Most people (80%) expected to live in mega-cities (20M+)  
• EU28 population remains stable around 525 million; some growth of cities  
• East EU28 likely to face a loss of working age people and an increased %age of old people | • Mega-cities will be wide-spread  
• EU28 must make wide-ranging adjustments to address aging requirements  
• Global demand for resources will increase dramatically | • Major changes to infrastructures (schools, hospitals, jobs, transport, etc.)  
• Co-ordinated, efficient, effective delivery of infrastructure elements  
• Education & government policies may reduce impacts  
| Food security               | • Crop-land growth not keeping pace with population growth; fisheries are depleted  
• Food wastage from seeds to garbage significant in all states, (rich waste food, poor suffer from poor husbandry) | • Climate change will affect supply (drought, storms, heat)  
• Local food shortages likely  
• Disruptions to global food chains | • More efficient supply chains will be needed.  
• Food wastage, diet preferences need culture change.  
• Crop engineering needed to reduce inputs, water  
• Machinery improvements are needed, everywhere | (McMichael and Dear 2010, Allouche 2011, Lee, Preston et al. 2012, Levermann 2014) |
| Energy security             | • EU28 imports about 60% of its gas, about 80% of its oil, both non-renewable  
• Provision of energy becoming more volatile, less reliable  
• Global population growth, coupled with ever-increasing energy demand per person indicate unsustainable future demand | • Fossil fuels harder to find & exploit  
• Loss of reserves for future generations  
• Politics will add volatility to fossil fuel supply chains  
• Public push-back on size of changes | • Leave fossil fuels in the ground  
• Big drops in energy use by manufacturing, construction, transport & end-users  
<table>
<thead>
<tr>
<th>Driver</th>
<th>Characteristics</th>
<th>Likely effects</th>
<th>Sustainability issues</th>
<th>Sources</th>
</tr>
</thead>
</table>
| Mineral resource depletion    | • Some important minerals are in short supply (e.g. ‘rare earths’, lithium, titanium)  
  • As depletion occurs, ores become lower in quality and are less accessible. | • Costs likely to increase.  
  • ‘linear’ (i.e. from ore to waste tip) usage of materials may become unviable; ‘circular’ (e.g. recycling) processes may become essential | • More costly minerals and fuels will force manufacturers into energy efficiency & recycling.  
  • Legislation needed to create incentives (‘pull’) and regulations (‘push’) to be sustainable  
  • Create change to business models and customer culture  
| Emissions & global climate    | • Sequence of IPCC reports show that emissions are driving climate change.  
  • About 50% of world’s population rely on coal or biomass for domestic energy; 20% have no access to electricity.  
  • More demand for heating/cooling in buildings. | • IPCC reports show a ‘tipping point’ for climate change may be reached.  
  • Severe weather events more likely  
  • More heat in hot/humid areas affects work capacity & agriculture | • Widespread changes needed to reduce emissions – sustainable energy, better grids, less usage  
  • Electricity supply extended into poorer countries, with benefits – health, work, etc.  
<table>
<thead>
<tr>
<th>Driver</th>
<th>Characteristics</th>
<th>Likely effects</th>
<th>Sustainability issues</th>
<th>Sources</th>
</tr>
</thead>
</table>
| Globalisation of economic & social activity | • Benefits to developed countries include access to non-local produce and goods; to developing countries, their economies can diversify from produce and raw materials.  
• Increasing pervasion and interconnection of IoT & CPS systems opens opportunities for improvements, but also amplifies the negative effects of the other global drivers  
• Network ‘brittleness’ is a risk | • Global benefits have local disruptions  
• Equitable benefits for people need both regulation and incentives, as well as attention to standards safety and security  
• Government and inter-government actions will be required | • A sustainable world will disrupt current certainties, cultural values, and accepted orthodoxies. There will be resistance to the changes.  
• Sustainability projects will require widespread preparation to address concerns, & cultural issues  
• Big sustainability projects need global views: materials, treaties and economics of global trade.  
| Community safety & security | • Increasing pervasion and interconnection of IoT & CPS systems opens opportunities both for economic and social improvements, and for malicious activities aimed at people, infrastructures and businesses  
• Mega-cities may result from unmanaged growth, leading to unwanted social inequities (70% of world population expected to live in cities) | • More asymmetric attacks (small cost, big effect) on critical networks  
• Increase in ‘normal accidents’ due to increasing complexities  
• Possibility of of more social inequality & increases in ‘digital divide’ | • Ashby’s Law: more societal complexity means more complexity of governance  
• New ideas for complexity in society  
• Continuous attention to risks in critical infrastructures is needed  
• Human ingenuity and competence still primary in technological world  
• Ethical & cultural issues will become significant factors  

Table 2.1 An outline of the Global Drivers, their likely effects and characteristics, together with mitigation possibilities, and further reading.  Adapted from (Siemieniuch, Sinclair et al. 2015)
However, we cannot treat these global drivers individually; they are interlinked in their effects. Fig. 2.1a and b below indicate some of the high-level interactions between the global drivers, and classes of actions required for mitigation.

Both diagrams treat population growth as a main driver, following Sulston, 2012; as an aside, it has been estimated by the New Scientist magazine in 2015 that ‘in one second, 4.3 people are born and 1.8 people have died’; it is the consequences of this growth that produce sustainability concerns. However, similar diagrams can be created with similar messages, whichever of the global driver is chosen as the initiating source.

Figure 2.1a: Interactions between the global drivers; Figure 2.1b Mitigation activities
Taking Fig. 2.1a and 2.1b together with Table 2.1, four conclusions may be drawn about these Global Drivers;

- Each of the Global Drivers, operating on its own, could have very significant negative effects on the world as a whole, including the EU28. Together, they pose a significant threat to the health and well-being of all of us on this planet.
- Mitigating this set of drivers necessitates a connected, comprehensive approach; it is evident that tackling one, or another, is unlikely to have much impact by itself.
- A combination of political persuasion and technology will be required to reach any satisfactory conclusion; a comprehensive socio-technical solution will be necessary.
- For all interventions producing physical effects on the Drivers (mainly on the right side of Fig. 1b), new devices, systems and networks, mainly in the form of Cyber-Physical Systems, will be required to upgrade, replace and/or extend the functionality we have in place now and to make more efficient use of resources in order to address the integrated nature of the Global Drivers. Without these, we are reduced to persuasion and prayer to fix our problems.

The last point indicates the critical role that the Internet of Things (IoT) and Cyber-Physical Systems (CPS) will play as the current century proceeds; while shorter-term considerations in the EU28 revolve around the role of CPS for competitive positions and energy efficiencies and security compared to the rest of the world, it is the longer-term sustainability issues which will have the biggest impact on the EU28 and its people. Furthermore, since society and its social institutions as a whole are slow to react, it is probable that the efficiencies and economies that are required to deliver and maintain a sustainable world will only be delivered within the desired timeframe by the agility, flexibility, and extensive reach of co-ordinated, co-operative CPS.

2.2 Science and technology issues arising from global drivers

Several points arise from the considerations above:

- CPS-oriented supply chains are likely to be global in extent, involving many different jurisdictions. Legal differences between these jurisdictions may place many different, incompatible constraints on the efficient operation of CPS. This indicates an important role for international trade agreements to mitigate these constraints, preferably negotiated before the constraints have strong negative effects.
- Security issues abound; it is likely that the quality of security for CPS component systems and their supporting infrastructures will vary across the world, providing many gaps for exploitation and abuse, indicating the need for international security agreements. The role of international standards and security agreements will be important in mitigating the problems, but given the lengthy delays endemic to the standards world, it may be an instance of serendipity that the current, ‘early days’ fragmentation in IoT platforms, thus creating ‘walled gardens’, may reduce the spread and seriousness of security breaches, albeit at the cost of reduced efficiencies.
- Within the EU28, differing rates of adoption within member states of both the IoT and of the CPS that will depend on it are likely to exacerbate the ‘digital divide’; this will hamper the economic development of some member states and limit the competitiveness of the EU as a whole, as well as hinder adjustments to attain sustainable societies. It is unlikely that this situation will be rectified without initiatives led by the EC.
- At international level, the efficiencies theoretically available from the global adoption of CPS may mean that the ‘digital divide’ that already exists between developed and less developed nations becomes magnified. Consequently, there seems to be a role for international organisations such as the World Bank and the International Monetary Fund in helping to
spread CPS more effectively to all nations.

- It is evident that wide adoption of CPS will not happen easily unless their development is accompanied by concerted, integrated, co-ordinated efforts by governments and other national and international agencies to bring about significant cultural and social change. It should be noted that however well-planned the introduction of CPS might be, they are likely to be disruptive for jobs and cultural values. Experience with other innovations indicates that there will need to be efforts to mitigate these disruptive effects; it is likely to fall to governments to deliver these efforts.

- The interoperating consequences of the global drivers indicate that CPS thinking cannot be restricted just to one sector, such as manufacturing, or health care. These are intertwined, indicating a need for better understanding of sustainability science, to be able to understand how these different sectors relate to each other, and interact. Furthermore, those national institutions and commercial organisations developing or extrapolating CPS will need access to simulators that model these relations and interactions, to be able to find risks and consequences for their developments. In this regard, it is indeed fortunate that the EU is whole-heartedly adopting the principles of Responsible Research and Innovation (EC-NANOCODE 2009, ExGpRRI13 2013, RRI@Rome 2014), that will provide some impetus to develop these models, simulators, and tools to construct them.

- If CPS networks are to spread across both the EU28 and the world, there will need to be a world-wide effort to provide trained, competent people to create, manage and maintain them. This effort needs to be co-ordinated with the spread of CPS, and be able to deliver trained individuals before they are needed.
3 Generic challenges to layers of the CPS

This section discusses the general aspects in the instantiation of CPS within our societies, for convenience treating the following as ‘layers’ within the structure of CPS; linking devices to the Internet, interconnecting the devices; orchestrating them to deliver a desired outcome; dealing with the issues of mobile devices; management and managing CPS operations; and some more strategic issues. Frequently there will be found sub-sections that outline pending issues that should be addressed for full adoption and implementation of the technologies discussed.

3.1 Connecting devices to the IoT

It is expected by many experts that within the next 10 years there will be more devices connected to the Internet of Things than there are people on the planet (Pétrissans, Krawczyk et al. 2012, Gide 2013, Jankowski, Covello et al. 2014, Aguzzi, Bradshaw et al. 2015). While this offers the opportunity to create distributed CPS to address the impact of the Global Drivers above, it will be missed if devices cannot talk freely to other devices and applications. At the present time, there is a big range of interface specifications and formats, creating ‘walled gardens’ (perhaps better described as ‘wild gardens’) and limiting the range of possibilities for the markets and CPS of the future. This corresponds to the early days in the widespread adoption of any new, disruptive technology (automobiles being an example), and the marketplace will undoubtedly winnow these down to a few fairly standard formats (an example is RFID). However, addressing the exigencies of the global drivers in concert is likely to demand a more open approach, where the ability to link a device is standardized, there is a recognized ontology for metadata, and the competition between platforms is on the basis of efficiencies, security, and related performance vectors rather than exclusivity. This will certainly require efforts in standardisation, and likely will require some degree of regulation.

It is recognized that achieving this state will not be easy, given the size and reach of the vested interests involved, and that agreement between political bodies may well be necessary, supported subsequently by co-operation and co-ordination among standards bodies.

One particular issue of concern, overlapping with the next section is the security of devices that are components in a CPS, linked by the IoT. An immediate concern is security for consumer devices that might be networked, such as cookers, toasters, etc. The rush to market currently under way has meant that many devices have little by way of security against hackers and there is an urgent need for some form of certification to ensure this situation is redressed.

Many of the projects of interest to Road2CPS have explored the issues involved in dynamic networks where devices may enter and leave the network, and may create different links between the component systems on a fairly continuous basis (transport CPS for example, or enterprises in which individuals are allowed to ‘Bring your own device (BYOD)’. It is unlikely that the security of all devices (including the itinerant ones) will be guaranteed, therefore necessitating good security on all connected devices. Explorations involving the SHODAN software application (OpenDNS-15 2015) have demonstrated amazing open-ness of many important safety-critical systems.

There are some significant technical challenges to be resolved satisfactorily in connecting devices to the IoT; among these are the incompatibilities in the embedded systems world, where the abstractions of software engineering do not match the real-time time-sensitive behaviour of devices. There are work-arounds of some subtlety to provide a better match and therefore better, more reliable performance, and new languages are being developed specifically for this area. Of some interest are
the DESTECs\(^7\) approach and the Compositional Interchange Format\(^8\), version 3 (CIF 3), which may enable many of the problems to be simplified.

### 3.1.1 Scientific and technological challenges at the device level

Three important challenges discussed above are:

- Standards for interconnection of devices to the IoT. Standards are available, such as IEC 61499 and IEC 61131, but their adoption appears to be limited. Tools that enable device design and interconnection are also available, for example the DESTEC co-simulation tool (Ni and Broenink 2014). Encouragement will be needed to develop additional standards, covering security issues, certification of devices and interoperability, and to encourage the uptake of these standards.

- Further development of high-reliability, long-life, low-power, low-maintenance and miniaturized sensors is necessary, as the reach of the IoT and CPS extends into the social and physical environments, and as we seek to create a sustainable society.

- Further development of architectures and tools will be necessary to enable the design and subsequent upgrades of devices when they are in operational CPS that for reasons of safety, etc. cannot be switched off.

### 3.2 Interconnecting devices

Section 3.1 above has indicated two of the big issues regarding the interconnection of devices to create networks; the dynamic nature of many CPS networks, and the issues of device security. Fortunately, these issues are already being addressed, though there is much room for further work to address issues of scale and efficiency as the IoT grows. Current technologies such as Software Defined Networking (SDN), Network Function Virtualisation (NFV) and Spanning Tree Protocols (STP) provide a basis on which to build further research, expected to be necessary as we enter the phase of continuously-evolving and expanding networks and capabilities, ‘fog computing’ and other architectures, and distributed, mobile interconnection.

#### 3.2.1 General aspects of interconnection

In step with these developments, it will be necessary for interconnected devices and applications to talk to each other. Given the sheer size of the IoT and the parallelism of technology development that we may expect in the next few decades together with the different characteristics of the domains discussed in Section 4, it is to be expected that there will various dialects in the talking that takes place. It is immediately apparent that for there to be some minimum level of communications both within each dialect/domain of application and across the dialects/domains there must be a widespread effort in standardizing the metadata to ensure sufficient communications and efficient operations.

A parallel problem is scalability; as CPS grow in extent and in interconnections between them, there arises the problems of computing power to handle the vast increases in data flows and content that then arises.

#### 3.2.2 Scientific and Technological challenges arising from general aspects

Five areas of scientific and technological challenge are apparent, bearing in mind that many CPS will be of global reach and significance:

\(^7\) [http://www.destecs.org](http://www.destecs.org)  
\(^8\) [http://cif.se.wtb.tue.nl/index.html](http://cif.se.wtb.tue.nl/index.html)
• Metadata for Standard Operating Procedures. Clearly, in an open network, component systems within a CPS must be able to describe their functions in an easily-understood, standardized, open format for broker applications to be able to match services to queries.

• Metadata for Standard Process Instructions. Equally, a device must be able to interpret the instructions it will be asked to carry out by some other agent within the CPS; their permissibility, goals and performance constraints, and resource demands. An application negotiating with a device to deliver a service must be able to communicate its service needs to the device, and to receive assurance that they can be carried out within the constraints set for it.

• Architectures for broker applications. These are necessary for broker applications to be able to match agent requests to service providers, both of these being in the CPS, and to do so in cognisance of the dynamic network issues discussed above. Issues of speed of negotiation, security, protection and trust will be of increasing importance as CPS evolve and grow, and it is likely that the legality of brokering operations will also come to the fore.

• For the above to work well, the network must present a standard communication surface on which the brokers and services can negotiate, and then interoperate. Given the likely lability of networks with many nodes transient and mobile, approaches such as software-defined networks need to be robust, reliable and with strong, standardised surfaces on which the services can co-operate. The rapid evolution of network technologies indicates that significant effort should be allocated to standardization as early as possible, given the slow pace of the development of standards.

• Security issues in communications. Discussed above were issues of device security. A second layer of security, at the network level, will be required, to protect the integrity of the network and its communications. Further developments in firewalls and sandboxes will still be necessary, as will developments of encryption and protection of keys. However, we do not discuss these issues further in this report due to the extensive efforts in security at various levels including large-scale commercial organisations to member states of the EU28 and up to international negotiations.

3.2.3 Aspects of mobile interconnection
Mobile interconnection is concerned with network nodes (devices, applications) that are not stationary, and therefore force changes to network topography. They are important from three points of view:

• Transport of goods and people; both vehicles and their contents may seek interconnection with a fixed network of nodes or with other mobile nodes, either intentionally in long-term networks or in ad-hoc, brief networks.

• Individuals; the anticipated explosion in prevalence over the next decade and beyond of smartphones and other wearable communication devices (RFID tags, heart rate monitors, etc.), together with a multitude of applications on smartphones in particular, both in the EU28 and across the globe indicate that these classes of hybrid network may predominate in future. It has been suggested that the very great usage of mobile devices, evident now among younger users, is turning us all into habitual cyborgs embedded within software-defined environments; if so, the ubiquity and reliability of mobile networks is of paramount importance.

• Disaster recovery, whether individual, localised or regional; if the disruption is severe enough to interfere with or stop the operations of the regular, established network of fixed nodes, then the generation of mobile-device-based networks will be required to enable those affected to restore some semblance of normality in as effective, efficient, resourceful and resilient fashion as is possible.
Current means of addressing these needs is mainly by cellular technology, mesh networks and communication protocols such as the IEEE 802 series. While these networks are fast, easy to use, and effective, there are scale and security issues, efficiency aspects and safety-critical aspects to their performance. For better performance, it is necessary to design the layout of the mesh network more appropriately for its use and users. This requires network modelling for understanding of the network and its behaviour; currently deemed to be a difficult proposition, and needing theoretical advances.

3.2.4 Scientific and technological challenges for mobile interconnection

Some recent technologies under development may simplify the problems outlined above:

- Named Data Networking (NDN), in particular seems to offer significant advantages, if only for its resistance to attacks; other advantages in reduced network flows and reduced latency are other boons. However, transferring to this concept faces significant challenges from the established technologies.
- Cognitive Networks represent another approach with significant potential in quality of service, but with the same barriers as for NDN.
- The area of models and modelling for network management needs both theoretical and technical development, to improve both quality of Service (QoS) and efficiency of networks. This will be necessary to make best use of ‘fog computing’ and other technologies, in effect distributing computing power to where it is needed, geographically.
- As in previous section security, privacy, safety and protection issues are fundamental, best addressed by ‘security in design’; as an approach this is fundamental to efficiency, effectiveness, and acceptability, albeit difficult to achieve. Developments in 5G technology in the METIS and METIS II projects may address these issues directly.
- The complexities of networking implied by very large CPS indicate that the reliability of interconnection in the network is a fundamental requirement, whatever technologies are being developed to cope with any other requirements.

3.3 Managing, controlling and maintaining functions

This section is concerned with the orchestration of applications and devices to achieve some given purpose. It corresponds to ‘middle management’ in organisations, and commonly referenced as ‘middleware’ in the software domain.

3.3.1 Architectural considerations

Essentially, there are two paradigms for the control of devices and other applications to achieve some given purpose; centralised control, and distributed control. Centralised control allows the power of Cloud computing to be utilised in control, whereas distributed control minimises network communications load and is better suited for rapidly-changing networks in a CPS, especially when the CPS can be described as an ‘ultra-large system of systems’ (ULSS), as is typical in Smart Community scenarios (Feiler, Gabriel et al. 2006, Sillitto 2010).

An important issue in choosing an architectural approach, whether distributed, centralized or some intermediate version, is uncertainty, often manifesting itself as emergence (unexpected, often unwanted, behaviour) within a networked CPS. To mitigate the effects of uncertainty, the usual approach is to develop predictive models to be embedded into the (software) controllers of both networked devices and of the applications that co-ordinate and manage them, together with feedback loops from observed performance to adjust the models for better effect. Some significant advances have been achieved in a number of EU projects such as EMBOCON, HYCON2, AGILE and Local4Global,
involving real-life test cases, and a body of theoretical and practical knowledge concerning Non-Linear Model-based Predictive Control (NMPC) now exists.

While this can be applied to centralized architectures, it probably offers best hope for distributed architectures. It appears to have a significant advantage for those CPS that must accommodate mobile, itinerant nodes, typically in transport networks, in which each node has its own NMPC.

In contrast, several projects have explored centralized architectures, typically for fairly fixed CPS networks, such as in large buildings, controlling access and internal environments (e.g. UnCoVerCPS, SCUBA and GreenerBuildings). These imply that a CPS control approach based on concepts of Big Data and a Common Operating Picture could be adopted, leading to fine control of local and global effects.

3.3.2 Scientific and technological challenges for the control of interconnection

While significant advances have been made, there are further developments required. These are listed below.

- Theory of architecting. Given that the goal of a CPS network is both fast, efficient, reliable, interconnection and fast, efficient, reliable control of the network to adjust to changing circumstances in the CPS and its environment, we need theoretical understanding of both architectural principles and of the trade-space in which these principles are evaluated to arrive at a decision on the most appropriate architecture, both now and into the future.

- Development of excellent knowledge and practice for the efficient implementation of any chosen architecture into legacy CPS and their legacy environments. This is necessary for the instantiation of CPS in real life. Most times, they will be implemented with legacy systems for reasons of continuity and cost. Furthermore, this knowledge may be a useful contribution the trade-space above.

- Development of applications for carrying out trade-space analysis. Current approaches are limited and are not very efficient; as the scope of CPS grows and many more trade-offs can be envisaged, there are likely to be problems of scale, especially in data storage and manipulation. There is an urgent need to research into tools and technologies in this area.

3.3.3 Autonomy and learning in CPS

Autonomy as a topic appears twice in this document; it is addressed here as an internal issue for CPS, and appears again later in section 5, looking at autonomy as an external issue for CPS operating in society.

Efficient, economical CPS will increasingly make use of autonomous devices to supplement the roles and activities of the human stakeholders within the CPS, and its customers. Autonomous devices are becoming widespread across society as the technology improves; autonomous vehicles now populate all physical environments from space to sub-sea, and are taking on ever-increasing roles in all domains in society. However, further extension of autonomy into the control of safety-critical systems, for example, and into ever-closer contact with people depends heavily on further understanding of the technology of autonomy and its application, including issues of legality, liability and governance as well as the more usual aspects of safety, security, energy efficiency, dependability and many other ‘ilities’. Because the latter, ‘usual’ aspects receive considerable attention already (for example the ARTEMIS CRYSTAL, EMC2 and CONCERTO projects and the wholesale move of large companies such as INTEL, IBM, CISCO, BAE Systems and many others into the cyber-security area), this section concentrates more on the societal aspects that have not received the same level on attention. While these aspects

9 https://artemis-ia.eu/all-projects/page-1.html
are often classed as ‘non-functional’, they are the ones currently that are major barriers to the adoption of autonomous vehicles within society, and by extension will be relevant to other classes of autonomous systems.

The latter aspects, in relation to human stakeholders who will interact with these systems, are considered further in Section 5.

Considerable advances are required in sensing and perception; the seemingly-easy human capabilities of knowing what to look for, and understanding the meaning of what is seen are actually complicated processes, making considerable use of knowledge and experience. For CPS, this may be simplified by the presence of data connections between the autonomous application (that which ‘sees’) and the other applications within the CPS (those that are ‘seen’) and the permissible actions that application can then select, or construct (i.e. in a closed environment). However, for open environments, especially when entities in that environment can move or change their nature and may not be communicative, the functions of sensing and perception become vastly more complicated, requiring much more inbuilt knowledge.

Likewise, decisions and their execution become more complex in an open environment. There is a requirement for the autonomous application to have some awareness of consequences, both from a safety and effectiveness perspective; the ‘precautionary principle’ will apply to their decisions and actions as well. It should be noted that autonomous actions may take place and/or have their effects at a distance from the location of the decision, perhaps in a different jurisdiction.

There is also a requirement for autonomous applications (and the CPS in which they are located) to behave ethically (note: not to be ethical, but to behave ethically). This is required firstly to stay within the legal framework that pertains where the behaviour is executed, and secondly to fit within the expectations of the human society in which they operate. People, in their roles of customers, controllers, co-workers, and casual bystanders, will each have expectations of the behaviour of autonomous applications and systems, with which the system will have to comply, both for safety and security reasons and for reasons of generating trust in the behaviour of the automated system. It is an unfortunate complication that ethical frameworks are so under-described and different around the globe.

To emphasise the point about ethical behaviour, consider the philosophical notion of ‘moral agent’ as applied to a robot (Asaro 2009, Asaro 2011, Asaro 2012). To be a moral agent (and hence to have a place and standing within society), in addition to a reasoning capability, there must be a sense of compassion, empathy, respect and appreciation of punishment (mens rea). None of these qualities are likely to be found in autonomous agents for some time to come. Hence, the most accomplished robot, beyond what is currently available, may at best achieve the status of a ‘quasi-person’ (note that if it had the missing qualities, it might well earn the right to vote).

Absent the qualities, and the robot fits the psychological description of a psychopath. Enable it to communicate with other robots, and potentially science fiction becomes fact; ‘the (distributed) robots are coming!’.

Leaving science fiction aside, there are clearly governance concerns arising from autonomous systems. These become more complex when autonomous systems are capable of learning; a necessity for autonomous systems operating in open environments. This is considered in the next paragraphs.

It is possible to consider learning as falling into three classes; first-loop, second-loop and third-loop learning, as in feedback mechanisms (Argyris and Schön 1978). First-loop learning is concerned mainly with learning geographic locations, routes, processes, and the like; becoming competent for the role. Second-loop learning is about improvements; shorter routes, small improvements to processes, better
avoidance of mistakes; becoming polished and proficient in the role. Third-loop learning is about strategy; ‘Why are we doing things in this way?’; ‘Why is it necessary to do this?’; ‘I’m busy; you do it.’ Autonomy almost always requires the capability of first-loop learning in order to be functional; second- and third-loop learning may be necessary, depending on the role undertaken. Particularly for the latter two classes, there are two consequences of providing learning capability; firstly, as the autonomous entity learns, it distances itself from what it was, and has to be understood as a different functional entity (which may be a surprise). Secondly, a cluster of identical robots will not behave identically as time passes, and each learns different behaviour. Both of these raise problems for control within CPS. These issues have been discussed fairly widely by several disciplines (but without much coherence across them), and a multitude of projects have explored the aspects outlined above, but a more coherent body of theoretical understanding allied to engineering knowledge needs to be developed further. Pointing the way ahead are:

- The ROBOLAW project, D6.2 (E. Palmerini, F. Azzarri et al. 2014), discussing in more depth all of the topics above and more
- The development of a standard for ethical behaviour for autonomous systems (BS WD 8611 - Guide to the ethical design and application of robots and robotic systems)
- Metrics for autonomy, such as Sheridan’s scale, repeated below (Parasuraman, Sheridan et al. 2000)

Sheridan’s scale is shown below, where a software ‘agent’ is granted autonomy:

1. The agent offers no assistance, human must decide all
2. The agent offers a complete set of action alternatives
3. and narrows the selection down to a few, or
4. suggests one,
5. and executes that suggestion if the human approves, or
6. allows the human a restricted time to veto before automatic execution, or
7. executes automatically, then necessarily informs the human, or
8. informs the human after execution only if it is asked, or
9. informs the human after execution if the agent decides to do so,
10. The agent decides everything and acts autonomously, ignoring the human.

The current recommendation, based on the state of the art, is that in general the level of autonomy given to an agent should not exceed level 6 on this scale; for particular situations where all available actions are enumerated and known to be ‘good’, it is reasonable to go above this level.

3.3.4 Scientific and technological challenges in autonomy and learning for CPS

The challenges are legion, given the multitude of ways in which autonomous operation may be introduced into the CPS environment. Some of the more important in terms of need, likely impact and readiness date are the following:

- Improving perception in autonomous agents. It is fundamental that agents should have better situation awareness in their current scenario, so that the ‘affordances’ in the scenario can be discovered (Gibson 1979, Bohme and Heinke 2008, Roberts and Humphreys 2010). This may be helped by the rapid increase in the number of objects with a presence on the IoT, announcing their functions and characteristics and thereby reducing the need for perception; there are implications for metadata ontologies, etc. for this to happen.
- ‘Growing’ an understanding of the process and knowledge required in order to produce
reliable, ethical behavior by autonomous agents that is attuned to the scenario in which they are operating. This is likely to require significant effort over a period of time, and could be achieved by a sequential set of case studies.

- Develop the theoretical underpinnings of autonomous behaviour as a cross-disciplinary study, with the purpose of supporting engineering technology in developing autonomous agents.
- Develop techniques for run-time verification and validation (V&V) to ensure that autonomous entities are safe, reliable, and produce ethically acceptable behavior for any relevant scenario.
- V&V will be essential for those systems that learn. While machine learning has come a long way since the early days, it is still a technology devoid of ethical judgement, as discussed above. Furthermore, learning is without purpose if it does not result in changed behavior. Changes of behavior can mean that the components of a CPS no longer behave as designers and implementers intended and may surprise the stakeholders of the CPS. Machine learning technology requires much elaboration to ensure that devices and CPS components remain trustworthy (including no unpleasant surprises) and transparent with regard to what they have learnt.
- Develop design tools and techniques that enable designers to embody fundamental principles such as ‘Do no harm’ (or its softer version, ‘Do no lasting harm’) and ‘Where possible ensure that terminal decisions (i.e. decisions that cannot be undone) are among the last options available’ in their processes to achieve products that are ‘ethical by design’.

### 3.3.5 ‘Big Data’ in CPS

Following on from the discussion about autonomy, it is timely to consider the impact of ‘Big Data’; in an open environment, autonomous systems are likely to require large volumes of data and information to enable apposite behaviour. Big Data has been defined in terms of 3 V’s (or 4 V’s): Volume (of data), Variety (of data types), Velocity (how quickly the data is available for analysis); and Veracity (data integrity and trustworthiness) has been added as an important attribute.

A major implication of the Big Data approach is that the data sets used in the analytic programs have moved from small sample sizes to close to the entire population of interest, and therefore it measures reality directly, without need for inference (Mayer-Schonberger and Cukier 2013). Advances in sensor technology, computational power and connectedness have made possible the collection of vast data sets, and this trend is expected to grow (with corresponding issues for data management, storage, and analysis). The potential for identifying hitherto unknown patterns (albeit based on correlations) in the manifold behaviours of society and its pervasive CPS have provided great impetus to the development of Big Data systems. Examples often quoted are the prediction of an influenza epidemic (Ginsburg, Mohebbi et al. 2009) and language translation (Halevy, Norvig et al. 2009).

Some of the characteristics of Big Data point to the need for care and circumspection in using this resource (Drury 2015). Some of these characteristics are:

- The data may have been collected for other purposes and may have hidden structure
- Large data sets, close to population sizes
- Concomitant requirements for large data storage and for large-scale automated analytic tools
- Data combined from different sources, giving more complex but less clean datasets

---

10 [http://www.villanovau.com/resources/bi/what-is-big-data/#.VaUPLXjAZzc](http://www.villanovau.com/resources/bi/what-is-big-data/#.VaUPLXjAZzc)
• Potential problems from time asynchronicities in the data collected
• Confidentiality and security issues may preclude the use of some data sources that are important for the analysis.
• Sparse data matrices may result from incomplete or intermittent access to data sources
• Data accumulated in near-real-time, with the potential for rapid answers to queries
• Issues of privacy and ethics in automatically-collected data

However, unfortunate combinations of these characteristics in the data can result in fictional patterns (Mayer-Schonberger and Cukier 2013, Harford 2014), and currently, there is a perceived requirement for human involvement, making use of the greater wisdom, experience and perceptions of humans that are currently lacking in Big Data analytics.

3.3.6 Scientific and technological challenges for Big Data
This is still a growing area for technology, with considerable attention from commercial organisations. Some challenges still remain:

• There are still problems of scale, both in volume of data, in complexity of relationships between variables, in missing data, in time synchronicity of data and in variety of variables. There is still room for developments in methods and tools to address these issues more comprehensively.
• The problems also affect the pre-analytic process of cleansing and categorising of data
• There is a need for improved tools for better visualisation of the data sets, of tool processes as analysis is undertaken (for better control of the analysis procedures) and for human understanding of the results of the analyses. Given that in future CPS it might be possible to create a seamless link between analysis and decision-making, there is a need for a form of control by humans, since someone will be held legally responsible for the results of the actions.
• Given both the scope and detail in the huge amounts of data scavenged for analysis in Big Data projects, there is ample room for privacy and security transgressions, both accidental and deliberate. This indicates a need for a regulatory framework and Code of Practice for Big Data, perhaps expressed as an extension to the ‘Responsible Research and Innovation’ regime being developed by the EC.

3.3.7 Verification and Validation for CPS
Verification and validation (V&V) are fundamental processes for the safety and performance of CPS, but there are a number of difficulties in fulfilling completely the intentions of V&V in relations to CPS:

• The complex nature and size of many CPS preclude full V&V (as currently understood) being carried out
• Changes in the configuration of a CPS over time make early V&V exercises irrelevant; there is usually insufficient opportunity to repeat these
• Most application vendors are prepared to support their COTS applications for a limited number of years; this may be insufficient for long-duration CPS
• CPS created with the aid of legacy components are unlikely to have the resources or time to re-V&V these components, even though these components may be entrained for uses not originally envisaged. There may be a lack of documentation for these systems as well
• Where component systems within the CPS have autonomy, and are enabled to learn because they are operating in open scenarios, near-continuous V&V will be required to ensure that what these components have learnt, and how this learning is expressed, have not contravened prior requirements for safety and performance.

New approaches have been developed; the concept of run-time health monitoring is one such strategy, thought this suffers from being component-oriented, rather than whole-system oriented. There is a real need for new approaches.

3.3.8 Scientific and technological challenges for CPS V&V

The biggest challenges in this area concerns heterogeneity of the disciplines involved, in the models that result from the different disciplines and perspectives, and in the languages in which the models are expressed (Lee 2010, Derler, Lee et al. 2012, Henshaw, Barot et al. 2013). However, recent developments (such as the Compositional Interchange Format 3 for hybrid systems)\(^\text{11}\) indicate some potential for improvements.

• The development of formal methods to improve the verification of designed artefacts for CPS that take account of hybrid models
• Development of modeling and simulation environments for those components and systems that currently are not amenable to formal methods
• Proof of the validity and then subsequent adoption of design processes for artefacts that fit the description, ‘extreme programming’
• Development of trade space technology to enable designers to ‘move’ functionality around the design such that the critical aspects can more easily undergo V&V
• Develop run-time V&V techniques and tools, necessary for evolving enterprise operational control systems that cannot be switched off.
• Develop methods and tools for carrying out V&V on autonomous systems

3.3.9 Modelling, simulation and control

It is widely accepted that modelling and simulation will be essential both to assemble a CPS, and also to exercise control over its operations (Camacho, Engell et al. 2014, Schätz 2014, Geisberger and Broy 2015). This is expressed succinctly by Schätz:

“The key principles of cyber-physical systems and main complexity drivers are the ‘cross’-, ‘live’-, and ‘self’-domain.

Due to these principles we expect that:

• the explicit use of models will play a dominant role in the engineering of CPS
• the traditional distinction between design/implementation and operation/maintenance of a system will be abandoned in favor of an integrated life cycle.

However, to meet these changes in engineering CPS, we are faced with the challenges:

• to provide a model engineering framework including both a common theory of modeling paradigms as well as methods to arrange (distributed) layers of models

\(^{11}\) http://cif.se.wtb.tue.nl
to turn a CPS into its own engineering and development environment, with built-in mechanisms to construct, analyze, and synthesize models of its environment, platform, and functionality”

Unfortunately, while this is a good prognosis, there is a shortfall in the required technology available to accomplish these goals (Henshaw, Barot et al. 2013, Paige, Calinescu et al. 2013, Kinder, Henshaw et al. 2014). For CPS, these shortcomings can be summarized as:

- They require sophisticated and often complex engineering languages to be used during their construction.
- They are developed using large, complicated and complex engineering and run-time models.
- The models often require large, complicated and complex manipulations - e.g., for querying, analysis, reasoning, transformation, versioning, matching.
- Underpinning theory for vast, hybrid models is sparse.
- Heuristics, incrementality and run-time analysis are underdeveloped in the Model-Driven Engineering space.
- These models are not constructed for operational use.
- They are not responsive to the need for evolution, in which the models are amended while operational, as might be required by incremental improvement exercises within the enterprise – consider Nestlé, who carried out 29 small improvement projects addressing sustainability and efficiency of their operations within 6 years at one site.

These shortfalls in the world of modelling and simulation have been recognised (Camacho, Engell et al. 2014, Rashid, Anwar et al. 2015). Delving further into modelling and simulation tools and methods, there are fundamental issues to be addressed:

- Model-based systems engineering (MBSE) tools do not match the complex requirements of real CPS component systems; and platforms for these tools are limited in capability (except, perhaps, for the ECLIPSE platform).
- Transforming models for purposes such as verification and validation is not as easy task, and the V&V process itself is notoriously long-winded.
- To quote the HYCON2 project verbatim: ‘One of the most difficult and important problems to solve in the near future is the integration of mathematically sound control design and analysis methods into industrial environments where heterogeneous software and formalisms dominate, and where design data, documentation, and models abound on all design levels. These have to be integrated in such a way that inconsistencies and errors are detected early. Such integration can lead to an enormous increase of the efficiency in the design phase and in later operations. While the lack of such integration today already leads to a large waste of resources and lack of robustness to errors, it can be expected that in future systems design projects which will become more and more complex, the lack of such integration mechanisms may lead to an inability to successfully complete complex projects at all.’

The situation is improving, however; in the EU28 the COMPASS (Fitzgerald, Larsen et al. 2014), DANSE (Gezgin, Etzien et al. 2012) and CIF-3 (Beek, Fokkink et al. 2014) projects are addressing a number of the issues above, in creating M&S eco-systems appropriate to the problems.

There is a need, recognized widely in the community, for novel thinking to address the shortcomings outlined above; for example, there are proposals to take a statistical characteristics approach rather than a direct control approach to the problem (Miguel, Johnson et al. 2012, Bujorianu and Mackay 2014), which might result in simpler models requiring less computational effort.
3.3.10 Scientific and Technological challenges for modelling, simulation and control

Fortunately, most of the short-comings discussed above are recognized widely in the relevant software community; however, solutions are likely to take significant amounts of time and require considerable effort for their accomplishment. The challenges have been aggregated below:

- Develop an understanding of the relationships between system evolution, run-time V&V, modularity, distribution versus centralization, and the associated ‘-ilities’ (e.g. security, reliability, agility, resilience, robustness, privacy, etc.)
- Characterisation of evolvable architectures. These architectures currently are thought to be different for different business domains as described in ARTEMIS; perhaps it will be possible to identify commonalities.
- Explore alternative approaches to the control and orchestration of CPS processes, to reduce the control demands and associated demand for computational resources.
- For legal and liability reasons, understand how human roles that involve responsibility and authority can be incorporated into the operations of a CPS enterprise; how a person in such a role can have situations awareness of the state of the CPS (local or global), the control options available, and the tools to explore alternative decisions to change the state of the CPS, and the consequent architectural issues for the design of the CPS.
- Develop implementation paths to move from a desired model via trade space analytics to a functional CPS embodying solutions to all of the challenges above.
- Develop a theoretical understanding of the relationships and feedback loops between component systems of a CPS, involving unanticipated transfers between sources, bearers and sinks of mass, energy and information, and the propensities for emergent behavior. Note that this emergent behavior might be detrimental, or it might provide opportunities for resilience in the face of adverse events.

It has to be said; this is a daunting list. Nevertheless, the reductions in time and effort that are potentially achievable mean that such an effort would be well worthwhile.

3.4 Strategy, co-operation and regulation

Although the banking industry is more of a cyber system than a cyber-physical system, the recent global financial crisis brought about mainly by failures in governance has shown the need for oversight in systems that are intricately interwoven into the fabric of society. It is likely that the IoT and CPS will rapidly achieve the same status; vital for the conduct of everyday life and maintenance of our civilization.

3.4.1 Supervision and regulation of CPS

There is a need for a supervisory regime to provide a sensitivity assessment for the fitness of a collection of CPS systems, to avoid the kinds of problems of recent years. Such a regime will necessarily involve political action to develop regulations and punishments for identified malfeasance; however, in isolation these are unlikely to be efficient effective or appropriate. It seems necessary to develop a framework to enable an authorized regulatory body to assess the integrity and latent vulnerabilities of collections of CPS in particular domains, perhaps also across domains.

Such a supervisory regime will probably have to have interfaces with several others; economic, security, and so on.
3.4.2 Scientific and technological challenges for a supervisory regime

To enable such a regime, the following approaches seem necessary:

- Develop modeling and simulation tools and techniques for use in the assessment techniques listed below
- Detection of the extent to which an individual CPS within an industry is reliant on untested or unsupported components
- Detection of the extent to which a group of CPS within an industry are dependent on a small, perhaps fragile, number of component system owners
- Detection of the integrity of the IoT communications patterns for CPS in critical industries (e.g. energy, flight, etc.)
- Assurance of valid, effective fall-back plans for CPS collapses (e.g. major power failures).
- Assurance of good governance in critical CPS
- A means of assessing the consequences of contracts that bind the component systems of a CPS together when placed under stress
- Assessment of the general security of the IoT and its critical CPS against attack.
4 Challenges for CPS in 8 domains

In the original Road2CPS proposal, it was stated that challenges in four domains would be addressed. These were:

- Smart Cities
- Transport
- Manufacturing of the future
- Energy supply

However, once the project was commenced, it was realized that if complementarity to the ARTEMIS project was to be achieved, it would be helpful for Road2CPS to address all eight domains identified by that project. Accordingly, the eight domains discussed below are taken from the ARTEMIS ‘Major Challenges’ report (Gide 2013), the industry-oriented report that guides near-future R&D for CPS. These domains are:

- IT&C, and the mobility of devices
- Energy generation, distribution and use
- Manufacturing
- Security
- Transport
- Health care
- Smart communities
- Agriculture and water

4.1 IT&C and mobility of devices

Many of the CPS challenges within the IT&C domain have been discussed in Chapter 2, from a perspective within CPS and their deployment. This section considers issues and challenges more generally, from the perspective of the IoT and its role in embracing CPS as well as providing support to CPS. The perceived challenges from this perspective are discussed below.

4.1.1 Scientific and technological challenges for IT&C

There is a range of noteworthy technological developments centred around efficient utilization of the IoT. Some of these developments are listed below:

- The steady adoption of Cloud technology by industry in all domains, coupled with the development of Big Data analytics
- The adaptation of the above for Fog computing, with its advantages of localization, efficiency, and reduced latency
- New concepts, albeit radical and disruptive in nature, such as Named Data Networks and other ideas for communications efficiency and augmented security
- Technologies to cope with evolving CPS that may be large-scale in both size and geographical distribution using concepts such as Software-Defined Networks and Network Functions Virtualisation

Developments in these and other technologies are ongoing and will continue; there will be a need for some initial funded research projects to bring the newer technologies closer to the market. However, there are other aspects of IT&C in relation to CPS operations that will need both scientific and technological exploration, requiring extensive effort.
Particularly for CPS, because of the tight co-ordination and parallelism of activities that are potentially available, ensuring the security of the network links and computational nodes while not compromising CPS efficiencies, is of prime concern. Security here is not aimed solely at attacks from unfriendly sources and actors; it includes aspects such as protection of IPRs, commercial confidentiality, maintenance of privacy, and assurance of the safety and longevity of private and personal data.

The development of ultra-reliable CPS software and hardware components will also be of great importance. Since individuals and communities are likely to find themselves both living in, and carrying out their daily activities within, a software-defined environment, reliability will be of great importance; it is, after all, one of the cornerstones of trust.

Much better understanding of the nature of complexity and the opportunities for emergent behaviour within CPS, particularly in relation to both the unpredictable nature of the CPS environment and of the effects of continuous evolution of the CPS and its functionality; continuous because of incremental improvements to the operations of the CPS and because of less frequent, larger-scale changes due to revisions of business models and strategies. Perrow’s ‘normal accidents’, inadvertently built into CPS, are one manifestations of emergence that we should try to avoid; ‘Brittleness’ of the CPS, due in part to its architecture and management, is a related manifestation.

There is a need to explore for better understanding the nature of business models and governance appropriate to CPS function, the permissions and constraints of contract networks in evolving CPS, and legal and liability issues arising from technological autonomy within the CPS.

There is a clear need for understanding and optimizing the roles of people within CPS-based enterprises; they are the main sources of strategy and innovation, and they are the ultimate providers of resilience to CPS. They are the only agents holding responsibility and authority within the CPS enterprise, with legal standing, important sources of information and knowledge, and the only sources of wisdom. If people are to exercise these capabilities while embedded within the CPS, then the CPS must be designed to enable them to do so. Given the characteristics of the CPS, this will require considerable developments in the theory and practice of socio-technical systems design beyond the current state of the art.

If model-based engineering of CPS and the extended use of these models to operate the CPS is the future of implemented CPS, then there will be a heavy demand for modeling and simulation tools and visualization techniques for the whole lifecycle of the CPS, including as it evolves. There are few of these available, and none that can manage the scale of modeling involved.

Taking the two lists above together, it is clear that there is a need for a sizeable program of RD&I to be undertaken.

4.2 Energy generation, distribution and use

It is helpful to separate the discussion into two sub-sections; the first dealing with generation, and the second with usage.

4.2.1 Energy generation and distribution

In 2010, the EU28 imported over 60% of its gas and over 80% of its oil (EC2011 2011, EC-Energy 2011). Complementing this, the “Energy Roadmap 2050” (COM(2011) 885 Final) outlines how the EU28 could reach the target set by the European Council to reduce greenhouse gas emissions to 80-95% below 1990 levels by 2050; see Figure 4.1 below. The roadmap points out that the achievement of this target is fraught with uncertainties associated with demographics, intergovernmental politics, the creation...
of appropriate market conditions and business models to encourage the creation and uptake of low-carbon technologies and the engagement of the public to achieve popular acceptance of the costs and degrees of change that are required in society.

Figure 4.1  Intended reductions for greenhouse gas emissions for the EU28 as outlined in EC Communication COM(2011) 112. The assumption in this diagram is that each sector will achieve this reduction by entrainment of renewable resources allied to energy-saving actions in the sector itself. The diagram includes expected developments in each sector.

CPS have an obvious role in generation; as we move from a model of as-needed, point generation of energy distributed unidirectionally through a network to nodes where it is needed to a network better characterized as multi-node generation and multi-node utilization, and where many nodes may be intermittent in their demands for energy or their provision of energy. Furthermore, this intermittency may mean that the reliability of energy supply must be assured by storage technologies; there is a wide range of these.

Figure 4.1 above makes it clear that fossil fuels (mainly oil, coal and gas) will dwindle in importance and in quantity of supply for energy; their role as a feedstock for process industries will still be important.

The further development of fuel-cells as energy sources mainly for vehicles but also for other mobile devices is based for the present on hydrogen technology and holds great promise for reductions in harmful emissions; its future, however, depends both on the development of much more efficient technologies for hydrogen production and the creation of networks for its subsequent delivery to locations where it is needed. These are two significant scientific and technological barriers.

4.2.2  Energy use

Within the EU28, considerable effort is being spent on initiatives to address climate change, such as the Climate Change Programme (ECCP), the Emissions Trading scheme (ETS), the ECODESIGN Directive, legislation regarding the minimum renewable content in energy supplies, the promulgation of insulation and energy-efficiency targets and support for the development of carbon capture and
storage (CCS). In most cases, success of such initiatives relies on managing the collective behaviour of many interconnected systems in which the behaviour of people will play a very significant part.

For those sectors that make use of generated energy, savings in energy may arise either by actions directly aimed at energy savings (e.g. in response to the EcoDESIGN Directive); they may also be in response to cost pressures and material availability (Allwood, Ashby et al. 2011, Allwood, Ashby et al. 2012, Gutowski, Sahni et al. 2013). New methodologies, too, will help in savings; the likely spread of additive manufacturing allied to the concept of distributed factories enabled by the CPS paradigm will firstly reduce manufacturing costs, and secondly go some way to reducing transport energy costs.

Significant savings have been achieved in buildings, both new designs and in old buildings, and may be expected to continue as CPS spread their reach in the built environment.

Energy savings may also accrue as a result of other savings; while each sector will have its own routes to energy savings, for almost all sectors, recycling is a major contributor; for example, by increased process efficiencies and design improvements Toyota, over a period of 20 years, has managed to reduce resource demands per vehicle: for energy (~74%), for water (~69%) and for waste (~60%). Similarly, over 6 years, involving 29 small-scale projects in one factory, Nestlé has achieved: zero waste to landfill, -22.1% in energy costs, -27% in water usage, and -22.2% in greenhouse gas emission, per tonne of product.

A lurking problem in this pressure for greater sustainability in energy use is the accompanying pressure for change in the component systems of CPS and in the parameters of these component systems. The Nestlé example above shows this; 29 small projects within 6 years implies there was overlap in time for these projects, each one changing established ways of working and changing process settings as well; perhaps removing or replacing processes as well. In other words, if the factory had been operating as a full CPS, it would have had to deal with continuous change, some of the time in parallel, for 6 years, and perhaps continuously into the future, since the factory is still committed to its sustainability programmes, and is faced with legal pressures to keep making progress. Perhaps incremental changing of parameters would be enough, at the beginning; however, as these mount up it usually becomes necessary to take more drastic action, changing the architecture of components and the CPS itself; and all of these classes of change could be happening in parallel, with no end is sight for the lifetime of the CPS.

It is unlikely that the current tools at our disposal for managing change will suffice for this environment, especially if we try to scale them up to deal with very large CPS. There is a need for better tools; not just design and evaluation tools, but management tools as well that can utilise design and evaluation tools to make changes to CPS while the CPS is running (Cengarle, Törngren et al. 2014, Schätz 2014).

4.2.3 Scientific and technological challenges for Energy generation, distribution and use

A number of pressing challenges emerge from the discussion above:

- Control of ultra-large-scale systems of systems (ULSS). Given the wide range of energy generation method, the wide-spread sources of this energy across the geography of the EU28, and the need for always-available energy for our society, the control of the network is a priority. Again, because the energy grid falls into the ULSS class, classic methods of control will be insufficient, and some form of distributed control will be necessary. While direct, precise control may be the ideal, the variability in the system may preclude this goal; there is a need for exploration of novel methods of ULSS control for hybrid systems. For example, it may be sufficient, and more feasible, to look to statistical control of the network and its performance.

41
• Management of continuous change. A serious challenge for future CPS is the management of constant change, as indicated in the Toyota and Nestlé examples above. The mini-projects that produced the savings indicated overlap in time, and may be extensive beyond the boundaries of an individual organization. Given that in a future CPS world, processes will be software-defined with sequences of people and devices embedded within software environments, there is likely to be an issue of software-updating involved. Furthermore, given that many of the software components will be COTS packages, probably designed without the exigencies of real-life incremental improvements in mind, and perhaps with no formal support available because of the passage of time, there is a clear need for system software (hypervisors) to be aware of impending changes, making appropriate adjustments to the CPS, and, given the ever-tighter control over activities that is the defining characteristic of the CPS paradigm, exploring the consequences of proposed changes.

• Developments in energy storage technologies. A number of alternatives exist in prototype form; for example high-speed rotors, high pressure gas, water storage in lagoons and reservoirs, large-scale battery systems, use of in-vehicle batteries, etc.

• Development of fuel cell technology; this is very much a multi-disciplinary challenge involving most of the engineering professions and many scientific disciplines as well.

4.3 Manufacturing

For clarity, manufacturing in this Deliverable includes chemical and other process industries, food and textiles, as well as discrete parts and composites.

As argued above, global drivers make a significant case for sustainability in manufacturing, both as a primary means to mitigate the effects of the drivers, and also because of the energy and materials demands that current manufacturing methods and processes require.

The general conclusion is that all nations in the world need to move from a ‘Linear Economy’ (from extraction of resources to landfill) to a ‘Circular Economy’ (recycling, with minimal extraction and landfill), coupled to resource efficiency (EC/2011/112/2 2011, EC-circ-econ 2014). This applies to all sectors of manufacturing and is represented in Figure 4.2 below. It should be noted that other sectors will employ the products of manufacturing to turn their own linear processes into circular ones, too.

More specifically, recycling/re-use includes the following:

• Re-use – redeploying a product without refurbishment – e.g. reselling mobile phones, ‘obsolete’ in the developed world in other regions.

• Remanufacturing – restoring a product to its original performance. For example, Caterpillar has a successful engine remanufacturing business (Foresight 2013, Lavery, Penell et al. 2013).

• Cascaded use - using a product for a lower value purpose – e.g. turning used clothes into pillow stuffing (Foresight 2013).

• Recycling (also ‘upcycling’)- extracting a product’s raw materials and using them for new products – e.g. aluminium and steel are widely recycled.

• Recovery – using a product’s materials for a low-value purpose such as road base.
Figure 4.2: Illustration of ‘Circular Manufacturing’, as an instance of the ‘Circular Economy. Linear manufacturing runs directly from the Natural environment through to Landfill.

Triage, the pre-process for recycling/reuse as shown in Figure 4.2, is a fundamental process, relatively unexplored at the present time, and ripe for exploitation by CPS. Current volumes of household and business waste in the EU28 amount to 2.5 trillion tonnes per annum in 2012 (Table ten00106, Eurostat), if only half of this is recoverable, there are very significant savings to be made in energy and in global resources. Furthermore, the capability to re-mine old landfill sites represents a potential resource bonanza, as well as improving the quality of the environment.

Creating the Circular Economy depends heavily on the design of products, too; ‘design for disassembly’ is an important principle, particularly in relation to vehicles and other products where disassembly poses health and safety dangers.

Consider some aspects of Figure 4.2 in more detail, to enhance the picture:

4.3.1 Extraction and utilisation of minerals
Several reports address this issue; a sample set is (Clift and Wright 2000, Allwood, Ashby et al. 2011, Allwood, Ashby et al. 2012, Lee, Preston et al. 2012, Sulston 2012). Two common points are made; firstly, for many minerals, the cost of extraction and purification is steadily rising as a proportion of total cost, as the ‘easy’ sources become fully-exploited and miners must turn to lower-grade ores that are less easy to access.

Secondly, as we pass the point of ‘peak availability’ for a number of metals (copper being one of these; zinc is another), the cost is likely to rise considerably more (Prior, Giurco et al. 2012). Recycling is much less costly in environmental terms, and in economic terms too, since the materials remain in the circular economy. In this context, it is relevant to note that the European Commission (for example)
has passed a number of directives  \(^{12}\), supplemented by national governments, regarding manufacturers' responsibilities for waste management and which will reduce the triage problem in Figure 2. For instance, there is Directive 2000/53/EU and (2005/64/EC), both dealing with ‘end of life vehicles’\(^{13}\).

4.3.2 Landfill

Many countries are experiencing problems with landfill, ranging from methane emissions from landfill sites to lack of available space. For example, in Japan, it was reported in 2008 that

“Japan is experiencing a serious on-going situation in various respects: an enormous amount of waste, about 470 million tons, is generated annually and, at the same time, disposal of waste is becoming more difficult ... and there is a shortage of landfill capacity at final disposal sites. As for industrial waste, the remaining capacity is 7.7 years for the entire country and 3.4 years in metropolitan areas.” (MoE(Japan) 2008).

Similar problems are already apparent in many EU member states; however, reducing landfill in manufacturing to zero or a near-zero state is achievable, as several companies have demonstrated. Some good examples in the EU are Toyota Motor Europe at 8 sites, Caterpillar at 2 UK sites; internationally General Motors has achieved zero waste to landfill at 102 sites globally and claims that it now generates $1 billion a year from the reuse and recycling of production by-products (Lavery, Penell et al. 2013). On the other hand, finding technical ways to mine landfill would present a significant source of materials for re-entry into manufacturing processes; approximately 1 billion tonnes of waste per annum in the EU28 goes to landfill.

4.3.3 Enterprise effects from the ‘circular economy’

Business models are involved as well; the move to a Circular Economy implies an associated move to a service-oriented business model in which the product remains in the possession of the manufacturer (or a lease entity), with users leasing the product for a period. This causes many changes; to product design philosophy due to increased emphasis on longevity, reliability and adaptability to evolving uses; to choice of materials for recyclability of the product; to changes in architecture emphasising clarity and modularity for any or many future upgrades (improving on current practice, where subsequent upgrades for capital goods upgrades are planned years in advance).

Clearly, a CPS approach is best for this shift in business philosophy; the implications of longevity, change and resilience in this shift would be best addressed by embedded systems, allied to modular architectures appropriate for this new business environment. Brief, complementary discussions can be found in (acatech11 2011, Kastalli and Looy 2013, Visnjic and Looy 2013). It should be noted that a transition of this magnitude would have to be introduced slowly, and that regulation will be necessary to ensure that lessees have some protection against some classes of aggressive lessors.

4.3.4 Manufacturing processes

The discussion so far points to the need for manufacturers to be frugal with their resources, particularly in energy utilisation. There is some ‘push’ from legislation which can be quite stringent; in the EU28 the ECODESIGN Directive (2009/125/EC) mandates ever-decreasing limits for energy consumption of a number of classes of products, from a lifecycle perspective.

---


\(^{13}\) http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:32000L0053:EN:NOT
Added to this is the usual commercial supply-chain approach, evident in automotive manufacturing, where the dominant partner, usually at the end of the chain as the assembler of the vehicle, mandates that prices for components shall drop by ~3% annually for the duration of the contract, together with quality improvements.

These pressures imply a significant shift to better, more detailed, control of processes and products. The introduction of new technologies such as additive manufacturing, new materials such as graphene, alloys and ceramics, and new manufacturing concepts such as the fractionated, networked factory, distributed geographically, make a combined contribution to better control. These aspects are discussed extensively in several major studies; for example, ARTEMIS (Gide 2013) and the acatech documents (acatech11 2011#3943, Kagermann, Wahlster et al. 2013, Geisberger and Broy 2015).

Figure 4.3 below illustrates how the networking involved in manufacturing CPS might function. As discussed earlier, the Virtual Objects in Figure 5 may be repositories for data from sensors, or they may have processing power both to analyse these data and to communicate with other virtual objects. They may have further processing power, to adjust to their environment as it changes (e.g. autonomous vehicles), and they may be given significant learning capabilities to enable them to have even more autonomy (e.g. personal care robots).

These aspects regarding autonomy and learning apply even more so to the Composite Virtual Objects (CVOs.). At this level, there can be significant software resources for connecting sensors and actuators, for co-ordinating of the behaviour of the virtual objects within the CVO, for communicating and negotiating with other CVOs, and for interpreting and executing strategy emanating from the machinations of the Business Application Suite. In a stable environment, the decisions of the middleware may be made by rule-sets, established during the Design and Implementation phases for the CVO. In a dynamic, non-repetitive environment it is more likely that there will be a significant involvement of Artificial Intelligence and Machine Learning, with guidance from people.

It is also evident that in providing capability at this level there will be a multitude of software applications of varying capability available, performing a multitude of different functions. Immediately it becomes obvious that interface standards and extensible meta-data formats to enable varying combinations of applications to work well in this environment will be essential. In respect of this, it is fortunate that the ARTEMIS programme has initiated both the CRSTAL and Arrowhead Innovation Pilots, the former to create ‘ultra-reliable applications and workflows’ and the latter to create collaborative automation.

Nevertheless, it is necessary to acknowledge that CPS will largely be driven by component systems of legacy software. While this will be replaced or upgraded in future, legacy systems will be operational for a considerable time to come. Unfortunately, current levels of reliability of existing software applications indicate that breakdowns will occur, necessitating the presence of people to restore systems, to find work-arounds, and to apply wisdom at opportune moments. Two quotations illustrate this:

"For a useful perspective on the system design and engineering challenge, it is worth noting that the findings from Capers Jones, [http://www.spr.com], and others indicate that deployed software systems contain approximately 0.4 latent faults per function point. To our knowledge, this indicator of dismal [operational availability] has improved only about three-fold in the last four decades. Upon comparing this to the 30-fold reduction that automobile emissions engineers have achieved in less time, it is possible to develop an appreciation of the work that remains to be done on software for resilient systems." (Ring and Madni 2015)
“COTS software products are particularly challenging to integrate. They are opaque and hard to debug. They are often incompatible with each other due to the need for competitive differentiation. They are uncontrollably evolving, averaging about up to 10 months between new releases, and generally unsupported by their vendors after three subsequent releases. These latter statistics are a caution to organizations outsourcing applications with long gestation periods. In one case, we observed an outsourced application with 120 COTS products, 46% of which were delivered in a vendor-unsupported state …” (Boehm 2006)

Consequently, we may expect CPS not to work as well as intended for some time to come.

When CVOs are combined together by a business application suite, so that the strategic goals of an entrepreneur can be turned into sequences of required behaviour, we have an operational Cyber-Physical-System-based enterprise, necessarily involving human interaction for reasons of legality, liability and resilience, but accomplishing most tasks automatically and with a substantial degree of autonomy.

The discussion above is not predicated on large companies alone; the CPS could be a Small- or Medium-sized Enterprise (SME), employing relatively few people and with a modest annual turnover. It can then join other companies in long-term or very short-term relationships to create very large CPS; but only if its models, processes, procedures, and the semantics of its business match those of its partners. Naturally, cyber-security issues such as authentication, certification, ownership and responsibility, encryption, confidentiality and privacy, will be of great concern, as will issues of education and training, skills and tasks, and job design, responsibilities and authority.

![Figure 4.3: Illustration of the Internet of Things from a manufacturing perspective, omitting most of the complexities such as standards, interconnection protocols, interoperability contracts, co-operation and co-ordination and network security arrangements. Diagram based on CREATE-NET (Vlacheas, Giaffreda et al. 2013). Labels in red indicate the...](image-url)
ecosystem of organisations necessary to maintain an operational enterprise; market segments refer to business-to-consumers (B2C) and business-to-business (B2B).

### 4.3.5 Scientific and technological challenges for CPS in manufacturing

A large number can be identified (acatech11 2011, Geisberger and Broy 2015); the Road4Fame project\(^\text{14}\) has convenient lists. Some general aspects from the analysis of the 53 projects are listed below.

- Develop sufficient understanding of the challenges of recycling to enable implementation into CPS. The main challenge to be understood better is the process of triage in Fig 4.2, and the implications of this for design and manufacturing. In part this involves the physical sciences (how to recycle what we do not nowadays), but also technological (e.g. better tracking of materials, better collection and sorting technologies, better processes of recycling) and the social sciences (e.g. how to nudge the general population into better performance in recycling, what other regulations and incentives are needed to increase recycling and what is the best mix of these).

- Explore methods for mining landfill sites. This seems a good application for CPS, given the noxious and toxic aspects of landfill. At its core, the recycling of landfill is about triage; this challenge could be an extension of the challenge above.

- Explore methods for recovery of materials from sewage and similar wastes. Since these tend to be liquid wastes, there may be scientific challenges involving tailored micro-organisms, and technological challenges in turning these into a viable process (for example, it is encouraging to note that the Bristol Robotics laboratory in the UK has found ways to generate electricity from urine). Furthermore, such techniques may be able to deconstruct various chemical wastes that have deleterious ecological effects.

- There is a requirement for better, scalable modeling tools and simulation environments for assessing new business models, both for benefits and risks; as CPS pervade business and industry and become more interactive, it will be the consequences outside the particular venture under discussion that will need to be assessed. We do not have these tools and environments today; a category that specifically needs further development is tool and platforms for forecasting. There may be side-benefits as well, in replacing the mathematical models so beloved by economists by something better.

- Manufacturing depends critically on timed events; given that in the manufacturing domain are likely to be geographically distributed, secure, time-sensitive machine to machine (M2M) communications will be an essential technology to be implemented within CPS component systems and the IoT.

- Standards for interoperability will become even more important for platforms, products, and services of the future. To overcome the huge amount of different devices, systems, and protocols already existing standards need to be examined and adopted if possible.

- The control of enterprise CPS is under-explored, and requires appropriate tools, as indicated earlier. Modelling and simulation will be intrinsic to the design of CPS, and to the operation and governance of CPS too, both for ‘normal’ operations and as they adapt to the demands of change, driven by outside factors. However, in the latter case modeling and simulation of change to the CPS will have to take place while the CPS is running, since it is unlikely it could be switched off. Furthermore, in such circumstances it is highly likely that change will be undertaken by humans applying skill, expertise and wisdom; for them to be able to perform this task, modeling and simulation must enable them to have situation awareness of what is

\(^{14}\) [http://road4fame.eu](http://road4fame.eu)

©Road2CPS Consortium
happening in the operational CPS, what is likely to happen, and what options are available to
them in introducing change to the CPS.

- Future Cyber-Physical Systems will increase the number of physical and logical devices that are
  able to communicate autonomously over the manufacturing network. These security issues
  are feared by many manufacturing companies. The concern of data hacked through the
  internet is quite widespread within the manufacturing companies. Further research in security
  tools, protocols and strategies for firms together with the development of interoperability
  standards to protect the interconnected and distributed manufacturing systems will be
  essential to guarantee the balance between security cost and benefits to an organization.

- Since CPS in manufacturing (and other domains) are likely to be non-stationary, there is a near-
  continuous demand for certification of the safety and performance of the components of the
  CPS and of the CPS as an entity. While respecting the ultra-reliability aspirations of the
  CRYSTAL project within the ARTEMIS JU, it is expected that there will always be a need for run-
  time verification and validation of the CPS; perhaps best expressed as ‘continuously
  monitoring the health of the CPS’. This is both a scientific and a technological challenge.

- The incorporation of legacy systems into CPS presents a significant technological challenge,
  since it is likely that most CPS in manufacturing (and other domains) will include these systems
  for reasons of cost, technical familiarity and convenience; in some rare cases they may be
  included because they work, performing fundamental functions and nobody currently in the
  enterprise fully understands why and how they do.

- Incorporating legacy systems may mean that limitations and latent faults in the systems
  become apparent, to the detriment of the CPS. Tools and techniques for exploration and
  diagnosis of systems, perhaps based on the world of hacking and cyber-crime, may be a
  necessary addition to modelling toolkits.

- Among the many scientific and technological challenges to be addressed in future is that
  pertaining to the role of people in the CPS. While it has been widely recognised that people
  will be necessary, the need for change in their roles within the CPS has not. People bring
  several valuable capabilities to CPS; uniquely, they are responsible for the outcomes of CPS
  operations, they bring wisdom and experience beyond that of the CPS, strategic thinking,
  resilience when unwanted emergent events happen, agility in finding work-arounds, ethics of
  behaviour and more, all of which are lacking in the technology of CPS and all of which are
  necessary in real-world operations and interactions of CPS. Research is needed to ensure that
  human roles in CPS are designed to enable people to exercise these capabilities.

- While the design of roles and their associated training needs is a fundamental requirement to
  reap the benefits of CPS, these roles will require appropriate human-CPS interfaces for these
  roles to exercise their roles and responsibilities. The design of these interfaces, including their
  adaptation as the components of the CPS evolve and/or are replaced, is not sufficiently
  understood, and needs development. There is an extensive literature on ‘human error’
  and high reliability organisations (Roberts and Bea 2001, Leveson 2011); what is required is
  the technology to provide the cost-efficient interfaces that enable humans to control and co-
  operate with CPS for maximum flexibility, agility, performance and safety.

- Apart from training, education should likewise move to the forefront of CPS to guarantee the
  supply of future experts and to build awareness within the next generation of students and
  trainees. The generation of a cross-disciplinary science and study program is challenging but a
  necessary step to ensure the competitive position of European firms.
4.4 Security

While the EU28 as a whole has an enviable record for the security and safety of its citizens and institutions, it is clear that the proliferation of CPS and other transactional systems opens new vulnerabilities in terms of information security and safety dependencies. It is also a fact that many of our critical energy supply networks and industrial processes that were originally equipped with stand-alone IT control systems are now being networked for reasons of competition and control efficiency; however, these legacy systems were not designed with cyber-security in mind, and have been demonstrated to be open to easy attack in SHODAN exploits\textsuperscript{15}. This problem also extends into the home environment (OpenDNS-15 2015).

Cyber-attack represents the epitome of an asymmetric threat to society, with a low cost of attack compared to a high cost of protection. Cyber-crime recognises no national borders and so collaboration within Europe on cyber security (and the rest of the world) is essential. The pace of increasing connectivity (i.e. the intended or unintended increase in SoS proliferation), coupled with the ever-increasing capabilities of cyber-physical systems within these networks, seems unstoppable.

There are major research contributions being made around the world to technological security, both in hardware and software. ‘Security by design’ has become a mantra, and many architectural concepts have been proposed and explored. It is now clearly understood that the entire IoT system must embrace security at every level, particularly in relation to autonomous systems and safety-critical systems. Encryption, secure identification, firewalls and sandboxing and many other aspects have been very beneficial, but the ingenuity of hackers in generating different attacks still seems to be unbounded. It seems there will always be a need for further research and for new technologies to be developed.

However, there are two well-known social aspects to security in addition to technical security. The first is that organisations and the individuals within them can be a severe security risk, due to circumstance. An example follows (Gold 2010):

"In one instance, a senior lawyer received an email that requested information in the context of a tax law change, and he passed the email on to a subordinate, who then passed it further down the ‘food chain’ through several levels and eventually on to a relatively junior member of staff. Each time the email was forwarded, ... it gained ‘added authority’ from each sender, meaning that the eventual recipient did not think twice about doing as the email requested."

The second is that if security systems are made to be too restrictive, they may be circumvented in order to get the work done. An example of this from the Cold War in the last century is that of a site in which the control systems for air-to-air missiles were designed and built. Security was extensive; door locks, barbed wire, positive vetting, and security assessments happened regularly, creating a many-layered security environment. For extra security, it was decided that the passwords for all the gate-locks and door-locks would be changed every 6 hours. Since the high-grade engineers in the building had many reasons to cross the barriers each day, it did not take them long to place notes quoting the current passwords near the locks, on the rationale that all the other security measures would keep them secure.

4.4.1 Scientific and technological challenges for security

A number of challenges can be identified, though most of them are already being addressed globally"

\textsuperscript{15} http://www.forbes.com/sites/kashmirhill/2013/09/04/shodan-terrifying-search-engine/
As Ashby’s Law (Ashby 1956, Ashby 1962) indicates, because of the complex interactions between CPS component systems and between CPS as well, complex solutions will be required to deliver security. Because of the evolution aspects of CPS and of shifting global concerns; there will be a continuous need for better understanding of security issues, and of technological advances to maintain security.

Developments of security systems and mechanisms will need to be designed to acknowledge their application to resource-constrained devices (e.g. remote sensors), and to the functioning of large-scale CPS (i.e. for scalability).

While security is the means, trust is the requirement. However security is implemented, the users of secured systems must be able to have trust in their environment and operations. Measures of security need to be developed that include the issue of trust, for reasons of efficiency, communication, and convenience.

Since these networks will heavily involve human interoperation (planners, managers, workers, customers, etc.), ethical and cultural issues will arise; privacy, confidentiality, informed consent, informed command, digital divides, disability and care are issues that will need to be addressed in the integration of people and the technical components of cyber-physical systems. Dealing with these issues could be considered to be a ‘wicked problem’ (Rittel and Webber 1973, Daw 2007, Siemieniuch and Sinclair 2014). There is a clear need to improve our current understanding of this integration; our current understanding is insufficient for the complexities to come.

Inevitably, security standards and certification activities will be necessary, particularly at the interfaces of the CPS components and the components of any larger SoS encompassing the CPS; and especially for the information networks that hold everything together.

### 4.5 Transport

The European Commission has adopted a comprehensive Roadmap for Transport (EC-Transport 2011), the goals of which can be described as ‘stretch targets’, and are concerned with improving and integrating transportation networks and their utilisation, reducing the emissions associated with transportation and thus moving towards sustainability. This will require the following:

* Improving the transportation networks in all domains (air, land, sea) and increasing the level of intelligence within them
* Improving the integration of these networks, and smoothing the usage of them mainly by better implementation of IT resources
* Moving to non-carbon energy sources to power transport
* Shrinkage, minimisation, miniaturisation and dematerialisation of goods (as far as possible)
* Through other policies, and using the resources of IT, bringing transportation sources and sinks into closer geographical proximity (e.g. by ‘reshoring’, or by making use of recent developments such as distributed ‘3D Printing’ at local sites).
* Development of energy-minimising technology, in production, operation, and recycling of transport components.

Actions to achieve these objectives require the management of networks of heterogeneous systems (which necessarily will include considerable numbers of people) working co-operatively, even though...
the systems may not have been designed to work together; clearly the problem of legacy systems will need to be addressed.

Asset and fleet management, together with freight monitoring are well-developed technical areas, already making much use of networks for all modes of transport. There are further developments to be made to provide more efficient and sustainable transport of goods and people, particularly for roads and air transport.

While there is competition between the several modes of transport, each has its own particular advantages, indicating that there is a need for co-operation and integration across the modes to achieve savings in energy and time, and therefore costs. Considering each of the sectors in turn:

4.5.1 Transport at sea

Most internationally-traded goods still travel by sea and this situation is likely to persist into the future. The trend to ever-larger ships is likely to continue, bringing with it navigational issues in coastal waters near ports. Deep-sea issues may also become serious, bearing in mind the consequences of the loss of one of these great ships; better understanding of the nature of flows, and especially the occurrence of ‘rogue waves’ and other phenomena is required, with continuous monitoring, making use of satellite services. As ships become ever-more autonomous in operation, surveillance and forecasting of problems will be key technologies to accomplish, as well as ensuring the reliability of control software.

Handling the cargoes brought to port by ships is also now a well-developed area in distributed management, though there is room for improvements in the regulatory aspects of customs and general security; these improvements are likely to involve cross-border co-operation and monitoring, with a clear role for CPS, both in networking and in the development of inspection technology.

Extension of CPS-based systems for port operation to general voyage-planning and navigation at sea to synchronise entire port-to-port operation and into the hinterland of port operations is an obvious goal, similar to air traffic control systems. The MONALISA and MONALISA 2.0 projects, both supported by the EU, are delivering this. Given the impetus among shipping enterprises to reduce crew numbers on board, leading eventually to autonomous ships, these projects may need further development to provide a support ecosystem to accommodate the known infelicities of automation when presented with unexpected and unfamiliar circumstances. These may arise from unusual breakdowns, shifting sands, unavoidable collisions in narrow straits, and piracy. With regard to the latter, autonomous ships are likely to be more robust in resisting such attacks.

4.5.2 Transport in the air

It is expected that transport by air will become ever-more intense and more complete in coverage of the globe. Autonomous aircraft – drones – will take a larger role in this, mainly in the delivery of goods; it is expected that passenger aircraft will continue to have pilots on board, for safety and reassurance reasons, and cabin personnel for service, cabin management and control should any problems emerge.

Foreseeable developments in aviation technology will create wide-ranging changes of relevance to the pervasion of CPS into this domain. The demands of sustainability are driving changes in engine technology towards hybrid engines initially, and then to electric engines eventually. The required changes to energy supply will alter the construction of airframes, as will the drive to better flight performance through reductions in drag, better routing of aircraft to optimise weather flight and route conditions, together with better matching of aircraft to routes. As examples of airframe changes, manufacturers and airlines together are exploring the efficient utilisation of engines, the adaptability of wings, and means to achieve faster turn-rounds in airports, unloading and loading passengers and baggage in less time. In conjunction with airport owners, operators, and ground transportation
organisations there are efforts to harmonise the concurrent flows of people, supplies and information within current infrastructures for greater efficiency and less turn-round time for aircraft.

On the ground, airports and local transport infrastructure are already adopting the IoT and CPS; finding lost passengers and baggage, streamlining the resupply of aircraft; dynamic signage and communications to inform both travellers and staff of problems, ticketing and authentication systems, the management of airline operations and many other functions are all in place. Nevertheless, there is scope for improvements in managing the interface between the randomness of travellers, emergence characteristics of complex systems and the potential precision and efficiencies of future CPS systems.

4.5.3 Transport on the roads

Road transport for both passengers and goods is undergoing significant change both now and for some time to come. Chief among these are the changes to energy supply as described in (ECF 2009, EC-Transport 2011, EC/2011/112/2 2011, Gide 2013); the reign of fossil fuels for ground transport does indeed seem to be coming to a close, to be replaced by electric motors with energy supplied by either fuel cells or by batteries, or by both.

Coupled with this is the steady increase in software-provided functionality within vehicles, turning them ever more into software-defined vehicles. Combining this with the advent of competent autonomous control of vehicle motion, there is the opportunity to create Europe-wide networks of vehicular transport, where the network includes road furniture (signals, etc.) for added control. Such networks will depend fundamentally on CPS, both within the vehicle and in the road environment. Furthermore, given that the ‘last kilometre’ of goods delivery is typically provided by road transport, there is a role for these networks to be interlinked with the networks for other modes of transport.

While this vision is appealing, there are significant difficulties to be overcome. Among them are:

- **Provision of energy.** In the case of batteries, there will be a big demand for greater energy supply over the energy grid, together with the provision of access points to carry out the recharging of batteries. There is room for innovative CPS solutions here, including the use of vehicle batteries as a balancing mechanism for the peaks and troughs of general demand on the grid. For fuel cells, the difficulties are two-fold; cost-effective generation of hydrogen (or other compound), and the provision of a distribution network across the EU28. The latter problem may be eased by the conversion of fossil fuel stations into fuel-cell refilling stations; but there are still many issues to be addressed. Neither of these are likely to be adopted soon, nor pervasively, until the fears of the general public regarding ‘range anxiety’ and safety have been assuaged.

- **Liability considerations.** While autonomous vehicles may be demonstrated eventually to be much the safest form of road transport, they will be using the road systems with many other non-autonomous mobile objects such as bicycles, scooters and motorbikes, and aberrant pedestrians, all of whom may become involved in unfortunate incidents with autonomous vehicle networks. While this may be considered an argument for further integration (i.e. ‘smart’ objects), it will be a long-lasting issue that needs to be addressed.

- **Scalability.** The CPS networks outlined above are vast in size. While they may be created from inter-operating local networks (e.g. city networks), the latter will still be vast. The issues of modelling and simulation that are involved in operating such networks will involve considerable computational and data-handling capabilities (Paige, Calinescu et al. 2013). This is a general problem, for the other modes of transport as well.

- **Operational control.** The scale of road transport operational control is vast, non-stationary, complex (in the class of ‘wicked problems’), and, due to its geographical spread, with so many
overlapping jurisdictions that distributed control is the most likely and feasible architectural way forwards.

4.5.4 Transport on the railways

Railway networks are of increasing importance in the EU28, in view of their potential for safety, efficiency and sustainability. The recent announcements of new, high-speed rail links from China to the EU and to other Asian countries, coupled with the considerable increase in passenger traffic in some member states within the EU28, all indicate a potential revival in the fortunes and future of rail. Furthermore, the significant funding in the H2020 programme for rail and the creation of the ‘Shift2Rail’ Joint Undertaking (EUCReg642S2R 2014) indicate extensive support for rail developments. This is fortunate, given predictions of rising traffic demand, (freight transport is projected to increase, by around 40% in 2030 compared to 2005 and by about 80% by 2050; passenger traffic is expected to grow by 34% by 2030 and 51% by 2050). In addition, the linked challenges of congestion, fuel security, CO2 emissions and the need to create an efficient transport infrastructure to underpin growth in the European economy also provide drivers for better utilization of railways.

Current aims for rail transport in the EU28 include the creation of a Single European Railway Area, greater efficiency and effectiveness, greater competition among rail companies to drive down lifecycle costs, and a better end-to-end travelling experience for users. Furthermore, the spread of high speed services promises to bring growth to railways, over 50 city-to-city links have been identified, all within the 500 km / 4 hour limit for successful adoption by passengers; it is thought that these will be very competitive with short-haul flights.

To accomplish this there are large investments in electrification of the railways, expansion of rail networks, improvements in both trains and fixed infrastructure, and a big investment in information networking. The development of good rail links to Asia indicates that goods transport by rail may gain a much larger share of rail usage than indicated above, perhaps at the expense of sea transport, some air cargo transport, and of distance transport of goods across the EU28.

There are five main strands of development currently under way, all directed at the overall goal of a much better rail systems for the EU28. The first, the ‘Global System for Mobile Communications – Railway’ (GSM-R) is an international wireless communications standard for railway communication and applications. It is used for communication between train and railway regulation control centres. The system is based on GSM and EIRENE – MORANE specifications which guarantee performance at speeds up to 500 km/h (310 mph), without any communication loss. It provides a secure platform for voice and data communication between railway operational staff (e.g. drivers, dispatchers, rail yard members and station controllers). This supports applications such as cargo tracking, video surveillance in trains and at stations, and passenger information services.

Secondly, there is the ongoing introduction across member states of the ‘European Train Control System’ (ETCS), replacing current national signalling, control and train protection systems. ETCS requires standard trackside equipment and a standard controller within the train cabin which, in its final form removes the need for lineside signals which, at high speed, can easily be missed. It also provides much more flexibility in train separation on the same track, and much better real-time information to track controllers.

The third development makes use of these technologies to create the ‘European Rail Traffic Management system’ (ERTMS), nominally enabling common, complete traffic management across the EU28.

Fourth, a significant barrier to better performance is the train dwell time in stations, while passengers and some goods are loaded off and on to the train. Because of the stopping distances for trains, both
because of the small contacts between the wheel and the track (approximately 10 mm in diameter), and the need for gentle braking for the sake of standing passengers, this requires considerable separation distances between trains, thus minimising the number of trains on each track. The relatively simple act of improving passenger off/on times can have a marked effect on track utilisation, albeit there is an implied need for new rolling stock.

Lastly, there is a need (from the passenger’s perspective) for simple, uniform journey planning and ticketing across the EU28, including transfers between different train operating organisations.

Clearly, there are many challenges for the rail industry of the future.

4.5.5 Urban mobility

Urban mobility is usually taken to refer to cities and towns; villages and hamlets are usually ignored because their size does not warrant specific concerns about local mobility, and to the extent that these smaller communities are near towns or cities and form part of the conurbation, they will be included in town and city planning.

Two quotations from a European Parliament report (Gaggi, Fluhrer et al. 2013) are relevant here:

"Currently, some 74% of Europe’s population lives and works in cities and towns, and by 2050 some 82% of the continent’s population will be concentrated in urban areas (UN World Urbanisation Prospects, 2011). Urban concentrations provide impetus for economic and social development, and cities and towns are key drivers of the economy, contributing up to 85% of EU Gross Domestic Product (GDP)."

and

"The challenges of global warming, scarce energy resources and increasing energy prices are on the top of European, national and local policy agendas. In this context, green solutions are needed to reduce the environmental impact of transport in urban areas. A major concern is to find ways to sustainably reduce transport emissions because urban traffic is responsible for 40% of CO2 emissions and 70% of other emissions from road transport in the EU (EC, 2007a)."

Urban mobility includes walking, cycling, private motorised transport, car sharing, taxis, buses, trams, light rail, suburban rail, underground rail and occasionally more exotic systems such as monorails and funiculars. Each of these has specific attributes suited to particular sets of characteristics of cities and towns; urban density; width of streets, traffic lights and street furniture; infrastructure systems below ground; signalling and space for passenger stops; etc., making a mix of these systems a necessary requirement for mobility. Threading through this mix are the necessary supply systems for the city; freight and public waste management systems. Thus, a ‘smart community’ approach is necessary to optimise urban mobility; not for operating each of these transport systems in parallel, but also providing the information systems that enable their interoperation and journey planning. Adding to the complexities is the fact that for all of the systems, there are legacy issues in that the communities in their built environments are already in place and are working; they cannot be switched off.

Two of the fundamental issues to be addressed as priorities are those of emissions and congestion. Both of these can be addressed by changes to the energy provision for transport, by increasing the utilisation of public transport (any form where lots of people are moved in a vehicle), and by moving from long-term private ownership of vehicles to temporary ownership (leasing, car sharing, taxis, etc.).

Clearly, urban mobility constitutes a system of systems with a tangled and convoluted collection of feedback loops both within and between the systems, with a multitude of different goals for the community as a whole and for the individuals who make up this community. This is a description of a
large scale ‘wicked problem’ (Rittel and Webber 1973, deMeyer, Loch et al. 2002, Siemientuch and Sinclair 2014), and two of the characteristics of wicked problems are firstly that the solution to the problem depends on the initial assumptions, and secondly the solution has to be recognised; it is unlikely to be that at which the solution engineering was aimed at the start. Furthermore, given that communities are ecosystems that are continuously evolving, ensuring good urban mobility is a never-ending problem.

Under these circumstances, the best approach is incremental, with constant attention to the interoperation aspects. Each of the systems can gain real benefits from a CPS approach for both vehicles and for the system as a whole; at the interoperation level, there is also large scope for CPS for overall control, safety and resilience; the entire system constitutes all of the identified classes of System of Systems (Dahmann and Baldwin 2008).

Current approaches demonstrate this incremental approach, conforming to the goals of the white paper (COM(2011)_144 2011), though it is less obvious that the interoperation aspects are being considered to the same degree. An exemplar list follows:

- ByPAD bicycles; www.bypad.org
- ACCESS2ALL public mobility schemes: www.access-to-all.eu
- EBSF Bus systems of the future: ebsf.eu
- CIVITAS Smart Community Forum: www.civitas.eu
- SMARTFREIGHT www.smartfreight.info
- SUMPs sustainable urban mobility plans: www.mobilityplans.eu/docs/SUMP_guide;ones_web0.pdf
- CALM standards for V2V and R2V communication in freight vehicles, optimise supply routes, etc. http://calm.its-standards.eu
- CityLog urban freight management: www.citylog.eu
- Local4Global distributed traffic management: http://local4global-fp7.eu
- AMADEOS open system dependable architectures: http://amadeos-project.eu

4.5.6 Scientific and technological challenges for transport

In all the areas of transport discussed above, software and networking for identifying, tracking, tracing, distributing and delivering goods and people is highly developed albeit can be improved. Further developments, building on established systems, are likely to come from incremental improvements to IT systems for managing data rather than from revolutionary technologies. It is not envisaged that significant projects remain for these functions.

However, some challenges outside data-handling remain to be addressed. These are outlined below:

- Autonomy in the control of vehicles in all forms of transport requires attention. Control of the device itself is fairly well-developed, with the future of developments well-mapped and with funds already ear-marked. This has been based around navigation between identified points, safe operation of the vehicle and the avoidance of collisions; all predicated on the characteristics of the physical world, and directed at maintaining the integrity of the vehicle in executing its tasks. From a lifecycle perspective there are some unexplored areas, to do with autonomy and its necessary complementary capability of learning. In principle, if vehicles learn within different environments, they change their behaviour and become differentiated, and in principle, over time they become non-interchangeable. These aspects require exploration, both from a scientific and technological perspective.
• Secondly, the scope of autonomous vehicles is bound to expand, bringing them into social contact with humans, and social uncertainties. In such situations, autonomous vehicles and autonomous systems in general necessarily must behave in an ethical manner, appropriate to the social situation in which they are engaged. This aspect of autonomous system behaviour also requires exploration, both from a scientific and technological perspective.

4.5.7 Health care

More than any other domain, health has as its focus the individual human being. However, while having this focus, the processes and apparatus of health care provision form a complex whole. Figure 4.4 below provides an exemplar of this.

Figure 4.4 depicts a refugee from some crisis; old, poor, with little linguistic capability in this new environment and perhaps a little bewildered by his/her situation. There are some family members available who have local competence, able to provide some care. Fortunately, the refugee has been given a modern home, complete with a care robot to provide continuous monitoring and care as needed.

![Diagram](image_url)

**Fig. 4.4** Illustration of a network to deliver health and social care to an individual at home. An aged refugee lives there, with issues of a ‘vanishing mind’ and with limited language skills in a new culture. Some other members of his/her family are available to assist.

The diagram illustrates three interacting systems, of varying CPS content. Extending left from the accommodation is a CPS supporting the lifecycle of the robot and its complementary household sensors and devices, for better performance. Vertically from the accommodation is the CPS that maintains the physiological and mental health of the refugee. Between these two is the cps for social care, attending to the role of the refugee within the community. As the diagram illustrates, there are
many links and interactions between the separate CPS, forming a system of systems whose aim is the well-being of each individual, in their millions.

A noticeable aspect of this diagram is the need for co-ordinated management among the three CPS systems in order to deliver a coherent service and experience to the refugee. This co-ordination may have more of a system of systems flavour than a CPS, but it will be a necessary extension to the CPS.

4.5.8 Scientific and technological challenges in health care

In this domain, concepts of Responsible Research and Innovation that currently are being developed by the EC and other institutions (EC-NANOCODE 2009, ExGpRRI13 2013, RomeRRI 2014), together with a rapid proliferation of safety standards and guidelines (if one could ever use the word, ‘rapid’, in connection with standards), will provide a constraints framework for all future innovation in this domain.

Many challenges can be identified, some produced by the twin pressures of changing population demographics and the ever-increasing cost of care. A third class of challenges arises from the very fact that people are impaired by ill-health; a consequence of this is that the variance of capability, physiological integrity and postures among the impaired is significantly greater than is the case for the unimpaired population (an example comes from some degenerative diseases; in the unimpaired population, it is normal for the head to be above both the shoulders and the hips. In some diseases this constraint may not apply).

- Development of interoperation for personal, wearable devices for assessing the well-being of individuals. There is a strong and growing market for devices (e.g. FitBit™ bracelets, Apple Watch™) backed up by analytic software in the Cloud, supported by venture capital. For this reason, governmental aid is largely unnecessary. However, single devices are unlikely to have the sensor range necessary for a full outline of personal well-being, indicating that combinations of devices might be necessary. This indicates the necessity of developing interoperation standards, to allow a more complete analysis, across different devices from different suppliers.

- CPS for tele-health seem to offer significant benefits, both in delivering health care to the home, and in helping patients to maintain the medical regime that has been prescribed for them. This latter aspect from the better, more frequent monitoring of patient performance, allied to nudging the patient to follow the regime. Furthermore, by reducing the need for patients to make use of hospitals and local GP clinics, there are further savings to be made. But before this approach becomes the norm, issues of privacy, safety and security of data must be solved. Furthermore, ethical and legal issues in tele-health must be addressed.

- Compounding the problems for CPS design within the health domain is the fact that ill-health is a dynamic state; usually, one becomes worse, then better. For some cases of ill-health, the process is one-way. For both of these cases, the implication for CPS is that the requirement for competence for the ill individual changes over time, and furthermore, that effective management of competence delivery to the ill person may require autonomy between support visits from professional medical/social care staff.

- Particular groups of individuals may need special equipment to assist them physically in maintaining health and participation in the community; powered mobility and posture aids are examples. There is likely to be a demand for these devices as the EU elderly population expands. However, because of the smaller numbers of people, and the greater range of variability among these groups, there is less chance of appropriate, flexible devices being funded, creating a role for governmental funded projects.
• Current roles for CPS in carrying out treatments will involve initial triage into hospital/home treatment paths, perhaps with surgical and/or physiotherapy procedures. CPS systems are already being developed for this, but more extensive systems will be needed, bearing in mind the rise of the elderly population in the EU28.
• CPS systems have a large role to play in the training of medical staff, at all levels. There is large scope for development of this class of CPS.

4.6 Smart communities
Communities, whether villages, towns or cities are where are where most of us are born, live, love, grow old and die. They are places which give us sustenance and education, provide us with working environments in which our capabilities and talents can be expressed, and which offer some protection and security against unpleasant events, and they are the places where we can grow old and wise and accumulate a few regrets. They are places of economic opportunity, innovative services and cultural renewal, but they are also places that themselves require sustainability, and the processes that deliver sustainability.

Clearly, cities are very complex entities, with a multitude of interoperating and interlocking processes of varying duration and importance, and with a population hugely varied in the interests, actions, desires and intentions, all of which will need some freedom to be expressed within the cultural norms, values and laws of the society. While there are obvious roles for CPS in the brief commentary above, there are equally obvious risks that together, a set of CPS that are oblivious of each other and of the interactions and interlocks could bring a community to a halt, with potentially disastrous consequences for many.

Some of the aspects of sustaining community life are outlined below:
• The continuous provision of energy, clean water, food, community environment cleansing, waste treatment and sewage treatment.
• Providing the facilities, staff and resources for civil duties such as policing, expression of the Law through justice systems, and management of offenders.
• Robust protection and resilience against major environmental events such as rainstorms, flooding, land movements, fires and lightning strikes.
• Managing the built environment, including the provision of sufficient housing, community facilities, offices and workplaces, infrastructure for emergency services and for health and community care services.
• The provision of infrastructure to support citizens in exercising their talents and capabilities; to set up projects, create new businesses, to carry out artistic expression, to meet and to celebrate.
• The provision of communication facilities for businesses and individuals, including support for the provision of information and data to citizens that they can use in exercising their abilities and rights.
• Management of transport; the upkeep of roads, pavements and paths, the provision of traffic supervision and control.
• Supporting the provision of health and community care services – hospitals, medical centres, and services such as ‘meals on wheels’ for the elderly and infirm.
• Provision of education and training opportunities for all, from early years to end-of-life; in a CPS-enabled community, enabling citizens to access the CPS is vital.

While many of the points above could be implemented to the general benefit of the community (beyond current performance) by adoption of CPS, there are some aspects that must be addressed:
• The digital divide, in which some of the citizenry do not have appropriate access to CPS for any of a variety of reasons, and thus are deprived of some of the opportunities and benefits available to other citizens.
• Data and information protection and security, both for individuals and their privacy, for the community and its services, and for businesses. Issues of confidentiality of data may mean that ‘walled gardens’ must be created, which in turn point to the need for a regulatory function to manage this protection and security, and an ombudsman function for individuals.

4.6.1 Scientific and technological challenges for the Smart Community
It is evident that there are many challenges in the creation and maintenance of a smart community; these are listed below. Each of the bullet points listed in the section above requires a complex CPS to deliver satisfactory, sustainable, long-term performance; however, because of the overlap of effects from each of these CPS, to achieve good, efficient, economical performance of the smart community as a whole requires a further CPS for concertation across all of these single CPSs, since they are operating in parallel.

• Low-demand sensors for remote and difficult locations in the smart community, capable of working in noxious circumstances will need development, to increase the spread of CPs and complement the more usual sensors.
• Smart communities will generate very large collections of data, for which issues of scale and complexity will need to be addressed; this will demand further growth in Big Data analytics applications to reduce the quantities and to address initial safety and privacy aspects of the data.
• Tools and models to infer meaning from the data must be developed further. It is an inappropriate fiction to assume, as do many current tools, that individuals in the community represent statistical variations around a community norm, and then to devise tools and models based on this fiction. The design of tools that aggregate individual human behaviour to discover normative patterns is required.
• The availability of CPS within and across the community provides a wealth of data for better governance of the community’s processes, as listed in the section above. However, governance depends on situation awareness, and methods and tool need to be developed to allow governing bodies to achieve up-to-the-moment situation awareness. These are not currently available.
• As a result of introducing CPS widely into a community, it becomes possible for the community to become more efficient and effective in its operations. However, the interoperation and interlocking of these CPS may mean that the whole system of systems becomes brittle, when faced with unexpected scenarios and unusual behaviours from the ever-changing population of the community. CPS health assessment and management tools will be required.
• Community acceptance of CPS actions depends on those actions being seen to be ethical, and in the interests of the community as a whole. Currently, this is achieved by systems being guided by humans, with Call Centres available to fix individual problems. In future, as autonomous systems become components of CPS, these systems themselves will have to deliver ethical behaviour (note that the CPS itself does not have to be ethical).
• Resilience in smart communities needs to be addressed, especially if brittleness is a potential problem. There is contemporary research in understanding how to design systems fit for purpose over the longer term when instantiated within evolving environments, but this needs to become a reliable engineering technology for very large SoS.
• Continuing this theme of resilience, there will be occasions when citizens have a problem with the decisions and actions of a CPS. The provision of an ombudsman function is a solution, but
only if the ombudsman has appropriate tools, authority and situation awareness to function properly.

- Citizens’ interfaces with the CPS in a smart community are likely to be based on smart phones. However, some groups of citizens may become victims of the ‘digital divide’ for any of a variety of reasons. Research is required to develop alternative means to enable all citizens to participate in the life of the smart community.

### 4.7 Environment & Agriculture

There are three parts to this section; agriculture, for provision of food; water, as the elixir of life; and the environment, for global sustainability.

#### 4.7.1 Agriculture

The EU28 is in economic balance with respect to food; however most imports are cereals and other basics and exports are of processed foodstuffs. Food security is, therefore, at risk due to changes external to the EU where population increase is more significant (UN-FAO 2009) and climate effects may be more drastic (Hanjraa and Qureshi 2010, Allouche 2011, Hunt, Wilby et al. 2014), and because there is little opportunity to increase cropland within the EU to mitigate these risks. Increases must come from improvements in crop genomes, husbandry techniques, and from assurance of foodstuffs from the rest of the world (WEF 2013).

A significant problem globally is food wastage (Allouche 2011), either due to personal habit (e.g. “Rich countries waste about the same amount of food as poor ones, up to half of food from shops goes straight into the rubbish bin or is thrown away by shops and restaurants … very roughly, 100kg per person per year … a result of personal habit and law” – The Economist, 24/02/2011) or a combination of insufficient husbandry and storage (rats, insects, locusts, etc.).

CPS have a large role to play in agriculture, managing or supplementing a seasonal processes between field and farm gate; preparing the fields, planting techniques, localised sensing of irrigation needs and crop health status, parsimonious spraying, and timely, efficient harvesting and monitoring of storage. Better knowledge of field conditions will also help to maintain or improve soil quality, to assure agricultural productivity.

Likewise for animal husbandry; CPS offer the opportunity to adjust farm conditions, processes and effects for each individual animal over its lifetime on the farm. Strays can be found, animals herded and fed appropriately, medical conditions can be identified, along with copious identification and documentation for each animal going to market. It is instructive that in the Federal Republic of Germany, there is an equivalent initiative to Industrie 4.0 for agriculture: Farming 4.0 (Porta, Tuncer et al. 2014) and that the USA-oriented Association for Unmanned Vehicle Systems International, a trade group, says that agriculture could account for 80 percent of all commercial drone use in future.

An added consideration comes from the fact that the EU28 as a whole depends on food from other countries, as mentioned above. Since a large proportion of our food comes from countries between the tropics, the effects of climate change on supply may be serious. For example, a number of studies have shown the negative relationship between temperature and work output once the temperature and humidity rise (McMichael and Dear 2010, Sherwood and Huber 2010, Zivin and Niedell 2010, World-Bank 2012); this will also affect livestock as sources both of food and work. It may be necessary to consider the deployment of CPS in other countries to ensure the supply of foodstuffs.

Fisheries are under some stress, worldwide, both from over-fishing, inappropriate fishing techniques causing wastage, effects of climate change and pollution. For fisheries, CPS are a two-edged sword; on the one hand, the capabilities being developed in the CPS domain could make fishing even more
productive at the expense of fishing stocks; on the other hand, the same techniques could be used both to protect natural fishing stocks and to enhance domestic farming of fish and other marine products for food. However, addressing the effects of climate change and pollution on the depletion of stocks requires more general action, involving all of the domains discussed above in this section.

4.7.2 Water

Perhaps the most important effect on agriculture arising from the global drivers is the provision of fresh water (FAO-water 2007). Rising populations, shrinking snow packs to feed rivers, overuse of aquifers, and climate change are all placing ever more stress on water supplies.

This can be addressed in two ways; by reducing the demand for fresh water in conurbations (where about 80% of the population will live), and by increasing supply by re-engineering ‘grey’ and ‘black’ water, as well as purifying sea water (in this respect, it is helpful that most of the world population lives near the sea).

Reducing the demand for water in conurbations is a ‘smart community’ issue; it needs a wide range of activities spanning the whole manufacturing domain, domestic water metering and changes of personal lifestyles, and the provision of CPS-driven infrastructure for the recycling and re-use within the conurbations of ‘grey’ and ‘black’ water. Reducing the demand for water in agriculture comes about in the near term from more precise irrigation, which in turn will be dependent on farm-level CPS. In the longer term, demand reduction will come from developments in crop science that enable new strains to grow well with less water. The latter is particularly important given population projections and the limits on the availability of agricultural land.

4.7.3 Environment

‘Environment’ in this section refers to the natural environment and its relationship to human society. As the Sulston report expresses it (Sulston 2012):

*Human wellbeing and the state of the natural environment are closely linked. The environment provides natural capital which, through production and consumption, forms the basis of many of the material and non-material inputs to human wellbeing. ... Like other species, humans are part of and dependent on these ecosystems and their properties. As organisms interact with each other and their physical environment, they produce, acquire, or decompose biomass and the carbon-based or organic compounds associated with it. They also move minerals from the water, sediment, and soil into and among organisms, and back again into the physical environment. In performing these functions, they provide materials to humans in the form of food, fibre, and building materials and they contribute to the regulation of soil, air, and water quality.*

Unfortunately, it appears that humanity’s ‘global footprint’ is much larger than our world; it is estimated to be on the order of 1.5 worlds\(^\text{16}\). Addressing this imbalance means addressing the Global Drivers, which collectively is a focus for this document, and for the roles of CPS in this.

However, there is a more direct role for CPS as well, in monitoring the state of the natural environment and the interaction with humankind. This is both a global issue and a local one, employing CPS component systems from satellites down to devices attached to small animals, sea creatures, and

some plant life, and the aftermath of Big Data analytics to adduce the state of the environment. Subsequent actions to address undesirable states will then entail CPS systems in the domains above.

One last aspect in which environmental CPS may be employed is in enhancing the interaction between the environment and humanity from a recreational and cultural perspective, improving spiritual enrichment, cognitive development, aesthetic experiences and play.

4.7.4 Scientific and technological challenges for environment and agriculture

A characteristic of these topics under discussion is that they have little respect for national boundaries and local laws. The implication of this is that comprehensive action to improve the state of agriculture and the environment will entail planning and co-ordination at the EU28 level, while respecting subsidiarity. The challenges below reflect this.

- The main challenges for CPS in this domain are to do with sensing, particularly in remote and difficult locations, followed by Big Data analytics and modelling techniques for complex data.

- From both agriculture and fisheries perspectives, the main challenges are for scale and for scope; the requirement is for farm-scale CPS so that small farmers can manage their farms more efficiently and with greater concern for their environment; supply-side CPS to move produce from farm gate to the plate for less wastage, and for food manufacturing CPS for greater efficiency, improved food safety, less ecological demand, less wastage and longer storage life. Interconnections between these CPS then lead to issues of scale and Big Data; both of these need to be addressed from a specifically agricultural perspective.

- CPS for the management of water, as well as being of fundamental importance to communities, are also of national concern, since watersheds both define boundaries between member states but also can divide member states raising flow and quality issues between them. Conservation actions, as stated above, are best addressed by ‘smart community’ CPS because of their inherent complexity.

- Likewise for environmental CPS; while many actions are complex and local to smart communities, several are of national and continental scope, best addressed with governmental assistance.

- Given that the EU28 depend on food supplies from the rest of the world, developing CPS technology for export may prove to be valuable self-help exercise.
5 Society and CPS

This section has been introduced because of the very great impact on society that can be expected as CPS pervade and proliferate through our societies around the world, coming into contact with people of different cultures, with different beliefs, values, expectations and modes of behaviour, in different jurisdictions and political systems. CPS will have to interact and interoperate with individual people in these societies, and, so far as the CPS is concerned, where the individuals may be owners, managers, operators, co-workers, maintainers, etc. within the CPS and customers, consumers, or itinerant bystanders or passers-by who happen to become involved with the CPS.

In relation to the CPS these individuals may be experts, competent or novices; they may be disengaged, angry, timid, drunk, or in any number of other states, and in different states at different times. They may fall into classes such as disabled, diseased, deprived, or vulnerable (children, aged, mentally impaired, etc). They may be engaging with the CPS for honourable, dishonourable or illegal reasons; they may be acting as individuals or in collusion or concert with others.

In short, the logical internal environment of CPS technology will have to perform its designated functions in an external, complex, evolving, non-stationary human environment of limited predictability. And it is this seemingly-chaotic human environment which has control over the CPS world through its mechanisms and channels of power and authority.

This section outlines some of the issues of importance at the interfaces between CPS and human society; it builds on the social discussions in several of the 53 projects explored in Road2CPS, and especially on the acatech document ‘Living in a networked world’ (acatech11 2011), the Robolaw project (E. Palmerini, F. Azzarri et al. 2014), the ARTEMIS project (Gide 2013) and the forthcoming British standard on robots and ethics (BS 8611 “Robots and robotic devices: Guide to the ethical design and application of robots and robotic systems”\textsuperscript{17}.

For convenience, this section is divided into three subsections (CPS and consumers, CPS and co-workers, CPS and society), and is followed by some challenges that should be addressed.

5.1 CPS and consumers

One of the key issues in the interactions between people and CPS is ‘Who is responsible for the consequences of CPS decisions and actions?’. This rapidly becomes a complex issue, with many unresolved aspects. However, some important general issues that should be addressed from a design, management and operation point of view are discussed in the next section. Among these, and fundamental to the operation of CPS are Informed Command and Informed Consent.

5.1.1 Some legal and governance considerations

There are some significant human issues that cannot be ignored in this context, especially in relation to liability, legal and resilience issues. Four in particular stand out. These all stem from the role of humans both as customers of the network and as controllers of networked processes, in which semi-autonomous, cyber-physical systems play a part. This section concentrates on humans as consumers.

\textsuperscript{17} http://standardsdevelopment.bsigroup.com/Home/Project/201500218
• ‘Informed Consent’; for example, what are the consequences of consenting to an action to pass data to an external database that is suggested by a home management CPS? It is unlikely that a person would know, or ever could know, who or what has access to that data, for how long this access will be enabled, how these data will be combined with other data, what meaning(s) will be inferred from the data, which organisations will ‘own’ these data, and so on. This is self-evidently a design issue for systems thinkers in general, and CPS designers in particular. Solutions are not immediately evident, though it is good news that the US Senate is developing a bill to regulate the activities of data-broker organisations that may be linked to such CPS (Senate bill S. 668).

• ‘Informed Command’, as given, for instance, by a consumer to a service CPS; what are the consequences for the CPS itself, and for the external environment of an operator’s command? The UK Ministry of Defence has an operational rule for this, summarised as ‘Whoever gives the last command is responsible for the outcomes.’ The implication is that whoever gives a command must be able to anticipate the likely outcomes and side-effects of any command. This, of course, presumes that the command-giver can evaluate the likely outcomes, and if surprised, can alter the command in time. To forestall and bad outcomes. It is not obvious how any command-giver in the context of a CPS distributed across the IoT could be sure of the outcomes, especially if these outcomes are at a distance from the command-giver; in a different environment, in a different culture, in a different legal framework. Again, solutions are not immediately evident; nevertheless, this problem sits at the heart of many CPS.

• Identity. As a UK Foresight document has pointed out, each of us has many identities, and some of these are not constructed by us but nevertheless exist on the internet (Foresight-FFI 2013). There is a question of who owns and who can use these identities and for what purpose, especially those we have not constructed ourselves. This has implications for the notions on informed Consent and Informed Command, above, especially if some of these identities have been created or utilised with criminal intent.

• Many humans giving many commands to a CPS. One possible scenario arises in the context of a smart city; it has a CPS that communicates with vehicles and their drivers, and controls all traffic lights in the city, to optimise journey times for all drivers. Assume an emergency arises, and police vehicles are called to provide assistance. The CPS arranges the traffic lights to display green lights for all the routes of vehicles attending. However, trying to get to a hospital across these routes is an ambulance with several very ill people on board, also calling for a green light route. In principle, the middleware is now faced with an ethical decision (though in this example there may be enough degrees of freedom to minimise the ethical considerations). Other scenarios can be envisaged in which ethical issues will arise for many CPSs, often created by many humans interacting within a single CPS. The design of a distributed interface for this scenario, exhibiting ethical decision-making that is capable of being trusted by its multiple, individual users, is an open, complex problem for systems ergonomics. Likewise, there will be ethical issues in decisions made by the CPS and affecting large numbers of customers, all of whom are individuals with different needs, goals and desires.

While these issues are clearly important from a legal perspective, they are also important from a trust point of view, too; that of consumers trusting the CPS that delivers services to them. There is a implicit promise (or bargain) in interactions between consumers and any service provider; that in return for payment up front, the service promises to deliver what the consumer has requested on time, in full, and to the quality expected. This argument prompts the next section, on the need for CPS to behave ethically.
5.1.2 The requirement for ethical behaviour by CPS

The previous section outlined some legal aspects of consumers interacting with CPS potentially leading to a loss of trust. In an earlier section on autonomy (section 3.3.3) the need for ethical behavior was discussed; this section extends that argument with some other aspects.

First among these is the fact that CPS may well be offering services to a very wide range of consumers: children, impaired, and very elderly, as well as ‘normal’ adults; what might be termed ‘vulnerable’ people. There are philosophical reasons (Ross 1930, 2002, Haidt and Kesebir 2010), commercial reasons such as Corporate Social Responsibility\(^\text{18}\), the Precautionary Principle (Anon 2000), and developments in Responsible Research and Innovation (EC-NANOCODE 2009, RomeRRI 2014), together with international standards such as ISO 31000 on risk assessment, and legal reasons from a wide range of laws and regulations that have implications for a duty of care in the performance of CPS.

Secondly, there is a behavioural aspect, concerning trust between consumers and the performance of devices in general and CPS in particular, especially where the latter have some degree of autonomy (Blomqvist 1997, Whitworth and Moor 2003).

Most of us have learnt to trust the devices that we use; the electric kettle boils water and switches itself off, the vacuum cleaner sucks up dust and dirt and we understand its little foibles, and the automobile works well until it needs a service.

However, once their intelligence reaches a level where autonomous operation and learning is involved, characteristic of CPS, the situation changes; we have entered the realm where systems may exhibit unexpected behaviour, or longer-term behaviour changes. An obvious example is the household robot, which will become more useful to you as it learns your habits and adjusts its behaviour accordingly. But for health, safety and security reasons, it may record your behaviour and transmit it to some analytical entity outside your direct control; insurance companies, maintenance centres, and so on, thereby creating an identity for you over which you have no direct control.

Summarising this: CPS may not behave as expected, and may utilise information in ways that are opaque. Most times, this will be benign, but there may be occasional unpleasant surprises, and it is these that cause lasting mistrust. But even if the surprise is benign, the fact that the behaviour was unexpected (in other words, not the behaviour one would normally expect) can cause a loss of trust, and this loss is enhanced with further examples. This is where ethics and culture are of importance in determining behaviour, summarised as ‘the way we do things round here’.

There is a requirement for the designers and managers of CPS to understand this, and ensure that the behaviour of the CPS is ethical and trustworthy. If we cannot work out how to accomplish this beforehand, no doubt bitter experience will show us.

5.2 CPS and co-workers

All national programmes akin to the FRG’s ‘Industrie 4.0’ programme (for example, the UK ‘Future of manufacturing’; in France, ‘La Nouvelle France Industrielle’) emphasise the importance of people in this networked manufacturing environment.

To a lesser extent, this is also true of most environments in which people will be working and interacting with CPS.

5.2.1 Keeping the CPS in operation

The new approaches, whether in business models, enterprise networks, new materials and/or processes, all mean that jobs will change, as a result of becoming ever-more embedded within the CPS. In effect, most of what people do will be done through the medium of software, as most of the tasks of airline pilots in aircraft have become software defined; however, these changes do not replace the human attributes of real-world knowledge, wisdom and experience, nor do they replace the human capacity for resilience in the face of both expected and unexpected change. They do emphasise the importance of particular skills in IT, particularly in modelling and simulation, in problem-solving, in distributed team-working, and the like. These skills must be distributed across the organisation’s workforce, including managers, professionals, operators, and apprentices. This appears to be an implicit recognition that moving to the network will not remove problems; it may solve some, but it will redistribute the rest, and perhaps introduce some new ones.

Earlier in this document, the example of a Nestlé factory was outlined, in which over a period of 6 years, 29 improvement projects were undertaken as the factory moved towards sustainability. It is this frequent state of change that will create roles for people to exercise their capabilities; this is supported by several characteristics of software. Firstly, most manufacturing systems engineers have become used to the phenomenon of two connected software applications, both constructed to the same set of standards, failing to interoperate because of slightly different interpretations of the standards; we may expect this to happen in the complex world of the CPS. Secondly, two quotations from systems engineers are revealing of the state of software;

“For a useful perspective on the system design and engineering challenge, it is worth noting that the findings from Capers Jones, http://www.spr.com, and others indicate that deployed software systems contain approximately 0.4 latent faults per function point. To our knowledge, this indicator of dismal [operational availability] has improved only about three-fold in the last four decades. Upon comparing this to the 30-fold reduction that automobile emissions engineers have achieved in less time, it is possible to develop an appreciation of the work that remains to be done on software for resilient systems.” (Ring and Madni 2015)

and,

“COTS software products are particularly challenging to integrate. They are opaque and hard to debug. They are often incompatible with each other due to the need for competitive differentiation. They are uncontrollably evolving, averaging about up to 10 months between new releases, and generally unsupported by their vendors after three subsequent releases. These latter statistics are a caution to organizations outsourcing applications with long gestation periods. In one case, we observed an outsourced application with 120 COTS products, 46% of which were delivered in a vendor-unsupported state.” (Boehm 2006)

While both of these quotations are looking backwards in time, and acknowledging the instantiation of the CRYSTAL project within the ARTEMIS collection of projects to create ‘ultra-reliable’ software, it seems wise to accept the necessary presence of people to keep CPS running.

But people can only perform these functions if they are given the necessary knowledge firstly to be aware of the situation, then be equipped with the resources to reach a decision about what can be done given the situation, and then exercise their delegated authority to make changes considered necessary. In a complex CPS where the triggering causes of the current situation may be widely dispersed and fleetingly apparent, there is a real problem in designing interfaces to the CPS to be able to carry out such tasks. Indeed, one good analogy is the pilot of an airliner and the cockpit software
necessary for the pilot to maintain control – except that the software for the pilot will not change nearly as often, and will have had much more resource given to its design and implementation. A second is in the world of finance, where traders are immersed full-time in a software environment that has a significant amount of autonomy and that occasionally has exhibited costly emergent behaviour that has taken some time to unravel and understand.

5.2.2 Co-working within the CPS
A further issue arises when people within the CPS are in a team working with autonomous systems as co-workers.

For simplicity, consider robots as co-workers in a team. An example is in the manufacture of some classes of aircraft parts from composite materials; for some complicated shapes it is not possible at the present time to use machines or robots to create these parts; they must be constructed by humans, with some assistance from robots.

Because robots are always alert, powerful and indefatigable (until the power runs out), there could be real advantages in including them in a work team. But there is more to teamwork than work. Most teams rely on communications within the team; verbal, visual, postural and locational, and perhaps using their own technical jargon. All of these will raise problems of understanding for robot co-workers in situations in which working in co-operation is the norm.

But there is a further issue: teams develop their own camaraderie and culture, on which team communications depend; individuals within the team develop an understanding of the skills, team-working capabilities and trustworthiness of others (Tannenbaum, Salas et al. 1996, Kozlowski and Ilgen 2006, Sinclair, Siemieniuch et al. 2010); and all of these have a heavy reliance on emotional intelligence (Goleman 1995). This raises problems of misinterpretations by the robot, particularly for non-verbal communications. Equally, humans will have difficulty because of the lack of non-verbal communications by the robot, perhaps causing surprises for the humans.

While the Robolaw project (E. Palmerini, F. Azzarri et al. 2014) has generated much understanding about the issues involved, it is clear that considerable further work will be required in this area to bring about a proper, safe technology for co-working.

5.3 Management of CPS
Two quotations from Industrie 4.0 illustrate this:

“It is very likely that the nature of work in Industrie 4.0 will place significantly higher demands on all members of the workforce in terms of managing complexity, abstraction and problem-solving. Employees will also be expected to be able to act much more on their own initiative and to possess excellent communication skills and the ability to organise their own work.”

and

“It is likely that their role will change significantly as a result of the increase in open, virtual work platforms and extensive human-machine and human-system interactions. Work content, work processes and the working environment will be dramatically transformed in a way that will have repercussions for flexibility, working time regulation, healthcare, demographic change and people’s private lives. As a result, in order to achieve successful integration of tomorrow’s technologies they will need to be smartly embedded into an innovative social
organisation [within the work-place]. “ (Kagermann, Wahlster et al. 2013), bracketed words added.

The report also makes the point that these changes in the nature of work within the CPS may lead to more diverse and flexible career paths better suited to the demographic changes that are expected, and may lead to a better work/life balance for the workforce.

The rationale in the quotations above can be expanded; it is driven by the sustainability argument (particularly energy-saving, renewables and materials recovery), by legislation (for example, the ECODesign directive, and the Directives on the treatment of wastes) and by the role of networks (particularly the IoT) for organisations to maintain a competitive position in industry.

A brief but excellent synopsis of CPS (Schätz 2014) makes many relevant points. The most important is that these systems are a paradigm shift for CPS engineering because of three attributes:

- they are large-scale and demand a cross-disciplinary approach beyond the usual engineering disciplines,
- they are frequently mission-critical for both systems and system of systems performance; they may extend across organisations, and cannot be switched off, and
- because of these two attributes, they must include their own engineering tools and knowledge to enable upgrades and to recover from unwanted or undesirable states.

These points imply:

- a large range models of different domains, disciplines, and technologies are used, and they may not be fully interoperable
- the use of models is extended from the design and implementation phase into the operation and maintenance phase, requiring operators and other stakeholders to be competent in manipulating these models and tools for understanding and control of the CPS; models for the control of devices, models for management and co-ordination in the middleware layer, and models at the strategy level to make sure that commands do not have unwanted consequences. As (Schätz 2014) says, “Furthermore, since CPS can autonomously reconfigure or adapt their behaviour, especially models of their platform and functionality, [they] must be made explicit at runtime. As a result of this shift, not only the construction of these models, but also corresponding analysis and synthesis methods must be made available during operation and maintenance, turning a CPS into its own engineering and development environment.”

Unfortunately, this scenario is made more complex when several companies are joined together to create a CPS. Under these circumstances, it is unlikely that there will be a unitary, hierarchical system of control; each participating organisation will maintain control of its own operations, subject to contracts that may exist between the partnering organisations (Maier 1998, Maier 2005, Dahmann and Baldwin 2008, Firesmith 2010). In other words, a system of federated control applies, bringing with it issues of Intellectual Property Rights, commercial confidentiality, and trust. The first two of these are business issues, and typically have the effect of preventing full transmission of important, currently-valuable information (Whitworth and Moor 2003, Siemieniuch and Sinclair 2012, Siemieniuch and Sinclair 2014, Siemieniuch and Sinclair 2015) and will affect the operations of CPS.

The third is mainly concerned with the future behaviour of organisations and the humans within them, and is a matter of direct concern for CPS designers and managers in the form of organisational design and culture, and in job design. In the context of CPS, we may need to extend trust to include trust in software, trust in the behaviour of devices, and, interestingly, the level of trust that autonomous systems can and should have for their human co-workers. The latter is an issue not normally

©Road2CPS Consortium
encountered in the CPS literature, but one with which designers, engineers and managers will have to deal in the near future.

5.4 Autonomous CPS operating in society

This section extends the discussion of autonomy in section 3.3.3, to include societal aspects. The topics of autonomy and concomitant learning pose some difficult problems for CPS operating in society. These are explored below; initially, some discussion of the concepts occurs, before exploring the challenges.

5.4.1 Autonomy

Autonomy in the context of CPS is defined as

‘a system that has the ability to perform intended tasks based on current state, knowledge and sensing, without human intervention’ (ISO 8373).

Autonomy is a multi-dimensional concept; there are a number of dimensions on which autonomy can be considered. In other words, given that these dimensions are uncorrelated, they can create an envelope in which a cognitive agent can be active. These are outlined below; however, in reading this it is very important to bear in mind that when an autonomous system makes a decision and some action follows, if the action impinges on humans, the action should be ethical in the context in which it takes place. In this regard, two documents of some importance are Robolaw (E. Palmerini, F. Azzarri et al. 2014) and a standards document under development and expected to be promulgated in 2016 – BS WD 8611 ‘Robots and robotic devices — Guide to the ethical design and application of robots and robotic systems’, from the British Standards Institution.

There is an assumption that the design and implementation of CPS that have component systems that are autonomous will include these dimensions to ensure that the exercise of autonomy happens within the envelope described above.

Degree of autonomy

There is an amount of autonomy that an autonomous system might have; in other words what the system permitted to do on its own. This is a fundamental issue, since legally only humans can be held accountable for the behaviour of technological systems. The military principle that ‘the last person to issue a command is responsible for the outcomes’ is an expression of this.

As an example of degree of autonomy, Sheridan’s scale, first mentioned in section 3.3.3, is repeated below:

1. The autonomous system offers no assistance, human shall decide all;
2. the autonomous system offers a complete set of action alternatives;
3. and narrows the selection down to a few, or;
4. suggests one;
5. and executes that suggestion if the human approves, or;
6. allows the human a restricted time to veto before automatic execution, or;
7. executes automatically, then necessarily informs the human, or;
8. informs the human after execution only if it is asked, or;
9. informs the human after execution if the autonomous system decides to do so;
10. The autonomous system decides everything and acts autonomously, ignoring the human.

It has been recommended (Parasuraman, Sheridan et al. 2000) that no autonomous system/ cognitive agent/ robot, civilian or military, should be designed to operate above level 6 on this scale; the US Department of Defence (DoD), as one of the world’s most prolific users of robotic devices, has...
expectations for military robot autonomy that are generally at level 5. For civilian scenarios, this could be even more important, particularly in the case of care-giving robots working with vulnerable people.

Other scales for the same purpose (but of less discrimination) are the ACL chart (Clough 2001) and the PACT scale (Hill, Cayzer et al. 2007), both developed for ‘uninhabited air vehicles’ (UAVs).

Class of function

This refers to the kinds of functions that autonomous systems can perform. There seems to be fewer ethical issues to do with automated guidance systems and automated sensing systems so that high levels of autonomy are acceptable – witness the DARPA Grand Challenges, or Google’s autonomous automobile, among many others. In all these cases, the avoidance of collisions with people and other objects by deference or by other strategies can be considered an appropriate process. For other capabilities, for example military weapon systems, ‘Irrespective of the future capabilities of these systems, responsibility for taking life is a human action that cannot be delegated.’ (Makin 2008). This is a widely-shared viewpoint (DoD 2007, Sparrow 2007, DoD 2009, Wallach and Allen 2009, Gillespie and West 2010, Allen and Wallach 2012). In other words, autonomous systems will operate at level 1, perhaps 2, on Sheridan’s scale for this function, whatever other levels on which it might be operating to get to the point of considering lethal action. Hence, autonomous systems will have different levels of autonomy, depending on what functions are operative at a given time in a given scenario.

It is important to note, as indicated earlier, that an autonomous system with control of a gripper (or other prosthesis) can change its functionality. Consider a hospital robot as part of a CPS that is carrying a packet of dressings. It is likely that its level of autonomy might be quite high for most of its functions while doing so. On the other hand, if the same robot is carrying surgical instruments such as scalpels and saws, its functionality is likely to be constrained to carrying, and not using, the implements.

Furthermore, if the autonomous system is able to communicate with a prosthesis at some distance from it, and is able to issue commands to it, we have a situation where functional and ethical considerations can proliferate around the whole CPS (Asaro 2011). Since one of the guiding principles of CPS and the Internet of Things is that over the lifecycle of a CPS, component systems can join and leave, the need to consider ethical issues becomes an imperative in the design and operation of CPS; if autonomous components are included, then all systems may have to consider autonomy.

Duration

This refers to the period of time over which the autonomous system is able to exercise its autonomy. This might be for the duration of the system’s operational life, or it might be deliberately constrained to a shorter period by some higher authority in its statement of the mission for the system. Alternatively, it might be constrained by a circumstance perceived by the autonomous system, causing it to refer to a higher authority (for example, in the case of a robot, the loss of a GPS signal, or the arrival of children in the vicinity where actions are taking place). As an added complication, it might be necessary to take into account global time zones.

Spatial location

Using the hospital situation with a robot as an exemplar, it may have received the command, ‘You, robot, can use the scalpel in the operating theatre, but nowhere else.’ Thus, the functionality of an autonomous system will be constrained by the location in which its decisions have effects. For autonomous systems embedded within a CPS, both the location of the system and the locations where the decisions become actions will need to be considered, especially if the locations are under different jurisdictions. Furthermore, there can be severe secondary effects at a distance; for example, the command to a CPS that manages water resources to open the sluice gates on a reservoir could be
calamitous for the communities downstream in the valley, a scenario about which the CPS may have had no cognisance.

5.4.2 Learning

Learning is defined by the Oxford English Dictionary as

‘the acquisition of knowledge of a subject or skill in an art by study, experience or teaching.’

Systems that have autonomy and are open to a changing environment must be able to learn, else after a while their behaviour will cease to fit the environment in which they are operating.

For convenience, learning can be divided into three classes: ‘first-loop’, ‘second-loop’, and ‘third-loop’; these terms stem from control engineering.

Using a health-care robot as an example, first-loop learning refers to learning that enables the robot to find its way around the house of the beneficiary and where things are stored. It is concerned with basic understanding of its environment.

Second-loop learning builds on first-loop learning, it includes the improvement of the paths and processes that the robot uses to serve the beneficiary; for example, the robot learns that the beneficiary is left-handed, and places cups, forks and other tools to the left of the person rather than the right. It might also learn the routes through the house that the beneficiary uses most often, and redirect its own routes to minimise the chance of collisions in doorways.

Third-loop learning is more subtle still; the robot has the ability to query the existence of processes and strategies, and perhaps has the ability to suggest new ones. It also includes the assessment of outcomes; whether they are ethically acceptable, or whether they might increase the risk of later whole-CPS failures.

The capability of autonomous systems to learn can be a mixed blessing. One benefit is that the autonomous system that learns is able to fit its decisions and/or actions better to the evolving circumstances of its environment and thereby execute its duties faster, better, cheaper, and perhaps less costly to the environment. On the other hand, the system becomes less predictable in its behaviour, especially if it is capable of second- or third-loop learning. Furthermore, each individual instantiation of the autonomous system, if in a different environment, will learn different things and as a result of this their behaviours will diverge as time passes. It also implies that simply replacing one instantiation of an autonomous system component with another may have unexpected, unpleasant results. As one commentator said, it also distances the system from its designer.

More importantly, if the systems has learnt new knowledge, the systems with which it interoperates (including human co-workers) may not know this and may experience an unpleasant surprise, particularly if what the system has learnt is not correct for the current situation; there is a requirement for any learning to be context-sensitive (i.e. to have some understanding of the contexts in which the learning can and cannot be applied).

There are also considerations where learning can be transferred between autonomous systems. Some of the problems above are relevant; co-workers may be surprised; systems in similar scenarios may learn similar behaviours, but transference may produce clashes that stop the system functioning, or execute inappropriate behaviours.
## 6 Combining and conflating CPS technologies

This section has two subsections;

- Subsection 6.1 covers the state of technology for CPS as embodied in the 53 projects and repeats the findings of the complementary Deliverable D1.1 ‘Road2CPS State of the Art’. This subsection covers the ‘high level messages’, and shows the inter-relationships of the 53 projects using the diagrams in that Deliverable. Readers are referred to that Deliverable for more detailed information.
- Subsection 6.2 outlines some of the implications for organisations that arise from the challenges in this document, based on the 53 EU projects, from D1.1.

The 53 projects are listed below:

<table>
<thead>
<tr>
<th>ADVANCE</th>
<th>ENOSYS</th>
<th>MADNESS</th>
</tr>
</thead>
<tbody>
<tr>
<td>AGILE</td>
<td>EOT</td>
<td>makeSense</td>
</tr>
<tr>
<td>AMADEOS</td>
<td>ERA</td>
<td>PLANET</td>
</tr>
<tr>
<td>AXIOM</td>
<td>EUROCP</td>
<td>Road2SoS</td>
</tr>
<tr>
<td>CLAM</td>
<td>GENESI</td>
<td>SAFURE</td>
</tr>
<tr>
<td>COMPASS</td>
<td>GreenerBuildings</td>
<td>SCUBA</td>
</tr>
<tr>
<td>CONSERN</td>
<td>HYCON2</td>
<td>T-AREA-SoS</td>
</tr>
<tr>
<td>CPSELABS</td>
<td>HYDROBIONETS</td>
<td>TAPPS</td>
</tr>
<tr>
<td>CPSoS</td>
<td>IMC-AESOP</td>
<td>U-TEST</td>
</tr>
<tr>
<td>CyPhERS</td>
<td>IMMORTAL</td>
<td>UnCoVerCPS</td>
</tr>
<tr>
<td>DANSE</td>
<td>INTO-CPS</td>
<td>Verdi</td>
</tr>
<tr>
<td>DYMASOS</td>
<td>Karyon</td>
<td>VITRO</td>
</tr>
<tr>
<td>EC-SAFEMOBIL</td>
<td>Local4Global</td>
<td></td>
</tr>
</tbody>
</table>

Table 6.1 List of 53 projects for assessment in Road2CPS

### 6.1 Mapping of projects in Table 6.1 to show technology outputs and coverage

A cube, related to that used in the ARTEMIS project, was developed within the Road2CPS project to classify the findings from the 53 projects in Table 6.1 above as a fundamental input into D1.1 ‘State of the Art and Impact’. This cube had three dimensions; ‘Interoperability’, adapted from the NCOIC Interoperability Framework (NCOIC 2011), ‘Infrastructure’, for the class of output, and ‘Domain’. The latter used the same domains as in the ARTEMIS cube. However, cluster analyses of these 53 projects for D1.1 demonstrated that this dimension did not differentiate the projects well in terms of their output, albeit the projects did fit quite well into the domains in which they were originally positioned. In other words, the findings were more general across the domains than the domain in which they were identified. For this reason, in the diagrams that follow the domain axis has been compressed and the diagrams are essentially two-dimensional but with indications that a third dimension exists.

Figure 6.1 shows the two-dimensional version of the cube, with the space divided into the major classes of findings from the 53 projects. The four major classes are:

- Strategic technology research, concerned more with
- Technology implementation, concerned with implementing CPS within an environment
- CPS support ecosystems, concerned with design, development, safety, business contracts, etc.
• Systems of systems, concerned with high level complex distributed systems and enabling strategies, architectures and methodologies.

It should be understood that the boundaries between these four classes are much more fuzzy than is indicated in the diagram.

Shaded indents on the infrastructure axis are sub-classes within the main label in the shaded area.

Figure 6.2 includes labels on the cube, providing some more detail about the four classes in figure 6.1.

Figure 6.3 includes all 53 projects, each one positioned repeatedly to show the various classes of findings that the project has either made (for finished projects) or expects to make (for those still running). Each cluster of projects indicates an overlap of findings, but not that there is a common frame of reference. Where clusters do not fit neatly into the rows and columns of the cube, this indicates that the cluster embraces the adjoining cells. Gaps in positioning indicate no coverage in that particular area among the 53 projects.

Figure 6.4 plots the findings from all the 53 projects combined, showing coverage within the cube, and labelled to indicate the scope of the findings. Again, where there are gaps, there is no coverage.

Together these three diagrams indicate the state of the art from the 53 projects. For more detailed information, the reader is advised to consult D1.1; the main, ‘high-level’ messages from D1.1 are as follows

• Strategic CPS research is cross-domain. This indicates that strategic CPS research is not classified to any specific domain.

• Overall domain independence of cluster. No top-level cluster of CPS projects is defined by Domain. The clusters are defined entirely by their categorisations within the Infrastructure and Interoperability scales. This is not to say that the Domain scale is unimportant, but rather Domain categorisation is not useful when trying to group projects into clusters.

• Gaps in coverage of education, training and financial arrangement. “Contracts & financial arrangements” and “Education” are poorly represented in the coverage of projects, and yet these topics both constrain and enable the functioning of CPS.

• There is domain bias in technology implementation. Energy; IT&C; Manufacturing; Smart Community; and Transport are well-represented as domains covered by projects in the Technology Implementation cluster. Conversely, Environment and Agriculture; Healthcare; and Security are almost completely ignored. Since strategic research is cross-domain, it may be that implementation details have created this diversity. On the other hand, it may indicate opportunities for transfer of capability at lower cost in time and funding, given that the strategic aspects are common.

It is pleasing that many of the outputs of these projects are around NASA Technology Readiness Level 6 - “System/subsystem model or prototype demonstration in a relevant environment (ground or space)”, implying that future projects funded by the EC should be to consolidate the technologies and demonstrate their potential in pilot projects in societal environments. It is accepted that there will be issues involving Intellectual Property Rights (IPRs) and that the technologies have been developed somewhat in isolation, creating what might be difficult problems at the interfaces (both technological and political), but this might be an efficient way to ensure technological leadership for the EU28.
Figure 6.1 The Road2CPS cube, from D1.1, with the Domain access compressed. It shows the 4 main areas expressed by 53 projects.
Figure 6.2 The cube, with some explanation of the contents of the 4 areas.
Figure 6.3  The cube, with the 53 projects superimposed, classifying their various outputs for Infrastructure and Interoperability. Gaps in coverage exist.
Figure 6.4 The cube, with technology contributions from the 53 projects combined.

©Road2CPS Consortium
6.2 Technologies organized by interoperability level

Table 6.2 below classifies the technologies mentioned in this report into interoperability levels, adapted from the NCOIC classification (NCOIC 2011). The intention is to provide some guidance for organisations, rather than direction.

<table>
<thead>
<tr>
<th>LEVEL</th>
<th>DESCRIPTION</th>
<th>DEVELOPING TECHNOLOGIES</th>
</tr>
</thead>
</table>
| Political/ Economic/ Regulatory/ Business Board level | Technology addresses needs issues and opportunities that should be addressed either by government (e.g. creating regulations, programmes, agencies, etc.) or by the Board of a company (e.g. recommendations that affect why the company exists and what it does; governance, legal and financial aspects). Discussion of pre-requisites for business models to be successful. | • Pre-requisites for business models – concepts measures, methods, single-issue tools  
• Evolution of IoT; standards, connectivity, etc.  
• Data security and protection (eg firewalls, sandboxes, encryption, authentication etc)  
• Cloud computing  
• Additive manufacturing  
• Big Data and data storage applications  
• Common Operating Picture/Situational Awareness techniques and models  
• Trade space analysis applications  
• Governance for CPS  
• Adoption of CSR, RRI, methods  
• Evolution of required standards and regulations to incentivise CPS adoption  
• Incorporation of autonomous systems in CPS  
• Adoption of Model-based Engineering  
• Modelling and Simulation capabilities  
• Technical /Engineering Governance Frameworks  
• Socio-technical systems methods and tools |
<table>
<thead>
<tr>
<th>LEVEL</th>
<th>DESCRIPTION</th>
<th>DEVELOPING TECHNOLOGIES</th>
</tr>
</thead>
</table>
| Business objectives: strategy & policies level | Technology helps formulate the plans which government/ industry/ companies should develop to reach desirable business objectives; may also indicate how to implement the plan(s) in order to avoid unwanted side-effects and consequences). Evaluation of business models. | - Pre-requisites for business models – concepts measures, methods, single-issue tools  
- Evolution of IoT; standards, connectivity, etc.  
- M&S capability for generating and exploring alternatives  
- Novel methods of ULSS control for hybrid systems  
- Triage recycling technologies  
- Development of Open architectures & Platforms, Characterisation of Architectures  
- Data security and protection (eg firewalls, sandboxes, encryption authentication etc)  
- Big Data and data storage applications  
- Common Operating Picture/Situational Awareness  
- Trade space analysis applications  
- Approaches for Ethical behavior & standards  
- Development of Autonomy: technology, capabilities etc  
- Extension of M&S to Cognitive Behavioural Models  
- Real time Health Monitoring and diagnosis  
- Model-based Engineering  
- Development of Modelling and Simulation ecosystems  
- Technical /Engineering Governance Frameworks  
- Cloud technology  
- Fog computing  
- Socio technical systems methods and tools |
<table>
<thead>
<tr>
<th>LEVEL</th>
<th>DESCRIPTION</th>
<th>DEVELOPING TECHNOLOGIES</th>
</tr>
</thead>
</table>
| Business context: aligned operations level                 | Technology addresses the harmonisation of functions such as planning, manufacturing, marketing and finance in relation to each other and/or to strategy and objectives. “Aligned operations” can also refer to operations along a supply chain, so that different companies can work together more efficiently. Standards and codes of practice are indicators of this level, as would discussion of MOUs, Collaborations, and workshare arrangements | • Evolution of IoT and platforms  
• Development of Dynamic network configuration tools and methods  
• Security standards and certification activities  
• Development of Standards for network development and configuration  
• Exploration of Open architectures  
• Novel methods of ULSS control for hybrid systems  
• Triage recycling technologies  
• Implementations of Data security and protection (eg firewalls, sandboxes, encryption authentication etc) for Mobile device-based networks  
• Development of Non-Linear Model-based Predictive Control (NMPC)  
• Statistical control methods  
• Network modeling for network management  
• Evaluation of Big Data and data storage applications  
• Development of Common Operating Picture/Situational Awareness  
• Adoption of Trade space analysis applications  
• Exploration of Sensing and perception technologies  
• Development of Run time V&V techniques, also Real time Health Monitoring and diagnosis  
• Development of technology for Autonomy: technology, capabilities etc  
• Evaluation of Cognitive behavioural models  
• Model-based Engineering  
• Improvement of Modelling and Simulation capability  
• Technical /Engineering Governance Frameworks  
• Cloud technology  
• Fog computing  
• Socio technical systems methods and tools |
<table>
<thead>
<tr>
<th>LEVEL</th>
<th>DESCRIPTION</th>
<th>DEVELOPING TECHNOLOGIES</th>
</tr>
</thead>
</table>
| Business context: aligned procedures level | Technology addresses the procedures within a function (such as manufacturing) that can be matched better with the goals of the function (e.g. to make savings in time, costs, waste, efficiency, etc.) Technology may address the alignment of procedures running across several companies. Standards and codes of practice are also important | • Evolution of IoT  
• Utilisation of Data security and protection (eg firewalls, sandboxes, encryption authentication etc) Standards for network development and configuration  
• Development of Mobile device-based networks  
• Statistical control methods  
• Novel methods of ULSS control for hybrid systems  
• Triage recycling technologies  
• Development of Non-Linear Model-based Predictive Control (NMPC)  
• Development of Network modeling for network management  
• Development of Common Operating Picture/Situational Awareness  
• Adoption of Trade space analysis applications  
• Sensing and perception technologies  
• Development of Run time V&V techniques, Real time Health Monitoring and diagnosis  
• Development of Autonomy: technology, capabilities etc  
• Model-based Engineering  
• Improvement of Modelling and Simulation capability  
• Technical /Engineering Governance Frameworks  
• Cloud technology |
| Semantics: knowledge & sharing of knowledge level | If the technology allows or recommends adoption of, or suggests changes to, ontologies, taxonomies, thesauri, or discusses knowledge sharing (e.g. IPR agreements) among different groups, companies, etc., then it is at this level | • Exploration of Open architectures & ontologies  
• Implementation of Data security and protection (eg firewalls, sandboxes, encryption authentication etc)  
• Security standards and certification activities  
• Investigation of Cognitive Networks & Cognitive behavioural models  
• Exploration of Network modeling for network management  
• Implementation of Modelling and Simulation capability  
• Implementation of Technical /Engineering Governance Frameworks  
• Development of Socio technical systems methods and tools |
<table>
<thead>
<tr>
<th>LEVEL</th>
<th>DESCRIPTION</th>
<th>DEVELOPING TECHNOLOGIES</th>
</tr>
</thead>
</table>
| **Semantics: information & interoperability level** | Understanding of concepts contained in messages passed between interfaces. Technology may deal with glossaries, or classes of information, in the context of transferring meaning from one head to another, or between CPSs or software agents. Discussion of protocols would also indicate this level. | • Definition of standards  
• Implementation of Data security and protection (eg firewalls, sandboxes, encryption authentication etc.  
• Security standards and certification activities  
• Sensing and perception technologies  
• Elaboration of Run time V & V techniques  
• Development of Real time Health Monitoring and diagnosis  
• Exploration of Autonomy: technology, capabilities etc  
• Exploration of Ethical behavior & standards  
• Modelling and Simulation capability  
• Technical /Engineering Governance Frameworks  
• Exploration of Cloud technology & Fog computing  
• Adoption of SDN and NFV  
• Development of Socio technical systems methods and tools |
| **Syntactic interoperability** | Technology addresses formats, compression techniques, encryption and other ways of representing knowledge, information and data for transfer between functions, organisations, etc. Standards and codes of practice regarding interfaces and message structures are indicators of this level, as is discussion of integration of models. | • Data security and protection (eg firewalls, sandboxes, encryption authentication etc)  
• Wearable communication devices  
• Security standards and certification activities  
• Big Data and data storage applications  
• Run time V & V techniques  
• Real time Health Monitoring and diagnosis  
• Ethical behavior & standards  
• Autonomy: technology, capabilities etc  
• Model-based Engineering  
• Modelling and Simulation capability  
• Technical /Engineering Governance Frameworks  
• Cloud technology  
• Fog computing  
• Network Functions Virtualisation |
<table>
<thead>
<tr>
<th>LEVEL</th>
<th>DESCRIPTION</th>
<th>DEVELOPING TECHNOLOGIES</th>
</tr>
</thead>
</table>
| Network interoperability                 | Enables the exchange of messages between CPSs across a variety of networks. Technology addresses networks and networking, interface descriptions, and analysis of network architectures | • Evolution of IoT  
• Dynamic network configuration  
• Standards for network development and configuration  
• Security standards and certification activities  
• Mobile device-based networks  
• Novel methods of ULSS control for hybrid systems  
• Cellular technology  
• Mesh networks  
• Communication protocols  
• Network modeling for network management  
• Named Data Networking  
• Model-based Engineering  
• Modelling and Simulation capability  
• Technical /Engineering Governance Frameworks  
• Cloud technology  
• Fog computing |
| Physical interoperability level          | Technology /Mechanisms to establish physical and logical connectivity and which address issues of physically connecting together devices, using Ethernet cables, plugs sockets, wireless, or transferring pieces of paper | • Standards for network development and configuration  
• Data security and protection (eg firewalls, sandboxes, encryption authentication etc)  
• Run time V & V techniques  
• Model-based Engineering  
• Mesh networks  
• Communication protocols |

Table 6.2 Interoperability levels and technologies associated with each one. Technologies named in this report, which are based on the findings of the 53 projects.

7 Conclusions

The conclusions below address both the state of technology as represented by the 53 projects, and the implications for sustainability, as indicated in the Aim of the Deliverable, stated in section 1.1. These have been numbered, for future reference.

1. While the diagrams in section 6.1 above show that there are gaps in the coverage of technological and social considerations of CPS in the EU, there is a picture of across-the-board technical competence that provides a basis for EU leadership in the development and application of CPS.
2. There are overlaps in the research as indicated in the diagrams in section 6.1, but not much sign of a common reference framework. It is important that this is developed so that future projects can contribute more directly to composable technology.

3. In terms of interoperability, the lower, more detailed levels of operability have received wide attention; sufficient to show some important gaps at higher levels that need to be addressed in future to make sure that the technology can be adopted and interfaced without extended effort.

4. Societal aspects of CPS should be addressed to a greater extent; for example, the current delays in the deployment of autonomous vehicles are largely due to these aspects that are often described as ‘non-functional’. Societal aspects are not non-functional; they are functional requirements for the political, legal and social support systems that are necessary for acceptance of CPS into society.

5. While accepting that there is no common reference framework and an accompanying lack of standards, there is more complementarity in the technology than perhaps was expected. While domain-specific projects may be necessary to tease out details of CPS (c.f. the German proverb, “The Devil is in the details”), perhaps projects in future should be directed at a minimum of two domains with strong requirement for adoption of technology from earlier projects that has reached NASA TRL 5 or 6.

6. There is a clear and pressing need to address the interoperability issues between different CPS system components; hybrid models, simulations, languages, tools, methods, frameworks, trade spaces, etc. Given the elision between design and operation that is recognised as fundamental for CPS, there is a danger of undue delays in the adoption of CPS technology.

7. Given that in the future many Cyber-Physical Systems will be expected to operate in an ‘always on’ mode (i.e. cannot be stopped), but will still be subjected to upgrades (both planned and unexpected), and to ‘normal accidents’ (Perrow 1999) and other emergent phenomena, it will be necessary to develop certified processes and standards for maintaining the integrity of the CPS during the ever-changing states and configurations over its lifecycle.

8. The technology for engineering autonomous systems requires further development, to address trustworthiness and the impact of autonomous learning. This is particularly important given the demographics of the EU28 as we head towards 2050, and an inevitable increase in the numbers of vulnerable people. This is also important from the perspective of people as co-workers with such systems.

9. The ever-growing role of smartphones and other wearable devices in turning people into mobile, networked cyborgs indicates a strong requirement for very extensive, high-capacity networks based on secure, ‘plug and play’ technology. The technology for this is becoming available, but will need more development for the full exploitation of CPS.

10. As the uptake of the IoT increases with ever-more devices being attached, the requirement for high-speed, low-latency, guaranteed secure communications (M2M) will grow. The technical base for this requires further attention.

11. There is a requirement that CPS behave ethically when they interact with people, both as individuals and in organised groups, if they are to be trusted and accepted. The technology to accomplish this is almost non-existent, and this represents a potential barrier to their deployment in society that needs to be addressed very soon.

12. It seems clear that skills and knowledge shortages in designing, operating, and maintaining CPS will hamper the adoption of CPS in the EU28 unless a systemic effort is made to impart the
necessary skills across the EU at all levels from individuals through organisations and into governments.

13. Given that the skills are available within the workforce, there is still the problem of applying these skills to CPS. This is an important area of enterprise system design to deploy skills into roles that are meaningful for the people who possess these skills, and then ensuring that the people have the interfaces into the CPS to exercise those skills appropriately. Given the likely extent and complexity of CPS in the future, a current analogy to the kind of interface that might be required in the aircraft cockpit, in which the pilot operates more as the manager of a suite of interconnected cyber-physical systems of significant complexity. But the situation for CPS may be even more complex; for the pilot, the systems do not change until a major overhaul period arrives. In the CPS world, given their reach and complexity, it is possible that a CPS will be in a near-constant state of change, as exemplified by examples in this report. Designing a cost-effective human-CPS interface for this situation represents a difficult problem beyond the current state of the art, and yet it is a necessary part of operational CPS. This is a potential barrier for the deployment of future CPS.

14. CPS technologies are likely to be encumbered with IPRs, confidentiality clauses and other legal considerations. For their effective deployments into CPS, there is likely to be a need for standard contract forms to enable the equitable creation of CPS in relatively quick real time. For some CPS operating in fast-changing environments (mobile is an example) it may be necessary to allow component systems in CPS to engage in contracts autonomously. This will require standard contracts.

15. From a sustainability perspective, the situation seems to be encouraging. There is a general awareness of the need for economies in materials, energy and emissions, and almost all of the technologies explored within the 53 projects are of evident value in bringing about these economies. However, combining them into CPS that will deliver these economies is still a big issue. Nevertheless, we are in a technological position to consider projects to develop real-world pilot systems in the near future.

16. The move from an end-to-end economy in the EU28 to a circular economy will be aided greatly by CPS and their technologies. Attaining a state of ‘no more landfill’ in the EU28 may be an achievable goal; what will help even more is the mining of landfill for materials. This role for CPS is under-developed, although many of the technical developments that have already taken place would make this a possibility to explore.

17. The need for a common reference framework, for composable technology to create CPS, for standards (including standard contract forms), and for bringing together the wide range of disciplines necessary to create and operate acceptable CPS indicates a requirement for a wide-ranging constituency of people and organisations to deliver such CPS. It is likely that a Joint Undertaking as exemplified by ARTEMIS and ECSEL will be necessary to create this constituency.
References

(2005/64/EC). Directive on the type-approval of motor vehicles with regard to their re-usability, recyclability and recoverability. European Union.


EC-NANOCODE (2009). A code of conduct for responsible nanosciences and nanotechnologies research.


Road2CPS

2.1 Road2CPS  Scientific & Technological challenges 1.0


Phone: +27 (0)21 883 2208, 883 8292, URL: http://www.tralac.org.


UN-DESA (2004). World population to 2300.

UN-FAO (2009). How to feed the world in 2050.


