ORIGINAL ARTICLE

The identification of knowledge gaps in the technologies of Cyber-Physical Systems, with recommendations for closing these gaps

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The paper reports some training, education, and operational findings from an EU Horizon 2020 project that included the production of technology road-maps for the domain of Cyber-Physical Systems (CPS). The project reviewed Deliverables from 72 CPS projects, all within Framework Programme 7 and Horizon 2020, including 18 from the ARTEMIS and ECSEL sub-programmes. This analysis led to the production of a 'Knowledge Map' containing 75 technologies identified within the 72 projects as nodes in this map, connected by interoperability links. Filtering this map for each node in turn has led, in combination with other parts of the project, to some 48 recommendations for future focus and funding of developments in these technologies to assist in the rapid adoption of CPS in all domains. While the focus has been limited to European Union research and innovation, it is believed that the recommendations are transferable to other regions of the world.

KEYWORDS
SEE04 Systems Science, *SEE06 Architectural Design*, SEE29 Other Systems Engineering Enablers

Abbreviations: CPS, cyber physical systems.

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1 | BACKGROUND

This paper reports on some of the findings of a Horizon 2020 project entitled 'Strategic action for future Cyber-Physical Systems (CPS) through roadmaps, impact multiplication and constituency building', with the more convenient acronym, 'Road2CPS'. The project website with all its Deliverables can be found at http://road2cps.eu.

The paper does not report all of the findings from this project; it is limited to those findings and recommendations regarding the technologies required for the future development of operational CPS that were delivered to the FP7 and H2020 management and which are likely to be useful to others involved in the world of CPS. The significance of these findings rests on the proposition that Cyber-Physical Systems and the interoperating collection of technologies that they represent provides the best hope for achieving a sustainable world by 2050, given that the global population is expected to grow from about 7 billion now to perhaps 10 billion by 2050 [1] and given that ecologists believe that we are already exceeding the world's ecological footprint [2]. In this background section, briefly we position CPS in the context of sustainability, and then explicate the relationships between CPS and overlapping concepts such as Systems of Systems (SoS), Joint Cognitive System (JCS), and the Industrial Internet (II).

1.1 | Sustainability and Cyber-Physical Systems

There are a number of inter-related concerns that will lead to an unsustainable world unless their unwanted effects are contained, the main ones being as follows: Population demographics; Food and water security; Energy security; Mineral resource depletion; Emissions & climate change; Globalisation Transportation; Community safety & security [3].

The evident interactions between these concerns indicate that we are in the realm of the 'wicked problem' [4][5] [6] [7][8], meaning that single-issue solutions are likely to have neither sufficient nor lasting effect and in turn point to the need for a comprehensive systems engineering approach. Since most societies on our planet have a huge and growing dependence upon an infrastructure of connected devices about our persons, homes, and communities and probably could not survive without their continued function, there is a new and massive opportunity for engineering a better future.

While adopting a systems engineering approach is a clear necessity, there is an important constraint in its application; the necessity of frugality in whatever solutions are provided. In fact, containment in this context is predicated on frugality in all of its aspects. The very close control of processes and resources that is one of the hallmarks of the CPS approach embraces this constraint very well; this is fortunate, because at the present time there is no other approach, incorporating a sufficiently wide range of disciplines, on offer to meet this constraint.

There is a second, fundamental constraint in this containment for sustainability that occasionally seems to be overlooked. As the comments above imply, there is necessarily a very close interplay between people and the devices that they utilize in living their lives; billions of people interacting with more billions of devices with even more billions of interfaces in complex patterns of activities and processes to accomplish their goals. Given this scenario it is clear that the design and subsequent operation of CPS for a sustainable world must take full account of human needs, capabilities, intentions and complexities in facilitating their interaction with or control of such systems. This applies to humans operating as individuals, groups or communities in pursuit of their work or leisure activities.

Cyber-Physical Systems

For convenience we give here the definition of CPS from acatech, the German Academy of Science and Engineering [9] that was adopted by the project:

"A Cyber-Physical System (CPS) is a system 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 records physical data using sensors and affects physical processes using actuators;
- evaluates and saves recorded data, and actively or reactively interacts both with the physical and digital world;
- is connected with other CPS and in global networks via digital communication facilities (wireless and/or wired, local and/or global);
- uses globally available data and services;
- has a series of dedicated, multi-modal human-machine interfaces."

This conceptual approach now dominates thinking on CPS in the European Union (EU) and in Europe in general and all governments in the EU now have CPS programmes in place. Moreover, globally there are cognate conceptualisations, and we include here a brief commentary, in the hope of providing some clarity.

Cyber-Physical Systems and Industrie 4.0: Aimed at a high level of organization and control over the entire lifecycle of processes and products and, latterly, services within society. It now includes notions of Corporate Social Responsibility, etc. [10, 11, 12].

Systems of Systems: Originally developed in the US Defence environment, but rapidly adopted within the civilian world. It is intended to cover the entire lifecycle of systems and their devices, and the concept is defined by the characteristics of managerial independence of the component systems, their operational independence, leverage at the interfaces, and stand-alone capabilities of the component systems. There is strong overlap with the Industrie 4.0 perspective [13, 14, 15].

Joint Cognitive Systems: Similar in concept to the above, but with a stronger focus on humans as a source of authority and responsibility within CPS, working with networked devices as mutually-embedded systems [16, 17].

It is evident that trio of core considerations are common to all of these conceptual approaches, the trio being close control, intercommunication involving the Internet of Things (IoT), and human involvement. However, there are important differences in emphasis for these three considerations, with consequences for other aspects that are included (or not) in the concepts. This paper embraces all three of the core considerations.

1.2 | The rest of the paper

The paper commences with a brief description of the Road2CPS project, and an outline of the methodology employed to deliver the findings reported in the paper. A 'knowledge map' is presented, representing the incompleteness of the current knowledge network that is necessary to deliver safe, secure, efficient and effective CPS systems in all sectors (manufacturing, agriculture, health, transport, smart communities, energy, etc.) that will enable us eventually to attain a sustainable future.

Finally, based on the knowledge map and reviews of other literature (examples include Industrie 4.0 documents [10, 11] HiPEAC [18], robotics [19, 20], Ultra-Large Systems of Systems [21], the Internet of Things [22, 23, 24] and many technical reports [25, 26, 27, 28, 29], a set of recommendations are reported that will assist in achieving the necessary closure of the gaps represented in the Knowledge Map

In this paper, a 'Gap' is defined as an area of knowledge that is incomplete or not sufficiently mature (i.e. at level 6 and below on the Technology Readiness scale [30]) in the knowledge network.

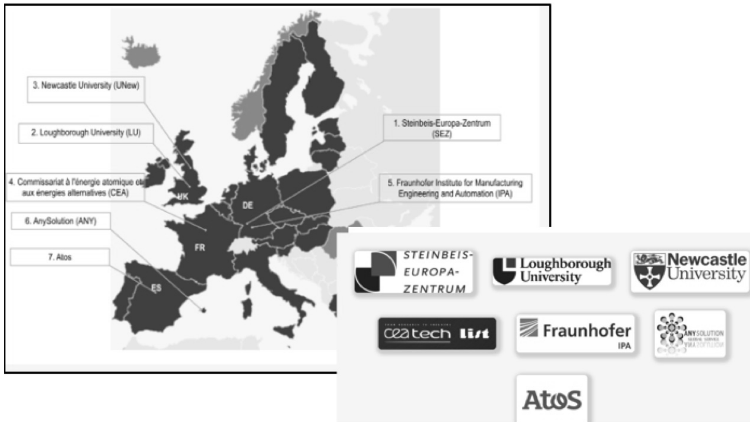

FIGURE 1 Partners in the Road2CPS consortium.

2 | THE ROAD2CPS PROJECT

Projects classed as H2020 Co-ordination and Support Activities (CSA), as the name indicates, are not expected to carry out ground-breaking research. They are undertaken to bring together the results of other, large Research and Innovation projects, and to show how these might be implemented for the benefits of society as a whole. This is demonstrated by the goals of the Road2CPS project, summarised below:

- To assess and multiply the impact of past and ongoing projects in CPS and related fields,
- To develop technology, application and innovation strategy roadmaps, to specialise the roadmaps into the industrial context via case studies and to derive recommendations for future research and innovation strategies.
- To bound and build a constituency aware of – and united by – their commonly faced challenges and demands regarding CPS and build task forces for specific actions (e.g. CPS and society; CPS and business; CPS and standards, interoperability, safety and security; CPS and the general public).

This paper addresses only the second bullet-point in this list and within this it focuses on technology roadmaps. However, the 48 recommendations for the future adoption of CPS technologies towards the end of this paper are based on technological findings for all three of the sub-goals.

Road2CPS was a two-year, €800,000 CSA project, Grant Agreement 644164, with seven partners from four EU member states, illustrated in Figure 1 below. The project ended in 2017.

2.1 | The methodology adopted

A week after the Grant Agreement was signed and funding agreed, the Commission presented the project with a list of 54 projects to be reviewed by Road2CPS. All of these projects had significant funding either from the Horizon 2020 programme or by its predecessor, the 7th Framework Programme and all were considered to be CPS-relevant projects. This list was much longer than was expected within the project and, given that the first set of deliverables (including a State of the Art Deliverable) was due some six months later, this list represented a significant 'stretch target' for the project, requiring significant changes to the planned methodology. The original methodology was predicated on the

72 EU projects providing the data set for Road2CPS project ***(Italics for ARTEMIS/ECSEL JU projects)***		
3CCar	*DEWI*	*MANTIS*
ACCUS	DYMASOS	MoVeS
ADVANCE	EC-SAFEMOBIL	OPENCOSS
AGILE	*E-SCOP*	PAPYRUS
ALMARVI	EMBOCON	PLANET
AMADEOS	*EMC2*	*R5-COP*
Arrowhead	ENOSYS	Road2CPS
Autoprofit	EOT	Road2SoS
AXIOM	ERA	*RobustSENCE*
BALCON	EUROCPS	SAFURE
BEMO-COFRA	*EXIST*	SCorPius
CLAM	GENESI	SCUBA
COMPASS	GreenerBuildings	SPRINT
CONCERTO	*HOLIDES*	*SWARMS*
CONSERN	HYCON2	T-AREA-SoS
COPCAMS	HYDROBIONETS	TAMS4CPS
COSSIM	IMC-AESOP	TAPPS
CP-SETIS	IMMORTAL	TERESA
CPS-SUMMIT	*InForMed*	U-TEST
CPSELABS	INTO-CPS	UnCoVerCPS
CPSoS	Karyon	Verdi
CRYSTAL	Local4Global	VITRO
CyPhERS	MADNESS	WiBRATE
DANSE	MakeSense	*WITH-ME*

FIGURE 2 A listing of the projects scanned by Road2CPS. Projects in italics are from the ARTEMIS and ECSEL Joint Undertakings (i.e. programmes with significant industrial contribution).

Cochrane protocol [31], considered to be the gold standard for meta-analyses; the new, streamlined, version of the methodology focused entirely on the publicly available Deliverables of each project. Resource and time constraints prevented the researchers from undertaking interviews with project participants or seeking other outside information as sources of data for triangulation and illumination purposes. It was considered that, as all project Deliverables are assessed for quality and coverage by external experts, they could be treated as dependable records of each project's findings. The section below on caveats and assumptions provides more detail about these changes to the methodology.

At the First-year Formal Review of Road2CPS a further list of 18 projects, 17 from the ARTEMIS and ECSEL programmes and one more from the Horizon 2020 programme was added to the previous set, making a total of 72 projects in all to be investigated. The ARTEMIS and ECSEL programmes are under the remit of Horizon 2020, but are much more concerned with implementation issues, whereas Horizon 2020 projects are much more about science and technology development. The full list of projects is shown in Figure 2 below.

2.2 | The vulture tool

To deal with the information load, the Vulture Tool [32] was rapidly developed within the project from open-source applications to enable knowledge 'snippets' to be collected from each project and its Deliverables, categorised according to content and context. This tool captured and categorized all the relevant data from the project Deliverables to provide a common base for all the analytical work that followed. Given the time constraints, all partners in the Consortium were allocated projects from the list and contributed 'snippets' from the Deliverables in an intensive effort over 5 months.

During this data capture exercise and production of the initial set of H2020 Deliverables, it was evident that, although each of the 54 (later 72) projects had accomplished much, they also identified shortfalls and other complementary work that would be necessary to ensure full, safe, efficient functionality of future CPS. It was also evident that these shortfalls – known as 'Gaps' in this paper - were interlinked. Accordingly, a spreadsheet was created from the Vulture database that lists the 75 Gaps that were identified by the 72 projects, briefly describes each one, outlines the benefits to be gained by closing the Gap, and identifies the projects that provided evidence for the Gap. This spreadsheet constituted the source data for another open-source tool, Gephi^{TM} (https://gephi.org), that was utilised to create the Gap network shown in Figure 3 below. It is important to understand that while this paper uses the word 'Gap', it does not mean there is no knowledge there. Much knowledge exists for each of the Gaps; however, from an implementation perspective the knowledge falls short of the industrial requirement; the knowledge in most of the Gaps is around Technology Readiness Level 6 or lower, instead of Level 9 for assured, safe technology [30].

2.3 | Assumptions and caveats regarding the methodology

There is a range of assumptions and caveats implicit in the data capture and analytics involved in the methodology described above. As stated above the original intention was to adopt the Cochrane Review protocols [31] but the size of the project list to be analysed made this impractical in the time available. The simplifying assumptions and associated caveats in the analysis that was undertaken are listed below, to assist the reader in evaluating the contents of the paper.

2.3.1 | Caveats

C1 The database for this analysis is limited to 72 Horizon 2020, Framework 7, ARTEMIS and ECSEL projects, all based in the European Union. While documents referring to work in other regions of the world were consulted and knowledge from these is included within the analysis, it is still a regional sample of projects.

C2 While the 18 ARTEMIS and ECSEL projects were concerned with the implementation of CPS technologies, most of the rest were focused more on scientific and technological understanding, not often progressing beyond prototypes (i.e. at Technology Readiness Levels 6 or below) This implies constraints on the applicability of the findings discussed in the rest of this report.

C3 Information retrieved from the projects in the sample was from Deliverables produced by the projects. Not all documents were readily available in the public domain and those that were available may not represent the full information and outputs generated by the projects. This limitation arises directly from the tight timescale for data collection allied to limited human resources as originally planned and agreed for the Road2CPS project.

C4 The analysis for the knowledge map was performed by academics with practical experience in industry and with training in the technologies of Systems Engineering. Consequently, the comments and analyses in this document are tempered by the perspectives of this discipline, and the authors accept that different interpretations are possible.

2.3.2 | Assumptions

A1 *The Deliverables produced by each of the 72 projects are an accurate record of the project.* Given that these have been reviewed by all the partners in the project consortium, by the EC-based Project Officer and by the EU-based Review Panels during and at the end of each project, this assumption is thought to be reliable.

A2 *The analyses and key messages reported in this Deliverable deliberately take no account of different domains of sectoral adoption of CPS technologies.* At the beginning of this project the plan for data collection and analysis assumed that there would be differences between industrial sectors and accordingly the project adopted the sector categories identified by the ARTEMIS Joint Undertaking, with its focus on implementation issues: Environment & agriculture;

Healthcare; Information technology and communications; Manufacturing; Security; Transport & mobility; Smart communities; and Energy. To the authors' surprise, the analysis of the data indicated that the important Gaps that were identified within the 72 projects did not differ significantly across these domains and were all likely to utilise the same core technologies that would be developed to close the Gaps. It is in the details of implementation that different adaptations for each domain will be required as the core technology is instantiated in real devices, software and systems. There is an analogy with the automotive field; in the early days there was a huge variety of designs and technical ways of providing transport, but a pattern soon developed that embodied a 3-box design with a wheel at each corner and a hydrocarbon-based reciprocating engine at the front. The core technology for this pattern has been the same the world over; however, instantiations can be varied, as any motor show will demonstrate.

A3 *The adoption of a bottom-up approach to these analyses is enough to ensure that the recommendations later in this paper are not re-expressions of prior expectations held by the authors.* In other words, the evidence-based approach means that the recommendations are not over-influenced by the understandings and assumptions of the investigators prior to commencing the project.

A4 *The decision to select just two classes of edges in the knowledge map and to weight the importance of these equally was based on the benefits of simplicity in the presentation and interpretation of the Gephi plots.* Two classes of links (directed edges) were used to create the network shown in Figure 3. These were: 'closing Gap X contributes directly to closing Gap Y' and 'closing Gap X complements and extends the effects of closing Gap Y'. It should be noted that these links are interoperability links, not the usual ownership links that are found in these classes of diagrams. Knowledge interoperates - it is not 'owned' by other knowledge. While it would have been possible to develop many other classes of edges (and a short-lived exploration of these was undertaken), the benefits of simplicity in developing the recommendations and in making them comprehensible for a range of different readers out-weighed the value of subtlety, notwithstanding the truth of the famous dictum, 'the devil is in the detail'.

A5 *A 'two-hop' approach to filtering the Gap network is sufficient to find the key messages lurking in Figure 3.* This assumption was forced; Figure 3 is almost impenetrable. It was decided to take each node in Figure 3 and follow the links to its nearest neighbours, including the links between these nearest neighbours, since this would ensure that the neighbours were a related set. It also enables homogeneous messages to be created. Thus, a 'two-hop' approach was chosen on the basis of simplicity, again. In support of this, it was discovered that if the analysis was extended to a third hop, it almost reproduced the original complex network of Figure 3, thereby making messages very hard to discern and disentangle, whichever node was selected as the starting point. However, the adoption of this 'two-hop' filtering strategy does have its drawbacks. Expectations that various important Gaps in categories such as tools, security, processes, etc. would appear in the plots are not always fulfilled.

A6 *It is enough for the aims of the project and this paper to concentrate on the key messages relevant to the closing of the strategic Gaps and derive recommendations from these messages.* By so doing, the recommendations resulting from these messages, illuminated by input from other parts of the project, are likely to be of most interest to the readers of this paper. The Appendix to this paper contains details for access to the data and the plots, should the reader wish to explore the implications of the knowledge map in more detail.

3 | CREATION OF THE GAP NETWORK AND THE DERIVATION OF KEY MESSAGES

Having populated the spreadsheet with pertinent information about each of the 75 Gaps, it was necessary to capture the evident links between them. This was undertaken by the three authors, working in teams of two over several weeks, with the third person providing some evaluation of the results as they accumulated after each session. As stated in assumption A4 above, two types of links were created to join the Gaps. These two types are not distinguished in the plots that follow; the rationale is firstly that both types of links are interoperability links and secondly that the key messages and recommendations that were elucidated from the plots refer to the cluster of Gaps, not to the nature of the links between them. The Gaps in Figure 3 are texture-coded by interoperability levels, following the NCOIC Interoperability Framework (NCOIC 2011), as shown at bottom left in Figure 3.

For the benefit of readers it should be noted that the on-line version of this paper has colour-coded diagrams, as do the resources listed in the Appendix.

Affixed to each of the gap nodes is a short title to define the Gap and an ordinal number to identify it. Firstly, it will be noted that Gap 5 is missing; at a late stage in the analysis it was merged with Gap 4 due to overlapping definitions. The ordinal numbering goes up to 76, for 75 Gaps. Secondly, it would be unwise to rely completely on the short name to understand the Gap; it would be better to refer to its long definition in the source spreadsheet, accessible via the Appendix. The size of the node is a measure of the number of directed edges associated with the node.

Self-evidently, this figure is hard to interpret, though there is structure within it. Nevertheless, it is possible visually to develop some inferences from Figure 3. Firstly the dense network of links between the Gaps, allied with the intermingling of Gaps from different levels of interoperability implies that future research programmes should not focus on individual Gaps. Instead, a more general set of objectives for each individual research area within the programme is likely to achieve better outcomes. Secondly, perhaps less obviously, this dense network has many feedback loops within it. Figure 4 below is an example of this. Since research and innovation starts with known, current facts but with little knowledge of future facts, these feedback loops imply surprises, sometimes nasty, and often more awkward the later that the surprises are discovered, when project resources have been depleted. This in turn implies that future individual research areas should encompass obvious feedback loops linking sets of Gaps. This observation supports the argument above. Finally even when looking at the Gaps at lower levels of interoperability, where one might expect the Gaps to be purely technical with little attention required to societal issues, there are often links to higher-level, more strategic Gaps, implying that most individual research areas should be multi-disciplinary, beyond the observed, perhaps orthodox bounds of engineering.

Figure 4 provides examples of feedback loops; in this case, between networking Gaps (dark-grey nodes plus light-grey node all reciprocally interconnected). There are many of these loops scattered through the full network; reciprocals, triangles and more complex loops. They imply that research programmes should embrace these loops, rather than focus on individual Gaps. A warning is repeated at this point; the Gaps in this figure have been given short names, in place of much longer definitions to be found in the source spreadsheet. Misinterpretation of the short names is possible. Furthermore, most of the Gaps are individually complex, encompassing a wide range of different disciplines within the boundary of the Gap, and frequently falling into the class of 'Wicked Problems' [34, 6, 35] when seeking the knowledge to close the Gaps.

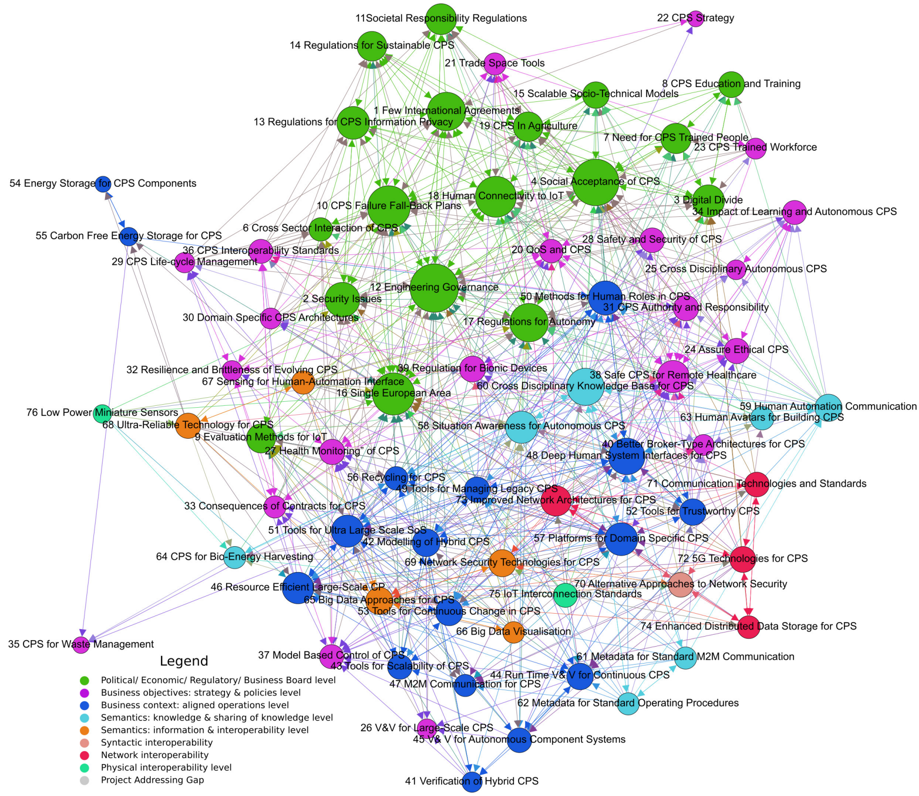

FIGURE 3 A Gephi plot for all the Gaps, projects and links. The on-line version of this paper is colour-coded and represents an interoperability scale, derived from [33]; the levels are given in the legend.It is recommended that the reader refers to the on-line version which makes use of colour coding.

3.1 | Examples Of Filtered Nodes

Five examples of filtering figure 3 are included below to aid the reader. Each one covers an aspect of importance for the future. Collectively, these five examples provide a good example of the breadth of technologies required for safe, effective, efficient CPS:

Gap 4 *Societal acceptance:* Need for concerted, integrated, co-ordinated efforts by governments and other agencies to bring about cultural, social & educational change to encourage wide adoption of CPS.

Gap 10 *Fall-back plans:* Assurance & adequacy of fall-back plans for major CPS in anticipation of failures (e.g. energy grids, other essential infrastructure networks)

Gap 27 *Health monitoring of CPS:* Theories, tools, architectures and devices for continuous 'health monitoring' of the fitness of operational CPS

Gap 31 *CPS authority & responsibility:* Theory and tools to explore architectures for the allocation of human authority and responsibility for CPS operations and behaviours, including legal and liability aspects, resilience and agility, etc.

Gap 57 *Platforms for domain-specific CPS:* Development of platforms and demonstrators for all domains (manufacturing, health care, etc.) to provide infrastructure and tools to enable swift construction and operation of CPS, and to show

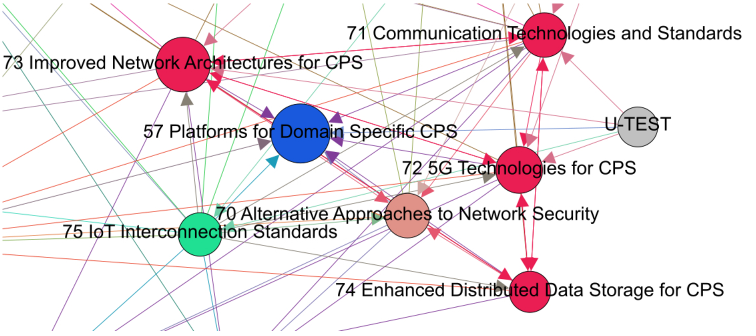

FIGURE 4 Example of feedback loops; in this case, between networking Gaps (red nodes plus pink node all reciprocally interconnected).

benefits and approaches of CPS

3.1.1 | Gap 4: Societal Acceptance

Figure 5 below shows the Gaps closely-connected to Gap 4: Social acceptance of CPS. It also shows those projects (light-grey nodes) clearly identified as direct contributors to closing the Gap.

Messages from Figure 5

- Social acceptance of CPS is an important goal for any government and for the communities and individuals who will find CPS technology essential to everyday life in the for the accomplishment of goals. In the same way that people do not expect to have daily battles with their washing machines or automobiles, they will expect CPS to work, and to have minimum fuss in achieving their individual goals. As with automobiles, CPS will be used for a multitude of purposes, some unexpected by their implementers, but all expected to be accomplished with little effort. There will be expectations of transparency, ethical behaviour (safety, privacy, etc.) in delivering the purpose(s), and failure-free performance. Furthermore, different communities will have different cultural norms; recognition of these is important for acceptance.
- It is for these reasons above that Figure 5 is complex. There is a wide range of complementary strategic Gaps that should be addressed to bring about acceptance by the public, each of which will have its own network of neighbouring technology Gaps. Combined, these strategic Gaps indicate the scope of effort required for good acceptance of CPS.
- There is a set of more directly-contributing Gaps for social acceptance, together with some of the 72 CPS projects that have generated (or are generating) appropriate technology to help close the Gaps.
- As a specific point, Gap 10, 'Fall-back plans' appears as a contributor to social acceptance. The implication of this is that in the event of a failure, the smooth adoption of an effective and efficient fall-back plan will not derogate from the public's level of trust.

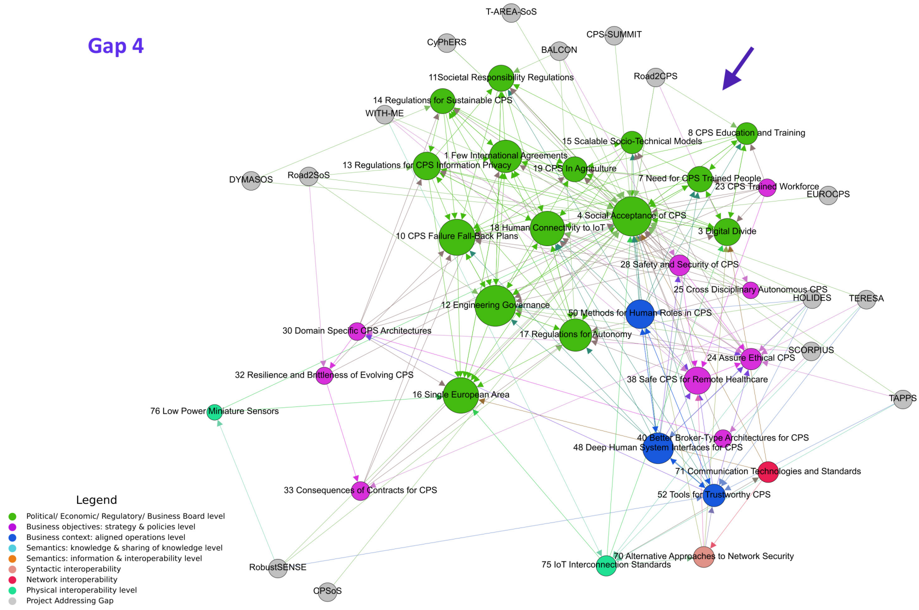

FIGURE 5 Filtered version of Figure 3 with Gap 4 (right of centre point) as the focus of this plot, and showing its local interconnected neighbours.

3.1.2 | Gap 10: CPS Fall-Back Plans

Messages from Figure 6

- Illustrating the point above for Gap 4 in Figure 5, Gap 10 which is a single node in Figure 5, has its own network of neighbouring Gaps in Figure 6 that contribute to it. There is overlap with Gap 4 which is expected as social acceptance and trust depends on resilience and speedy recovery of systems.
- There is also a considerable overlap of nodes in this network with the nodes in the network in Figure 7 below; however, there are differences in the links between them. This indicates transfers of different kinds of knowledge in different directions between the same Gaps, and that some of this knowledge may have accrued from other Gaps.
- It is instructive that a majority of the links involving Gap 10 are inwards, and that many of them originate from other strategic Gaps. The implication is that fall-back plans are not just exercises in technological resilience and recovery for CPS; they will need to take account of other societal and community-level issues as well.
- A wide range of technological Gaps are directly linked to this Gap; this is not surprising, but it is useful to have technology labels for the Gaps within the range.
- It is noted that only one project contributes directly to closing this Gap. One might expect that most of the ARTEMIS and ECSEL projects would have an interest in this Gap (MANTIS), but it may be that Deliverables that discuss this have not yet become available from the projects. It is acknowledged, however, that for critical infrastructures and industries there are significant efforts already being made elsewhere to address this Gap.

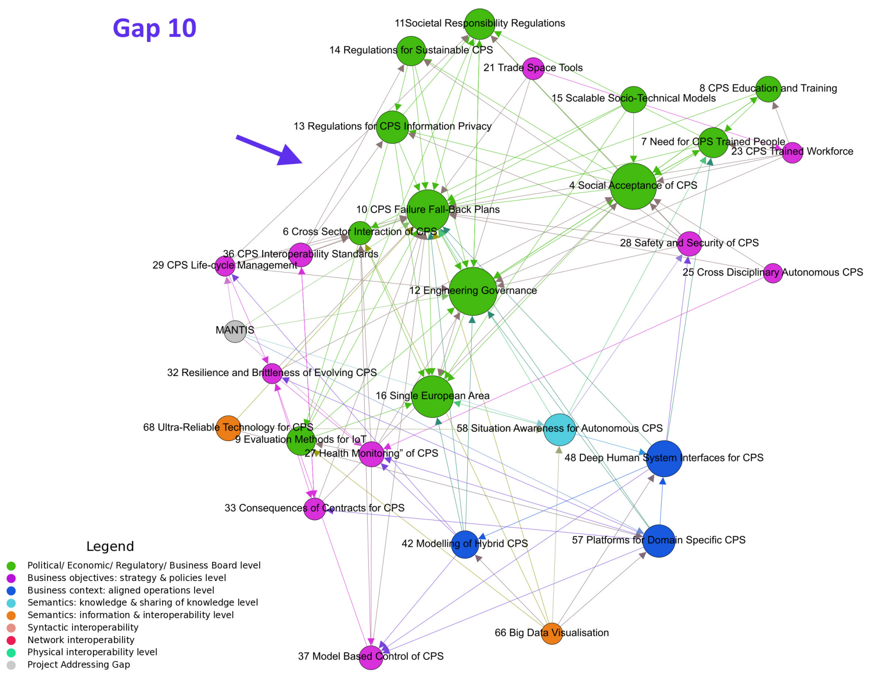

FIGURE 6 Filtered version of Figure 1 with Gap 10 (above centre point) as the focus of this plot, showing its local interconnected neighbours.

3.1.3 | Gap 27: Health Monitoring Of CPS

Messages from Figure 7

- The role of this Gap is to fulfil the feedback role implied by the third question of the Management Triad: 'Are we doing the right things?', 'Are we doing those things right?', and 'How do we know this?'. This function, the ability to assess the performance and integrity of a CPS, is of great importance in successfully closing the seven strategic Gaps shown in Figure 7 (large nodes) and there is an outward link to each one of these in the figure.
- Links to this Gap from the non-strategic nodes indicate a strong reliance on models and real-time evaluation. Unfortunately, as many other road-mapping projects around the world have also indicated, there are insufficient contributions of knowledge belonging to these two topics. Both of these are difficult research areas, requiring injections of resources to close the Gaps, and it would be of some benefit to all to address these more forcefully.
- It is noticeable that the projects with a direct connection to this network of Gaps are all from the implementation-oriented ARTEMIS and ECSEL projects, with no detected direct contribution from H2020 projects. While this is understandable, it indicates a need for some basic research in what is a difficult area.

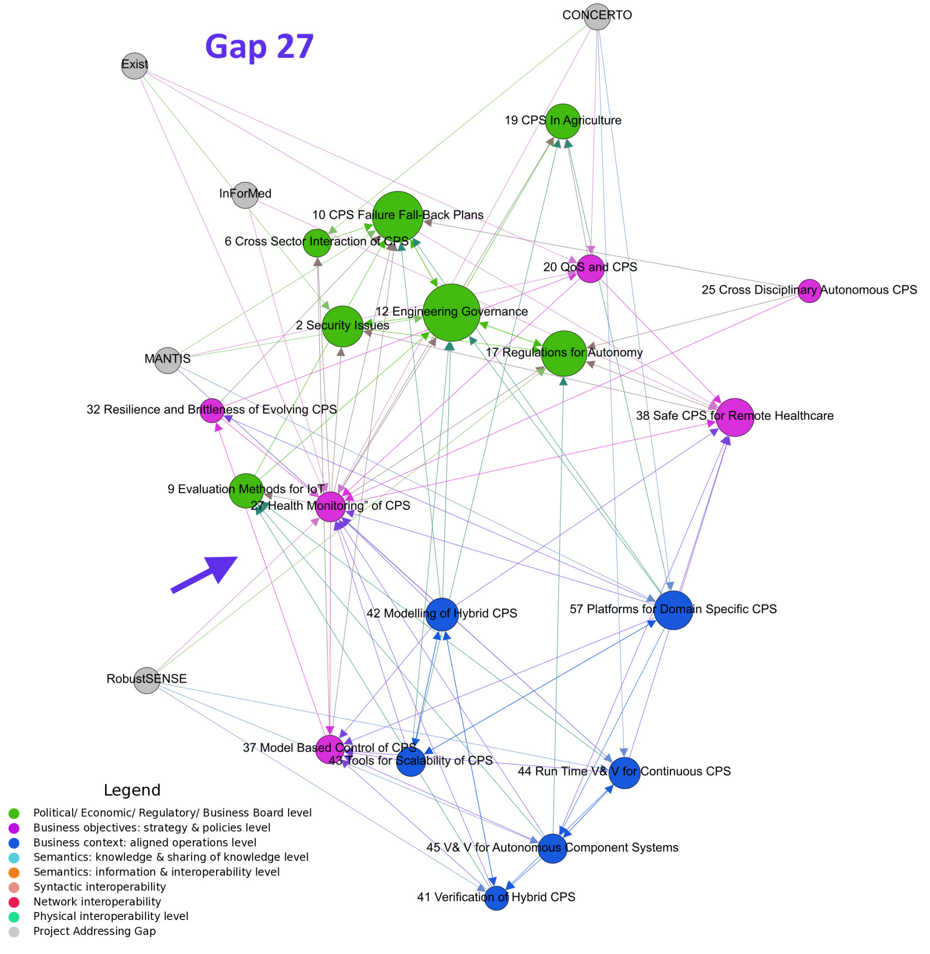

FIGURE 7 Filtered version of Figure 3 with Gap 27 (left of centre point) as the focus of this plot, showing its local interconnected neighbours.

3.1.4 | Gap 31: CPS Authority And Responsibility

Messages from Figure 8

- Control of CPS is of fundamental importance both for industries and for the communities and individuals who interact with these systems. It is therefore a little surprising that there appears to be only one project, HoLiDes, in the ARTEMIS programme that is exploring this Gap, particularly when one considers that (a) the physical configuration of the CPS may be determined only at run-time and may change at any point thereafter [28]; (b) autonomous decision-making components may be included in the CPS but humans will still be responsible for the decisions, and (c) the nature of inter-operation between the CPS and its components with human co-workers will undergo significant change over time [28, 36, 7]. It becomes considerably more problematic when autonomous components have the ability to learn and change their behaviour [37].
- Under current legal conventions, it is humans who will have authority over, and be held responsible for, the

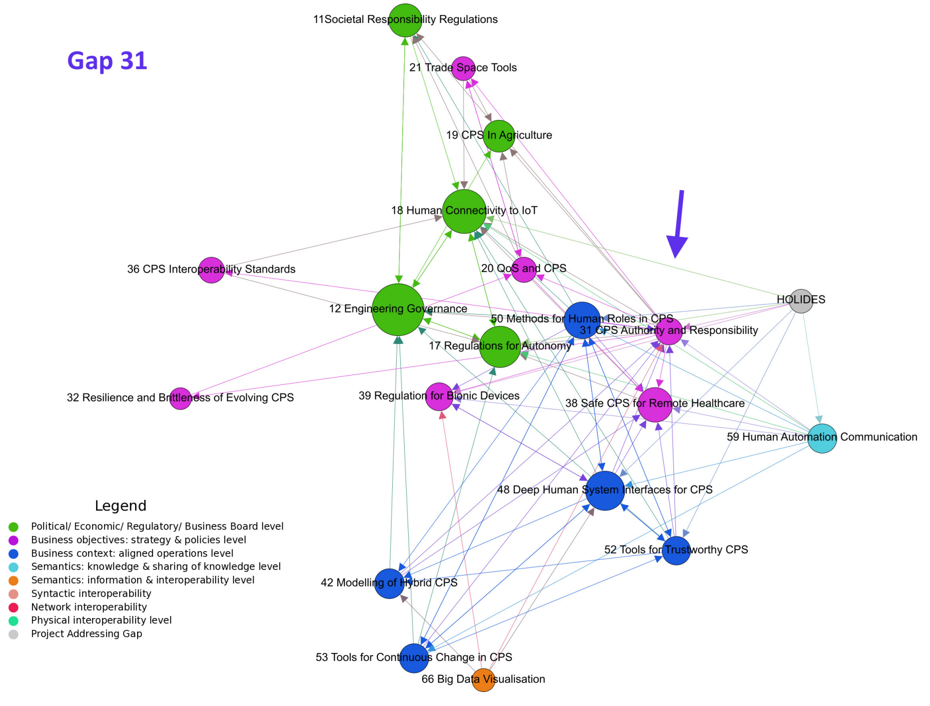

FIGURE 8 Filtered version of Figure 3 with Gap 31 (right of centre point) as the focus of this plot and showing its local interconnected neighbours.

operations and behaviours of CPS. For humans to be able to exercise this authority and responsibility, and to accept liability if necessary, they must be educated, trained, and be able to work on interfaces that provide suitable sensing and analytic facilities to gain situation awareness and to have access to decision support tools including modelling and simulation tools, communication facilities and command and control capabilities in order that they may exercise Informed Command and Informed Consent in their roles as responsible and liable system agents. For example: "One of the hard lessons of my 35 years of experience with Patriot [missile system] is that an automated system in the hands of an inadequately trained crew is a *de facto* fully-automated system." [38]. Because of the changes to tasks and jobs that the CPS environment and its technologies will entrain, current interfaces are likely to be insufficient. This represents a critical Gap in CPS technology.

- Furthermore, when members of the general public interact with a CPS, they are given delegated control to do so, through a dedicated interface. The more capable the CPS, and the more complicated the purpose of the customer, the more flexible the interface must be. This, too, represents a Gap, particularly when it is understood that most lay customers are not interested in how the CPS works; the lay customer just wants the CPS to deliver its results with minimum fuss and time demands and with neither complications nor errors. The realisation of such interfaces is currently under-developed, particularly when one considers the needs of the disadvantaged, the disabled, the vulnerable and the less technologically aware.
- Most CPS in their final operational configuration will be held together by a whole series of contracts of various kinds between carriers, devices, processes, organisations and support services. These may be of very short to very long duration, 'incomplete' [39] and repetitive. Four key aspects of contracts are promise, performance, payment

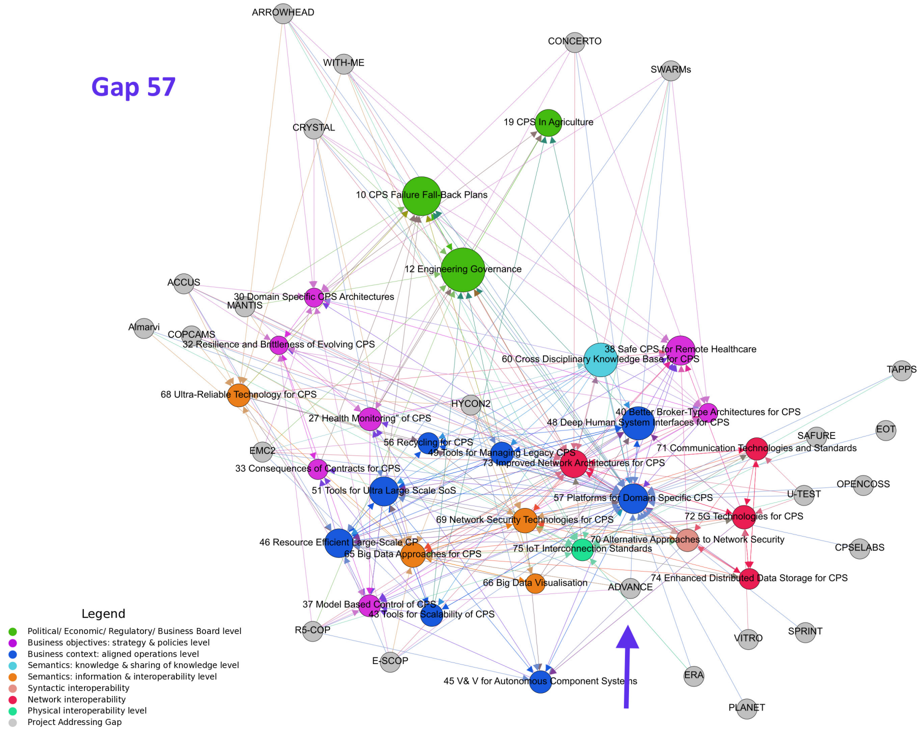

FIGURE 9 Filtered version of Figure 3 with Gap 57 (right of centre point) as the focus of this plot, showing its local interconnected neighbours.

and trust. Clearly, in a CPS world, current approaches to contracts are infeasible, and this appears to be a lacuna within this Gap. It may be that block-chain technology offers a means to combine the four aspects above that is convenient for its non-centralised, trusted-ledger qualities [40, 41, 42]. It was not evident in any of the snippets, etc. that this aspect is being fully explored.

3.1.5 | Gap 57: Platforms For Domain-Specific CPS

Because 'platform' has many different interpretations in different contexts, the viewpoint taken in this paper is that a platform is a composition of hardware and software, operated in part and where appropriate by human agents, that forms a range of strategic, technical and operational goals. It will be recalled that the acatech definition earlier does include HMI interfaces, through which their essential contributions can be made.

Messages from Figure 9

- This plot reflects the importance attached to platforms in the world of CPS, as evidenced by the 12 H2020 projects and the 12 ARTEMIS/ECSEL projects involved in this topic. Given the importance of platforms across the strategic Gaps (Gaps 1 to 18), it is perhaps unfortunate that none of the 24 projects has focussed efforts on addressing the strategic Gaps.
- The wide range of Gaps identified in this plot together with the high degree of linkage among the Gaps indicates

the sophistication and complexity of this Gap. This nexus of Gaps indicates that large projects are necessary to deliver substantial progress. While there is scope for smaller projects with a focus on an identifiable generic issue, such projects should attend closely to the requirements that emerge from the larger projects in order that the contribution of the smaller projects is properly usable.

- The amplitude of links indicates a strong role for standards, semantics and ontologies; this might be one of the important side-benefits of the work in generating platforms.

4 | RECOMMENDATIONS

The recommendations described in this section were derived from a range of sources: the 75 Gap analyses, including the examples in the section above; the database of project snippets collected from the Deliverables that were available from the 72 projects listed in Table 1 that are available in the Vulture database; the findings from other parts of the Road2CPS project more concerned with industrial aspects that are relevant to technology; and other snippets collected from other widely-respected reports and publications within the field of CPS. The full set of recommendations, including those from other parts of the project, can be found in Deliverable 4.1 available on the project website.[1]

In this paper we provide below an abridged set of these recommendations clustered under seven convenient headings. However, it was felt worthwhile to make some general comments to aid the reader to set the recommendations in context.

A quiet contemplation of the knowledge map in Figure 3 indicates that there is a shortage of professional people in the world of CPS in all flavours of engineering, especially electronics, hardware, IT and systems engineering that are able to bring to fruition good services for the peoples and communities of our world. But it is not just engineers that are needed; because CPS will pervade society very deeply, there is a need for other classes of professionals as well to ensure both acceptability and acceptance of life-supporting CPS, including those from the social sciences, who, perforce, must be knowledgeable in the increasing offerings of the CPS technical domains.

Many of the sections above allude to the need for more standards, particularly in connection with ontologies, to enable CPS to interoperate to form Cyber Physical Systems of Systems (CPSoS) and to encompass the complexities of daily life in human society. These ontologies should ensure coverage across all interoperability layers, from physical interconnection up to strategy and business. Absent these, especially those dealing with security, and we may expect operational failures of steadily greater significance as the failures occur up the interoperability hierarchy.

The capability to carry out comprehensive modelling and simulation is a *sine qua non* for the lifecycles of CPS, both in development and in operations. There is a dearth of tools, architectures, languages, aggregated modelling techniques and capable people to carry out this work. A fundamental barrier in this area that is being addressed but not yet overcome is that the IT industry has worked with discrete time, whereas other engineers have worked with continuous time.

A particular area of concern for the future is the explosion of data that will be created continuously as CPS and their associated networks of sensors are instantiated in society. This flood may come to threaten the provision of communications, computing and storage capacity to utilise the data to create knowledge and value. This problem exists from the network technologies upwards to people who query the data and interpret the resulting visualisations. It seems evident that close-to-sensor computing capability will be required, as addressed by 'fog' computing architectures.

Taking all these issues together, it seems evident that the near future, we may expect not just disruption to the external environment of business models, consumer habits, established procedures, and legal concepts; there will also

[1] `http://road2cps.eu/events/wp-content/uploads/2017/03/Road2CPS_644164_D4_1_Recommendations.pdf`

be disruptions within the CPS that in theory will deliver a bright new world. With all the simultaneous development that will be happening in so many complementary areas, we may expect “failures to be the norm in CPS” [36]. It seems evident that resilience will become a much-sought-after technical and social capability within society in the near future.

It is also noticeable that where a Gap involves political or societal aspects, there is a much greater inclusion of other top-level strategic Gaps than for Gaps that focus mainly on technology. This is not surprising, but the message of this is that governments might be reducing the effectiveness of their disbursement of funds and resources if they do not take greater account of societal issues in their planning of research and innovation programmes. Because of its intended pervasiveness throughout societies, CPS technologies cannot be separated from society if they are to work well and achieve acceptance.

It is the authors’ belief that we are not ready for the future world of Big Data. We have made great progress in sensors, and in adaptive AI systems, but the world of Smart Transport, operating in Smart Cities by utilising Smart Networks is still a distance away, partly because of societal issues, but also because we do not have sufficiently good techniques to assure high quality decisions based on accurate information distilled from floods of data. The issues range across all the levels of interoperability, from low layers, dealing with the ‘7Cs’ of data (clipping, classification, co-ordination, condensation, confusion, confounding and non-cancellation) through issues of semantics and on to strategy levels (trust, conflicting analyses, poor prognostics, etc.). The sheer volume of data reaching those responsible for decisions is such that AI, modelling and simulations will have important roles in situation awareness.

In addition we are not prepared for the levels of autonomy in devices that would be necessary to achieve the full benefits of the CPS approach, including the expected needs for hand-overs between humans and AI-based devices, especially as the latter gain more capability and competence. Already, there are issues of legislation [43], ethics [44][45] and ‘personhood’ [46] that require attention; these may be compounded when, for example, we reach the stage where AI-based devices can learn from each other without human involvement or oversight. At this point, such systems may distance themselves from what their designers and authority-holders intended. While such issues may be a long way ahead, currently there are very high levels of investment in autonomy, and it is time now that the more complex aspects receive attention, before the issues become acute.

Finally while acknowledging its caveats and assumptions, the existence of Figure 3 as a CPS ‘knowledge map’ has relevance for all the recommendations. Firstly, it provides a guide for research and implementation proposals to help ensure that their goals cover an appropriate range of knowledge topics, including their internal and external interfaces; for funding bodies, whether government or private it provides a guide to assessment of the intellectual worth and likely value of proposals, and for those institutions that issue Calls or Invitations to Tender, etc., it provides to opportunity to ensure efficient coverage in Calls and hence improves the likelihood of a good return on investment of funds.

A. Recommendations about CPS technologies directed towards governments

- Combining all the sources above, it is evident that CPS networks have no geographic boundaries regarding security, privacy, liability, efficiency and effectiveness. There is a strong need for standards, codes of practice, and international agreements to deliver the implied benefits that should arise from closing these gaps, at the same time avoiding their negative possibilities. In particular, agreements on cyber-security, allowable classes of interoperability and on legal and liability issues should be priorities.
- The opaque characteristic of systems of systems that will serve the needs of large communities indicate that many, perhaps most, of the users and operators of these systems will be bewildered, confused and antagonistic when interacting with these systems because they will have no useful mental model of the system nor of the interface protocols. This is an issue for all governments.
- Being able to take a synoptic perspective on all the Gaps and their messages provides an insight that might not be

immediately apparent. If any Gap that is targeted in the Figure 3 is to be properly closed, the implication is that each of the directly-related Gaps in the plot (and perhaps others not directly related to the target Gap) needs to be closed as well, either partially or fully, for the targeted Gap's benefits to be fully realised. In the real world of decision-making this may not be possible; however, it does indicate the need for careful thought about grouping related Gaps before formalising a research area in a research programme and allocating resources to that research topic. A convenient mantra for planners of future R&I plans is: 'No research area stands alone' (a clumsy version is: 'All research areas must be vertical and horizontal)

- It is noticeable that where a Gap involves political or societal aspects, there is a much greater inclusion of other top-level strategic Gaps than for Gaps that focus mainly on technology. This is not surprising, but the message of this is that the governments might be reducing the effectiveness of their disbursement of funds and resources if they do not take greater account of societal issues in their planning of research programmes. Because of its intended pervasiveness throughout societies, CPS technologies cannot be separated from society if they are to work well and achieve acceptance. In particular, following Lessig's comment, "Code is Law" [47], the inclusion of legal and ethical requirements in CPS projects must become mandatory. Fortunately, we are already heading in this direction through initiatives such as 'Responsible Research and Innovation' [48, 12, 49].
- Many of the plots have links between Gaps that are essentially technological and Gaps that are much more concerned with human involvement. The implied interfaces indicate that closing a technological gap should always include consideration of these interfaces and their socio-technical aspects. The pervasion of CPS technology into the everyday life of people is likely to require this, not just for the co-workers within the CPS. It is already recognised that large-scale CPS and CPSoS will operate in fault mode for much of the time [50, 36]. Of course, the converse is also true: projects dealing mainly with organisational, human and social issues cannot ignore the technological context within which these issues may sit, and on which they may depend.
- For many of the Gaps, both the plot and the comments may seem well-known and obvious; nevertheless, these plots show a scope and a depth that may be of benefit to research planners and implementers in ensuring sufficient coverage of a Gap to deliver a good solution.
- The full set of plots in the Gap analysis has shown that there are many overlaps among the plots, indicating the connected nature of research and innovation for CPS in achieving strategic goals. An implication of this is that there is a need for research programmes to adopt a 'mega-project' approach, characterised by an umbrella project that provides strategy and support to a number of smaller, more focussed projects, with an emphasis on complementarity, interoperability and temporal co-ordination among the smaller projects to address the implied feed-back loops. There is an associated requirement for co-ordination and orchestration in closing these various strategic gaps. Given the complexity of achieving this before eternity arrives, it is suggested that the planners of research programmes should adopt an approach based on a 'wicked problems' perspective. For a discussion of wicked problems, see for example [51, 4, 52, 6, 35, 53].

B. Recommendations for platforms, architectures, interoperability and standards

- Increase the reliability of CPS systems – this opens the door to the certification of secure systems, the creation of validation methodologies and the impact of these activities into the different standardisation bodies. Figures 3 to 9 above provide exemplars of the range of Gaps that must be addressed to accomplish this.
- Develop implementations of full CPS systems in different domains – currently there are very good solutions for individual parts of systems like smart grids, but there is a lack of full deployments allowing the validation of whole CPS ecosystems.
- Sustain the evolution of reference architectures and platforms - currently, much research and innovation has been

carried out regarding interoperability; the focus for the near future should be to consolidate and integrate platforms and frameworks with respect to data semantics and to promote their access to a wide audience of companies and communities

- To promote this current synergy in the long run, there is a need to integrate reference architectures and platforms into the educational curricula of engineers and technicians, and to encourage a change of mind-set in traditional slow-paced industries towards more agility which one assigns generally to the digital industries.
- Improvements and additions to the body of standards are required, especially for security; there is a compelling requirement for standards for every Gap.

C. Recommendations for modelling and simulation

- All 72 projects accessed in Road2CPS employed and/or emphasised the importance of modelling and simulation for the design and operations of CPS. As an example, it has been said that for many CPS the physical configuration may not be fully determined until run-time [28]. Consequently, the necessary processes of verification and validation for safety, etc. must rely on modelling and simulation, plus established trust in the individual components of the CPS. However, taking into account the recommendations above and the need for societal acceptance, there is a clear requirement for modelling and simulation tools, methods and approaches to embrace a socio-technical perspective, to ensure that the needs, fears, and support that individuals (lay people, co-workers within CPS, etc.) and of communities are addressed. As we all move into an urban-focussed world where daily life is mediated and supported by CPS-based services, modelling and simulation approaches based solely on a technological perspective will be inadequate.
- Academia-industry collaborations should produce tool support for heterogeneous modelling techniques, including model management and traceability support, including as well the ability to consider models of different levels of granularity and abstraction in appropriate relationships to each other. In the longer-term, as these techniques mature, they can be extended to support other useful types of modelling paradigms to capture, e.g., human behaviour. Figures 3 and 6 above indicate the scope of this effort.
- Also in the medium term, academic-industry collaborations can focus on combining formal verification and simulation technology, to produce system-wide simulation techniques that aid in detecting emergent behaviour and in system optimisation. In the longer-term, these can be extended to cater to systems that experience long-term evolution or short-term dynamic reconfiguration. In this effort it is important that the contract network that binds the CPS and its participating companies to the world of business is included in the modelling and simulation.

D. Recommendations for safety, security and privacy protection

- Academic-industrial collaborations should build on existing modelling techniques for fault tolerance or security aspects of dynamic or evolving systems, including the processes for achieving certification of such systems
- Encourage and support industry initiatives to extend or develop frameworks and tools that support reasoning about security at the systems level. It is acknowledged that such work is already under way and has been for some time; nevertheless, there is a pressing need for this work to extend to the world of CPS.
- Industry-academic coalitions to study and implement the role of the human operator in the CPS architecture. The state of current research is sparse and aspect-specific, and is in great need of expansion, especially to produce comprehensive models. 'Operator' here implies firstly lay people, to whom authority may be delegated to accomplish their purposes through a managed interface; secondly co-workers within a CPS ecosystem who are daily interoperators in the CPS, and thirdly CPS 'gurus', the resource of last resort in understanding CPS performance.
- Provision of education and training schemes to develop shared concepts of security between human, cyber and

physical sides, development of systems approaches, and training for engineers with different backgrounds and domains.

E. Recommendations for Big Data

- There is still a requirement to circumvent the issues of the '6Cs'in data; clipping, classification, condensation, confusion, confounding and non-cancellation. These may be found when combining heterogeneous data sources that have different owners. There may be a role here for distributed-ledger technologies to capture the provenance of data sets
- From a European perspective: decentralisation leads to disparate policies; a push is required to embrace innovation in some traditional sectors and to create stronger synergies between large companies and innovative SMEs
- From a market and business perspective, there is a lack of access to real Big Data infrastructures, and corresponding eco-systems are still in fledgling stages. Additionally, a boost in Big Data is particularly hindered by issue of data sharing and access rights, IPR and regulations. These are legal issues best addressed by the EC.
- Technical challenges are caused by insufficient interoperability, lack of common standards for data, security and confidentiality issues, intellectual property rights, 'unclean' data and time-compromised data, to name a few issues. There is a need to address these barriers to performance.
- The processing of very large flows of data may be within the capabilities of current and future computing systems, but there are responsibility and liability issues attached to these processes. Given that it is humans who hold these responsibilities, and must have situation awareness to execute these responsibilities correctly, there is an urgent need for the development of visualization technologies to enable situation awareness.
- Other factors determining the success and speedy adoption of Big Data solutions are the development of professional profiles, the readiness of users to change their behaviour within the data driven society, and the assurance of the safety and security of processes involving the use of data at all levels of the value chain.

More specific recommendations for Big Data were also included and are outlined briefly below:

- Development of Innovation spaces, cross-organisational and cross-sectorial environments that will allow the addressing of challenges in an interdisciplinary way.
- Development of policies and increased harmonisation of regulations that will support technological opportunities offered by Big Data and Real time analytics
- Promotion of new educational programs addressing the professional skills gaps that emerging technologies are creating
- Need for the development of common data ontologies that facilitate the integration of big data solutions and the replicability of the tools
- A requirement for Data Processing Architectures e.g. to reduce the cost per bit, to identify valuable data to be stored in the cloud and how edge computing modifies current approaches
- Co-alignment of Real time analytics requirements demands improvements in algorithms and processes that must be demonstrated and assessed through different use cases and in different sectors and exploiting computation capacity currently available
- Security is a major aspect to be investigated e.g. to assure the integrity of the data collected, ensuring that architecture can deal with advanced communication scenarios implementing E2E encryption and robust architectures.
- Moving data-based services and visualisations from abstract processing algorithms towards services exploiting the full potential of Big Data requires the development of visualisation techniques that help to understand potential

and value of solutions. There is a strong need to move from data floods to comprehensible information streams.

F. Recommendations for Autonomy

- Develop the theoretical underpinnings of safe, legal and ethical behaviour by autonomous agents as a cross-disciplinary, on-going study, involving disciplines such as engineering, IT, anthropology, metaphysics, human factors, the law and psychology.
- Develop 'situation awareness' technologies for CPS that contain autonomous decision-making components. This applies to both human and autonomous agents.
- Develop techniques for run-time verification and validation to ensure that autonomous CPS are safe and reliable. This applies both to system components and to the whole CPS, given that the final configuration of the CPS may not be known until run- time.
- Develop standards, protocols and APIs for autonomous agents within the CPS including their interconnections.
- Enhance modelling and simulation tools for autonomous agents both for their design and operation, and for the agents to use.

The main non-technical enabler for fast progress in autonomous operations is the generation of a regulatory environment, and business and insurance models to enable real-world testing of progress. The main barrier to progress is the lack of a well-educated, skilled, widespread workforce to carry out the necessary research, development, implementation and management that this area needs.

G. Recommendations for HMI

- Develop a platform for improved models for job design & a trade space to optimise the combination of human variability and performance, and to ensure safe, legal and ethical behaviour of CPS as individuals in society interact with them
- Develop a full understanding of how to achieve trustworthy behaviour for human-machine interaction, including the effects of cultures on trust and performance expectations and outcomes. Since trust is an earned quality of systems and people that can be destroyed in an instant, there are complex issues involved in its creation and maintenance. Trust between systems can be engineered; human trust in systems is amenable to engineering, education and experience; human-human trust is amenable to job design and task design, situation awareness, teamworking, and decision time; system's trust in humans is not well-explored yet and is likely to involve AI to a fairly large extent. Given the ever-increasing extent of safety-critical systems, partly driven by interconnections between existing systems, a full understanding of this topic is important.
- Improve interface technology for multi-channel, distributed interfaces to maximise team performance that is adaptable for different human skill levels and confidence. This may encompasses inquisitive teenagers and the like who are into how systems work; customers who just want to accomplish their goals with minimum fuss and who have no interest in how the systems deliver these goals other than security and safety; process designers, operators, etc. who have a vested interest in safe, efficient processes; and managers and others who have a strategic interest in keeping their systems adequate and effective as the environment changes around them.
- Enhance modelling & simulation tools and techniques to enable real-time verification and validation of human decisions and actions prior to execution.
- Develop standards, protocols and interface specifications to extend human interaction with advanced, autonomous CPS, allowing for different levels of human skill, knowledge and purpose
- Enhance modelling and simulation tools to make available human avatars for use in design and operations, to help

achieve the HMI goals in the bullet-points above.

The main non-technical enabler for fast progress in autonomous operations is a strong commitment to address the technology of human-machine interaction. One key barrier to progress is the lack of a well-educated, skilled, widespread workforce able to adapt to and carry out the range of roles involved in the lifecycle of a CPS from research to retirement that is needed.

5 | CONCLUSIONS

Sustainability is a fundamental concern for us all; the prospect of a 37% increase of the world's population by 2050, with each individual wanting a better life despite the world's land and mineral resources not increasing [54, 55, 56, 2], means that we have to find an alternative economic approach from the current linear model towards a circular economic model [57, 58, 59]. This model places great emphasis on efficiency and avoidance of waste in all its forms, to be achieved by the capture of floods of high quality data and the close control of processes. This applies to all sectors of society; health, transport, agriculture, manufacturing, mobility, etc. The technologies of cyber-physical systems offer the best approach to meeting these requirements, but these technologies are still under-developed, and time is pressing to improve this situation.

More by accident than original design, and apart from achieving its other objectives, the Road2CPS project has been able to generate a 'map' of the CPS technological landscape, highlighting where there are knowledge shortcomings, and the linkages between the different technologies. These are based on the findings of 72 projects in the domain of CPS across many sectors, and go beyond a pure, engineering view to take a wider, socio-technical perspective. This reflects the fact that the circular economy model will affect all parts of society, and there must be social acceptance of the large-scale changes to people's way of life. The process to generating the knowledge map can serve as a prototype for engineering knowledge curation; the capture of snippets from documents for 72 projects demonstrated that there are opportunities partially to automate the knowledge curation process, but it is also clear that despite the rapid progress of AI and machine learning, there will be a need for human intervention in the processes. The characteristics of this field of endeavour will require human involvement for the foreseeable future.

While the 72 projects were all based in the European Union, and therefore may be perceived to have an EU-centric bias, the problems and issues that still need to be resolved in the technologies of CPS have much in common with other regions of the globe. Physics does not respect boundaries, nor does software engineering. On the other hand, communities differ in their cultures, beliefs and understandings, and it may be here where the limitations of the knowledge map become evident.

Whether or not there is bias, there is room to populate the map with more layers of knowledge (abstract, empiric and observed practice) and with more classes of linkages between the layers. This may be a subsequent development in other projects; Road2CPS has come to an end. One of its legacies is the database that is open to others to explore for future benefit, which the authors encourage, to bring about the changes to society that we really need.

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APPENDIX

This Appendix is intended to help those readers who wish to explore the Deliverables and data sets generated by Road2CPS.

- The official EU website at `http://road2cps.eu` that contains all of the Deliverables of the Road2CPS project and some other resources as well, including some of the data-sets. *This is the best site for readers of project resources.*
- DOI's are provided for the full data-set. No passwords are required. *This is the best source for those who may wish to perform their own analyses of the data.*

The Official Site

The Menu-bar at the top of the Home Page has the category 'Resources'. Clicking on this reveals the public resources of the project. Under the title, 'CPS gaps in EU projects' is a downloadable file.

'Description of the contents of the Gaps folder' that describes the contents of the next file, 'CPS Gaps in EU Projects'. The latter holds all the titles of the gaps, Gephi plot for each Gap, and the spreadsheet containing information about each Gap, from which the Gephi plots were generated. These three sub-files are linked. Below these files are all the public Deliverables of the project, including the project e-Book. This provides a full introduction to the project and its achievements.

The Data-set

For practical reasons involving maintenance, this site was created for those readers who wish to perform their own explorations of the data-set. All the data is publicly published at the following locations:

`https://doi.org/10.17028/rd.lboro.5082088.v1`
`https://doi.org/10.17028/rd.lboro.5082082.v1`
`https://doi.org/10.17028/rd.lboro.5082067`

Each DOI links to a folder containing the datasets as used by the consortium, the use of which requires some care, and includes some descriptive text which should always be read first. All the files are in read-only format. Please note that while the consortium takes responsibility for the data, it does not accept any responsibilities for any further data-processing, results and conclusions that may be drawn by users of these data.

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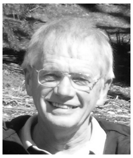

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