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EPSRC
Engineering and Physical Sciences
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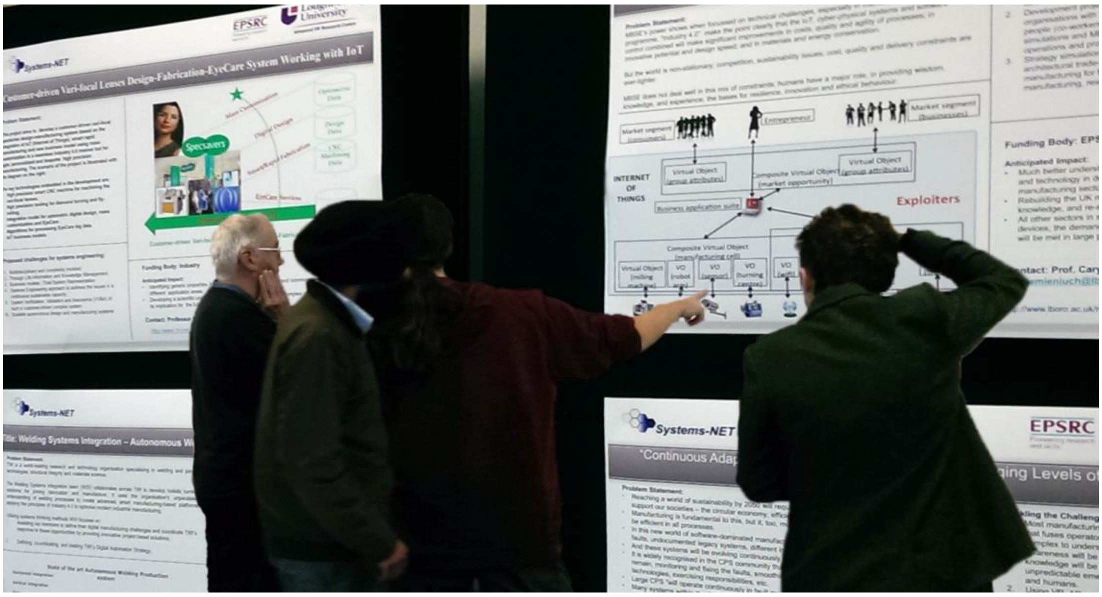
Research Top Challenges for MBSE in Industry 4.0 and IoT Workshop Report



Summary

The MBSE for Industry 4.0 and IoT workshop provided a forum to discuss some of the challenges currently being faced by the systems research community as the manufacturing industry moves into cyber physical systems and the era of smart factories. The objective of the workshop was to identify what are the key challenges in this transition to create fully representative models of systems that can cope with complexity, whilst maintaining privacy, security and safety at the same time. Systems engineering has the potential to simulate large complex systems as well as predicting their emerging properties as they evolve through time; the workshop provided an opportunity to formulate, discuss and reach a consensus amongst a group of participants from industry and academia to find out how such potential can be achieved. The resultant set of Top Challenges is presented in this report and is intended to signal the areas of MBSE where breakthroughs are required.

Contents

1. Introduction

Systems-NET is funded by EPSRC with the objective of drawing on and consolidating the strengths of major systems engineering centres and research groups across the UK to share knowledge and communicate best practice between application domains. Part of EPSRC mission is to ensure that national capability in engineering is developed and sustained through a) supporting long term and ambitious research, b) mobilizing leadership in engineering related fields and c) shaping the portfolio in relation to national need. Systems-NET was created on these bases as a network to bring together researchers and professionals in Systems Science, Systems Engineering and Systems Thinking. Systems-Net has been organising several events including workshops for the systems research community with the objective of breaking communication barriers between research groups and facilitate knowledge transfer. Given that systems research in the UK encompasses many different areas, often it is not easy to relate the systems research conducted in one discipline to another, therefore discussing the generic challenges for systems research allows the participants to contribute in a debate in search for the most inclusive understanding of where systems research should be moving forward. This has proven to be a rewarding exercise for all the participants and a step forward in bringing the systems engineering community together.

The workshop "MBSE for Industry 4.0 and IoT" is a successor of the workshop "Research grand Challenges for Systems Engineering" (http://www.lboro.ac.uk/research/systems-net/activitiesandevents/annualgrandchallengeworkshop/) organised at Loughborough University in June 2015 by Systems-NET, which gathered a list of Grand Challenges from the views of 47 systems researchers and practitioners in industry and academia. In the workshop a set of Grand Challenges was identified one of them being "Modelling the next generation MBSE for Industry 4.0 and IoT to allow scalability and add end to end value". This Grand Challenge was therefore the subject of the subsequent workshop reported here which was organised at Brunel University London in order to explore the many concerns that this challenge represents.

The workshop was hosted with the collaboration of Professor in Manufacturing Systems Kai Cheng at Brunel University whose current research interests focus on precision and micro manufacturing, design of high precision machines, smart tooling design and smart manufacturing, and it was attended by delegates from TWI, Holistem Ltd, Imperial College London, De Montfort University, Kings College London, Brunel University London and Loughborough University.

The aim of the workshop was to explore the top challenges for the application of MBSE in new smart environments. A top challenge in this context can be loosely defined as the obstacles and difficulties that need to be overcome in order to advance the capability of MBSE tools and techniques to deliver models that facilitate the management, understanding and analysis of large interconnected cyber physical systems. Their achievement can be one or two decades in advance and it is regarded as major milestone or breakthrough.

The workshop consisted of three sessions, two sessions for workshop discussions and one session for presentations. The presentations came from widely diverse areas of research and work and were intended to offer an insight into ongoing research projects as well as into the current understanding of MBSE issues. The presentations were highly valuable within the context of the workshop as the work presented served to offer well studied views from the various different research activities of the presenters. The first workshop session collected a set of challenges from all the participants which were later reviewed and discussed in a round the table exercise in the second workshop session that took place after the presentations. The intention was to enrich the topics of discussion with the presentations and also with several posters from the presentations that were also exhibited to offer more interacting opportunities.

The resulting challenges and votes are given in the following list.

2. Research Grand Challenges List

Challenge 1

Challenge Statement: **Develop platforms to support manufacturing industry and relationships to consumers/ business clients.** **Protocols for the communication and data representation to make the retrieval (of information) easier (and) to make the decision making (process) quicker.**	**Score** 10 stars
Context: To underpin CPS, SoS and provide security money transfers, etc. Due to the increased volume and complexity of data sets (involvement of heterogeneous data sets) from machines and humans Standardised protocols across different systems Standardised representation from the different datasets.	
Potential Impact: Help UK/EPSRC develop the digital economy and make it convenient to consumers. Improve the data retrieval and analytical process to support informed decision making. Avoid information conflict and different (interpretation of) systems views.	
Perceived Difficulty: Very complex will need collaboration beyond engineering; regulations trust, etc. Development of communication protocols and standard data structures will require understanding of requirement specifications from whole supply chain level.	

Challenge 2

Challenge Statement: **Changing educational establishment to produce a workforce for the digital economy.** **CPS and SoS and consumers need new classes of skills.**	**Score** 8 stars
Context:	

Complex CPS, SoS will be in fast evolution and will have many problems due to latent software faults, insufficient V & V, and incorporation of legacy systems.	
Potential Impact: Huge. CPS and SoS need these to operate efficiently.	
Perceived Difficulty: Complex, requiring change to institutions and cultures. Sociotechnical challenge.	

Challenge 3

Challenge Statement: **Future Systems Engineering environments that support** • **Evolutionary development** • **Merging of developments and operations** • **Handling of complexity to support engineers** • **Analysis and predictability of system's properties**	**Score** 7 stars
Context: • Large scale customisation • Systems of Systems • Development and extension of existing operational systems • Increasing complexity	

Challenge 4

Challenge Statement: **Real time model update of designed product during development/manufacturing.** **A verification and control management system that can check the product conformity to designed virtual model even through operational life; the model will be (able to be) updated for maintenance or servicing purposes.**	**Score** 6 stars
Context: High value manufacturing carries a potential risk of mismatch between specifications and product manufacturing. Even in the operational life the product may need servicing or update which (can be) monitored by relating and comparing the product (model) to developed product.	
Potential Impact: Preventing maintenance Project goes well planned	
Perceived Difficulty: Amount of sensors or monitoring resources (needed) during manufacturing & operation. Modelling system for model update Control system to detect potential misalignment (problems) and advising a solution.	

Challenge 5

Challenge Statement:	**Score**

How to integrate different models/ views of different parts of a system /different stake holders into an overall system which is consistent and has the ability to reflect changes of one view in other views.	5 stars
Context: Assembly lines are built from (component) machines from different providers and consume materials and products from a range of different sources to produce a range of products. All these constituents are produced specified (modelled) and configured independently and using different terminology, but need to be integrated.	
Potential Impact: Addressing this challenge is fundamental to MBSE and Industry 4.0 as it is fundamental to achieving control of the inherent complexity.	
Perceived Difficulty: High. The challenge is twofold: 1. Developing a system for managing viewpoints and their interactions - medium difficulty: this is being worked on in Model-Driven Software Engineering 2. Identifying the most suitable views and their specific interactions	

Challenge 6

Challenge Statement: **Achieving fidelity between models of anything in the real world and the real world.** **Data analysis** **Model fidelity** **Over engineered systems** **Real-time systems**	**Score** 4 star
Context: 1. Accuracy of measurement 2. Timing issues plus delays	
Potential Impact: Wrong decisions due to discrepancy of model V.S. reality.	

Challenge 7

Challenge Statement: **Building up standard framework for eliciting requirements, extracting information under the regulatory constraints.** **Building standard interfaces to liaise requirements between diverse stakeholders.**	Score 3 stars
Context: Eliciting requirements is most vital part of product development. In automatic development environment where a central artificial system uses initial input to arrange for process building and resource management,	

human users will require to follow a common framework which needs to be adaptable to user preferences and therefore provide room for potential changes/specifications.	
Potential Impact: - Disambiguation in communication - Concise requirements specification derivation - Clear relationships between requirements - No down the line hold ups due to potential risks - Effective change management	
Perceived Difficulty: • Ambiguity in natural languages (multiple interpretations) • Flexibility in framework • Integration of present external constraints (safety standards etc.)	

Challenge 8

Challenge Statement: **Establishing sound large-scale models of the interaction between properties of machines and assembly lines and properties of the resulting products.**	**Score** 1 star
Context: In order to make adaptation (or design) decisions about assembly lines, we need a predictive (model) capable of predicting the effect of different alternatives on product quality. Presently, the only way of testing new designs is through models for dedicated, small-scale experimentation. It is unclear if these will scale to real production environments.	
Potential Impact: Having these predictive models will enable quality-led design and adaptation decisions.	
Perceived Difficulty: High	

Challenge 9

Challenge Statement: **Flexibility in automation**	
Context: Humans have cognitive abilities – automation does not.	
-Potential Impact No flexibility for part variation- failed processes/parts	
Perceived Difficulty Sensing Communication Stakeholder mapping/ cross boundary/ skill set working / learning	

3. Results

A total of 44 votes were casted. Statistical analysis of the results is illustrated in Figure 1 and Figure 2.

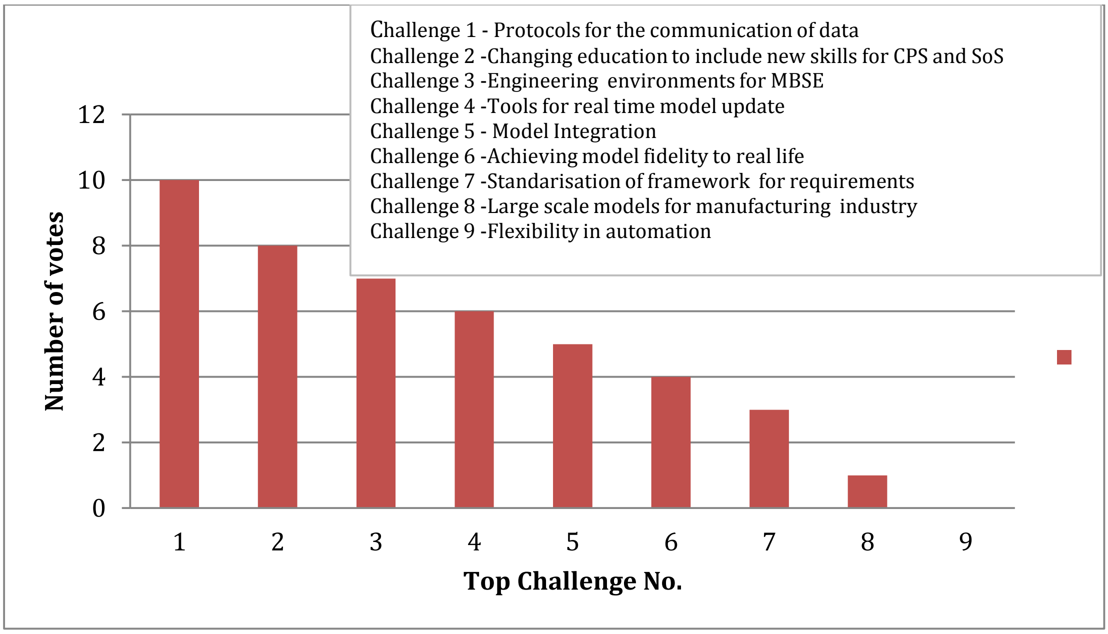


Figure 1. Top Challenges Consensus Chart showing the number of votes for each challenge

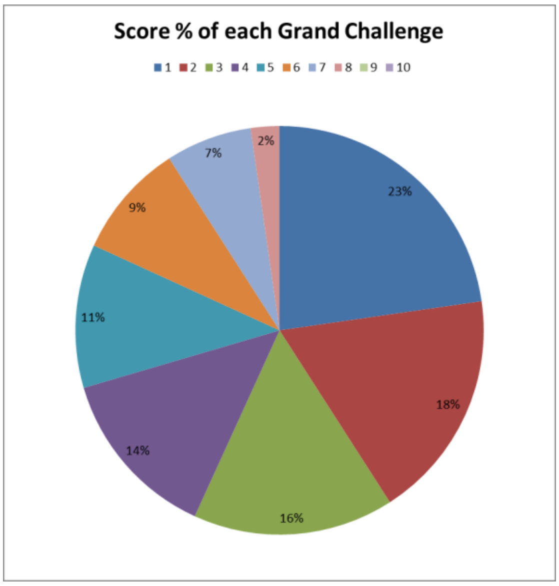


Figure 2. Vote Percentages for each challenge

The above figures are indicative of the participant's consensus over the importance of the challenges that were drafted in the first workshop session. Accordingly the Top Challenge "Protocols for the communication of data" was considered to be the most important by the majority of the participants. The following three challenges "Changing education to include new skills for CPS and SoS", "Engineering environments for MBSE", "Tools for real time model update " also point to areas the majority of participants thought to be very relevant. These four top challenges are discussed in the following session.

4. Discussion

As modern manufacturing products and processes rely more on the electronic and digital technology there is an increasing demand for MBSE tools that help understand the interconnections between the elements of systems, and represent all the components, stakeholders, their relationships and emergent properties. MBSE has the potential to represent the development of complex systems through special tools and languages, and this is of particular relevance when such systems bring different disciplines together such as digital and manufacturing technologies in Industry 4.0 and IoT. The term Industry 4.0 was derived from a project of the German government and refers to a new revolution in the advances of technology, the other revolutions being: 1^{st}- revolution triggered by the development of machines powered by steam, 2^{nd} -revolution prompted by the discovery and expansive use of electric energy at the beginning of the 20th century, 3^{rd}- industrial revolution brought about by automation of processes and IT, and the new 4^{th} industrial revolution, characterized by ability of parts to communicate with each other as they carry the information of their purpose to the manufacturing machines and give pace to smart factories. The Internet of Things (IoT) is somehow a wider concept that refers not only to the manufacturing industry but in general to the networking capabilities of devices with embedded computing sensors than can communicate with each other delivering real-time responses. This workshop aimed to exploring the systems engineering challenges that exist for MBSE to move into the new era.

The identified Top Challenges in this report point to several particular areas where breakthroughs are required, and can serve as a research agenda to lead MBSE into the new era of industry 4.0 and IoT. The top challenge "Protocols for the communication and data representation to make the retrieval of information easier and to make the decision making process faster" requires standardisation of protocols to overcome the difficulty of translating instructions from one set of technology to another, added to this there is a problem of big data as the volume of data sets from machines and humans can be overwhelmingly large and analysing them to support decision making requires of improved data retrieval processes. One example is the digital economy, which requires standardised protocols across different systems to make it convenient to consumers by means of a platform that backs public trust, satisfies government policies and works with the financial sector.

The challenge "Changing education to include new skills for CPS and SoS" relates to cyber physical systems and systems of systems requiring a new set of MBSE tools and skills; as the complexity of systems increases the problems associated with their compatibility are set to multiply due to software faults, insufficient validation and verification and also the incorporation of legacy systems amongst others. Over the several next decades a skilled workforce in MBSE will be required to deal with these complex systems and their connecting problems, therefore a large effort in education to provide MBSE knowledge and skills capable of dealing with the problems as they appear is necessary now. The risk of not doing it will be a future for which we are not prepared. However, the skills to be taught are still in process of development as MBSE is not universally established and even systems theory is understood differently by different research groups.

The third challenge "Future Systems Engineering environments that support evolutionary development, merging of systems, handling complexity, and analysis of systems properties" is closely related to the two first challenges in the context of the protocols needed for both: large scale customisation of complex systems and the development of existing operational systems. In relation to the required systems engineering professionals, it is clear that future systems environments will necessitate a prepared workforce whose existence depends on the education at the present time as in the above challenge.

The fourth top challenge "Tools for real time model update" directly points to the need of verification and control management systems with the ability to check the conformity of manufactured products to virtual models at several stages, not only during manufacturing, but also during the service life of the product. Furthermore real time model update would potentially reduce the risk of mismatch between design specifications and manufactured products. Even during the service life of the product, additionally verifying its conformity against a virtual model could facilitate maintenance and updates, and this could extend the life of the product or facilitate the recyclability of many of its forming parts and components. Overcoming this challenge could bring high rewards in terms of cost effectiveness and savings in the recycling of components and materials that are necessary for a sustainable future.

Although all of the challenges were enthusiastically debated by the attending participants, the remaining challenges are not discussed at this time as it is difficult to provide a full account of the actual discussion, even in a condensed version, without omitting or misrepresenting many of the important concepts. In reality the interpretation and analysis of each of the top challenges requires detailed and careful considerations that must be carried out separately from this report as it is important to revise each of them while taking into account current research and technical advancements that could help postulating breakthroughs for the issues that they represent. Nevertheless, the challenges presented in this report may serve to signal the areas of MBSE where further research is needed in order for systems research to support the transition of current manufacturing systems into the new era of Industry 4.0 and IoT.

Appendix A gives a list of the challenges drafted at the workshop by all the attending participants. Appendix B contains the Quad Chart presentations, given at the workshop. Appendix C describes the workshop process.

Note: The set of proposed Top Challenges reported here only reflect the concerns of the gathered community in this event, and we recognize that a different group of attendants could have proposed a different set of Top Challenges; nevertheless it would be expected that these will be of similar nature

Appendix A – List of all the Grand Challenges proposed in Session 1 of the Workshop

1

Modelling the next generation MBSE for Industry 4.0 and IoT to allow scalability and add end-end value

Top Challenge Statement

Real time model update of designed product during development / manufacturing. / Verification ~~artificial~~ of control management system that can check the product conformity to designed virtual model even off through operational life the model will be updated for maintenance or servicing purposes.

Context

High value manufacturing carries a potential risk of mismatch between ~~specifici~~ to specification of product manufacturing. Even in the operational life the product may need servicing or update which monitored (by relating + comparing) the product to developed product

Potential impact

- Preventive maintenance
- Project goes well planned
-

Perceived difficulty

- Amount of sensors or monitoring resources during manufacturing + operation
- Smart modelling system for model update
- Control system to ~~advice or~~ detect potential disalignment ~~between~~ + advising on solution.

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2

Modelling the next generation MBSE for Industry 4.0 and IoT to allow scalability and add end-end value

Top Challenge Statement

Establishing sound large-scale models of the interaction between properties of machines and assembly lines and properties of the resulting products.

Context

In order to make adaptation (or design) decisions about assembly lines, we need a predictive capability to predict the effect of different alternatives on product quality. Presently, the only way of establishing these models is through dedicated, small-scale experimentation. It is unclear if this will scale to real production environments.

Potential impact

Having these models will enable quality-led design and adaptation decisions.

Perceived difficulty

High.

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(3)

Modelling the next generation MBSE for Industry 4.0 and IoT to allow scalability and add end-end value

Top Challenge Statement
~~Standard Protocol for communication & understanding by all stakeholders~~
~~Skills gap~~
Flexibility in automation.

Context
Humans have cognitive abilities – automation does not.

Potential impact
No flexibility for part variation – field processes/parts

Perceived difficulty
– sensing
– communication
– stakeholder mapping / cross boundary / skill set working / learning.

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(4)

Modelling the next generation MBSE for Industry 4.0 and IoT to allow scalability and add end-end value

Top Challenge Statement
- Building up a standard framework for eliciting requirements, extracting information ~~related~~ under the regulatory ~~and~~ constraints. /
- Building standard interface to liaise requirements between diverse stakeholders.

Context
Eliciting requirements ~~is~~ is most vital part of product development. In automatic development environment where a central artificial system uses initial input to arrange for process building & resource management, human users will require to follow a ~~stan~~ common framework which needs to be adaptable to user preferences. Provide room for potential changes specification.

Potential impact
- Disambiguation in communication
- Concise requirements specification derivation.
- Clear relationships between requirements
- No down the line hold ups ~~in terms of risks~~ due to potential risks.
- Effective change management

Perceived difficulty
- Ambiguity in natural languages (~~due~~ multiple interpretations)
- Flexibility in framework
- Integration of present external constraints (safety standards etc)
-

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⑤ = 7

Modelling the next generation MBSE for Industry 4.0 and IoT to allow scalability and add end-end value

Top Challenge Statement

Protocols for the communication & Data Representation to make the retrieval easier to make the decision maker quicker.

end-to-end value? scalability? ('Look Ahead')

Context

Due to the increased volume & complexity of data sets. (Involvement of heterogeneous data sets) from machines & humans.
- standardized protocols across different ~~Mach~~ Systems.
- standardized representation for the different datasets

Potential impact

- Improve the data retrieval & Analytical process to support informed decision making.
- Avoid information conflict & different system views

Perceived difficulty

- Development of communication protocols & standard data structures will require understanding of ~~data~~ requirement specs. from whole supply chain level.

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⑥ = 11.

Modelling the next generation MBSE for Industry 4.0 and IoT to allow scalability and add end-end value

Top Challenge Statement

Data Analysis
Model Fidelity
Over Engineered systems
Real-Time Systems

Context

Potential impact

Perceived difficulty

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7 = 5

Modelling the next generation MBSE for Industry 4.0 and IoT to allow scalability and add end-end value

Top Challenge Statement
Develop platform to support manufacturing industry, and relationships to Consumers / Business clients.

Context
To underpin CPS, SoS, and provide security money transfer, etc

Potential impact
Help UK / EPSRC develop the Digital Economy, and make it convenient to consumers.

Perceived difficulty
Very complex. Will need collaboration beyond engineering; regulation, trust, etc

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8

Modelling the next generation MBSE for Industry 4.0 and IoT to allow scalability and add end-end value

Top Challenge Statement
Changing educational establishment to produce a work force for the Digital Economy and consumers
CPS and SoS need new classes of skills

Context
Complex CPS, SoS will be in fast evolution and will have many problems due to latent software faults, insufficient V&V, incorporation of legacy systems.

Potential impact
Huge. CPS and SoS need these people to operate efficiently

Perceived difficulty
Complex, requiring change to institutions and cultures. Sociotechnical challenge.

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(9)

Modelling the next generation MBSE for Industry 4.0 and IoT to allow scalability and add end-end value

Top Challenge Statement

FUTURE SYS ENG ENVIRONMENTS THAT SUPPORTS:
- EVOLUTIONARY DEVELOPMENT;
- MERGING OF DEVELOPMENTS AND OPERATIONS;
- HANDLING OF COMPLEXITY TO SUPPORT ENGINEERS
- ANALYSIS AND PREDICTABILITY OF SYSTEM PROPERTIES.

Context

- LARGE SCALE CUSTOMISATION
- SYS OF SYSTEMS
- DEVELOPMENT AND EXTENSION OF EXISTING OPERATIONAL SYSTEMS
- INCREASING COMPLEXITY.

Potential impact

Perceived difficulty

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(10)

Modelling the next generation MBSE for Industry 4.0 and IoT to allow scalability and add end-end value

Top Challenge Statement

How to integrate different models/views of different parts of the overall system and of different stakeholders into a consistent overall, with an ability to reflect changes in one view on other views

Context

Assembly lines are built from machines from different providers, consume materials and products from a range of different sources, and produce (a range of) products. All of these constituents are produced, specified (modelled) and configured independently and using different terminology, but need to be integrated.

Potential impact

Addressing this challenge is fundamental to MBSE and Industry 4.0 as it is fundamental to achieving control of the inherent complexity.

Perceived difficulty

High. The challenge is two-fold:

1. Developing a system for managing viewpoints and their interactions – medium difficulty: this is being worked on in Model-Driven Software Engineering
2. Identifying the most suitable views and their specific interactions

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(11) = 6

Modelling the next generation MBSE for Industry 4.0 and IoT to allow scalability and add end-end value

Top Challenge Statement
ACHIEVING FIDELITY BETWEEN MODELS OF ANYTHING IN THE REAL WORLD AND THE REAL WORLD.

Context
- ACCURACY OF MEASUREMENT
- TIMING ISSUES + DELAYS

Potential impact
- WRONG DECISIONS DUE TO DISCREPANCY OF MODEL VS REALITY

Perceived difficulty

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Appendix B – Quad Chart Presentations

1.- "Top Challenges for MBSE for Industry 4.0 & IoT" - Julian Johnson, Holistem Ltd

Title: Top Challenges for MBSE for Industry 4.0 and IoT Quad

Problem Statement:

Advantages in technology are driving change, and opening opportunities, at an increasing rate, think: electronics, computing, digitisation, communications, identification, sensors, actuation, robotics, AI, big data, semantic web. Applications ('systems') of IoT will arise in all sectors, in an almost fractal way; in manufacturing this opportunity is seen as Industry 4.0.

Characteristics of Industry 4.0 / IoT systems are wide ranging, some exhibiting one of more characteristics associated with 'Systems of Systems': managerial or operational independence, geographic spread, heterogenity. Such developments raise issues and opportunities, issues include: coping with complexity, identity, privacy, security, safety, prediction of emerging properties, incremental evolution.

MBSE will need to be applied to design and evolution of such systems, to make their development tractable, traceable, cost-effective, predictable, maintainable, evolvable.

Tackling the Challenges, what needs to be done?

1. Establish an ontology and associated metamodels for I4 / IoT definitions, full lifecycle perspective, linked domain models.
2. Build infrastructure and populated navigable libraries domain-neutral and domain-specific components.
3. Collate and / or develop models and analysis capabilities such that the values of system emergent properties can be determined (analytically or stochastically) for a proposed system and environment.
4. Assess IT/software engineering domain DevOps approaches, and extend for systems with approaches, techniques, tools, models.
5. Assess potential for chaotic and AI system design exploitation, and bounds of system predictability, and propose and develop associated capabilities.
6. Assessment of innovative techniques (fundamental and/or human interface) to enable engineers to cope with increasingly complex systems and their developments.

Proposed challenges for MBSE for Industry 4.0 and IoT

1. To have the breadth of formalisms and models, to embrace the rich definition of I4 / IoT systems, including organisations.
2. To have comprehensive, navigable, domain-neutral and domain-specific components / systems as libraries.
3. To have models and analysis capabilities such that the values of system emergent properties can be determined.
4. Abilities to co-host design and operational representations of systems, with incremental roll-out of evolving hybrid systems.
5. Support for analysis of predictability of designed systems, and design capabilities to exploit chaotic system design aspects.
6. Support to engineers for handling complexity.

Funding Body: Public and Private sources?

Anticipated Impact:

- Improved performance, cost-effectiveness and robustness of I4 / IoT systems.
- Accelerated development and evolutionary development of sound I4 / IoT systems vs requirements.
- Market advantage to those lead contributors and adopters to MBSE vision and capabilities.

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Julian.johnson@holistem.co.uk

holistem holistic perspectives, your systems

2015 06 25 Top Challenges for MBSE for Industry 4.0 and IoT Quad

2.- “Sustainable Loop-Infinite Manufacturing (SLIM)” - Ali Mousavi, Brunel University London

Sustainable Loop-Infinite Manufacturing (SLIM)

Problem Statement:

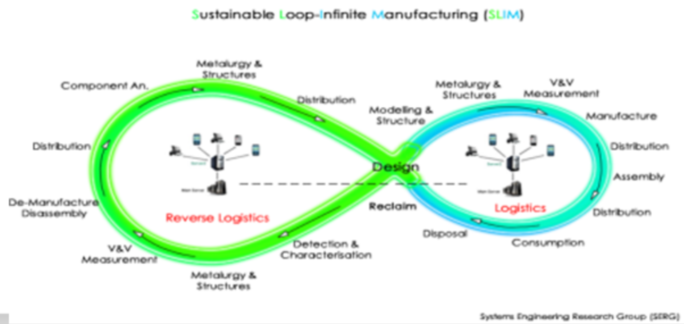
In a modern automobile plant it takes about 1000 minutes to put together a complete car. There is no accurate estimation, but based on limited postgraduate student simulation modelling projects, it may take months (best case scenario) or years to return the material extracted from disposed cars back into the manufacturing loop. The purpose of the research Hub is to create the capabilities for integrating and creating the key enabling technologies that automatically:

1. Identify, inspect and evaluate the disposed products.
2. Generate Bills of Material and their destination as (e.g. re-use, rework, salvage, transform, and detoxification).
3. Produce pathways or processing plans for the purpose of disassembly, de-manufacturing and re-distribution into the manufacture cycle.

The main outcome will be an infinite loop manufacturing system that makes and assembles complex products in time *T*, and is cable of returning the raw material back into the manufacturing process within (*3 X T*) – after the product is disposed.

Tackling the Challenges, what needs to be done?

1. Design philosophy for sustainable, traceable, reconfigurable, and re-manufactureble products.
2. Machine tools and techniques for automated detection, tracking and tracing, automatic disassembly, and production processes that are capable of exchanging the necessary data and knowledge vertically and horizontally throughout the supply chain (considering the full life cycle, in our case indefinite life cycle of products and service).
3. Use of advance materials technologies for design and development of highly recyclable and reconfigurable components and devices – to retain the energy and materials within the lifecycle of products, composites and material. No Loss Philosophy.
4. Create a robust and encompassing information architecture to ensure maximum traceability, security, mobility that facilitates implementation of complex optimisation techniques to maximise efficiency and minimise waste.
5. Creating an virtual interactive environment in which customers, industrialists, researchers, and education sector can follow this infinite loop. To discuss, understand, influence and adopt.



Funding Body: EPSRC

Anticipated Impact:

- Achieving zero-waste through Sustainable Loop-Infinite Manufacturing (SLIM)
- Vertical and horizontal integration of supply chains through SLIM - Sustainable Loop-Infinite Manufacturing

Sustainable, traceable, reconfigurable and re-manufacturable products – Sustainable Loop-Infinite Manufacturing (SLIM)

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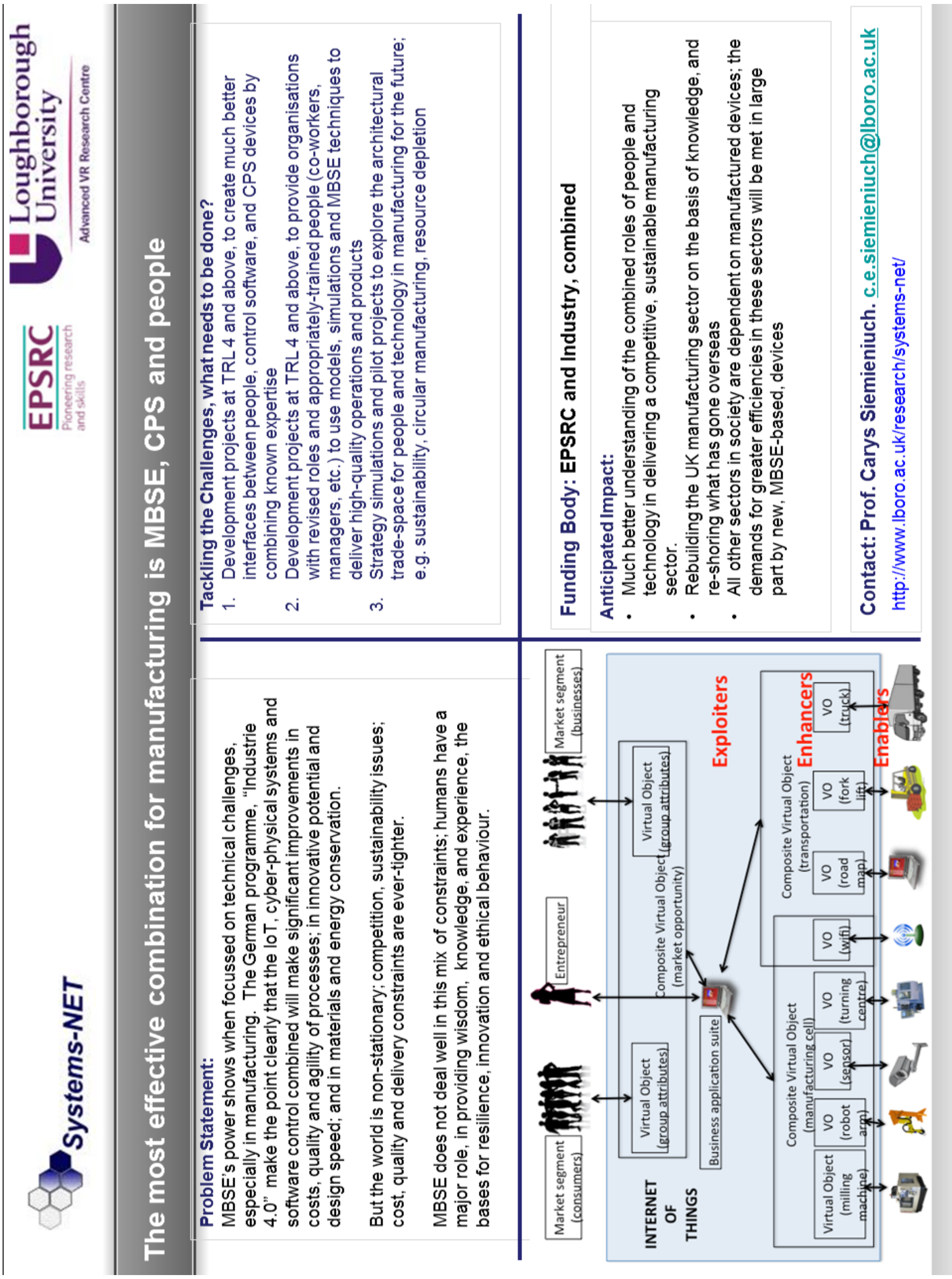
3.- "The most effective combination for manufacturing is MBSE, CPS and people" - Murray Sinclair, Loughborough University



4.- “Industry 4.0 and what it means to TWI” - Darren Williams. The Welding Institute

Title: Welding Systems Integration – Autonomous Welding Systems

Problem Statement:
TWI is a world-leading research and technology organisation specialising in welding and joining technologies, structural integrity and materials science.

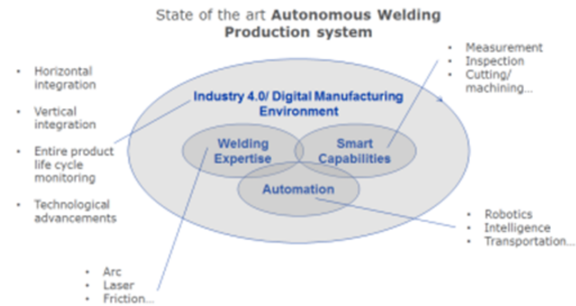
The Welding Systems Integration team (WSI) collaborates across TWI to develop holistic turnkey solutions for joining fabrication and manufacture. It uses the organisation's unparalleled understanding of welding processes to create advanced, smart manufacturing-based platforms, applying the principles of Industry 4.0 to optimise modern industrial manufacturing.

Utilising systems thinking methods WSI focuses on:

1. Assisting our members to define their digital manufacturing challenges and coordinate TWI’s response to these opportunities by providing innovative project based solutions.
2. Defining, co-ordinating, and leading TWI’s Digital Automation Strategy.

Tackling the Challenges, what needs to be done?
Machinery and robot systems in dynamic shop floor environments using novel embedded cognitive functions (FoF-02)

1. Capturing human craft into automation - complex integration between humans and automation facilitating:
   - Flexibility and Higher Quality
   - Increase Productivity
2. Understanding the complexities involved with automating manual tasks which could lead to culture/ skills mind-set adjustments.
3. Utilising innovative solutions to increase the flexibility and customisability of manual processes. Developing modelling and simulation techniques that facilities this.
4. Myriad capture of variables, translation of data into knowledge enabling (automated/ real-time decisions). Big data analysis, computational speeds, data security.
5. Utilising systems engineering principles via the effective and appropriate use of tools, enabling holistic thinking and approaches to improve the effectiveness and efficiency of an inherently complex problem.



Funding Body: H2020

Anticipated Impact:
(1) Automation of a manual production process. **(2)** Demonstration of machinery and robots with enhanced capabilities to facilitate production. **(3)** Reduced setup and NPI timescales. **(4)** Improvements in the adaptability of manufacturing systems **(5)** Standardised and certified system

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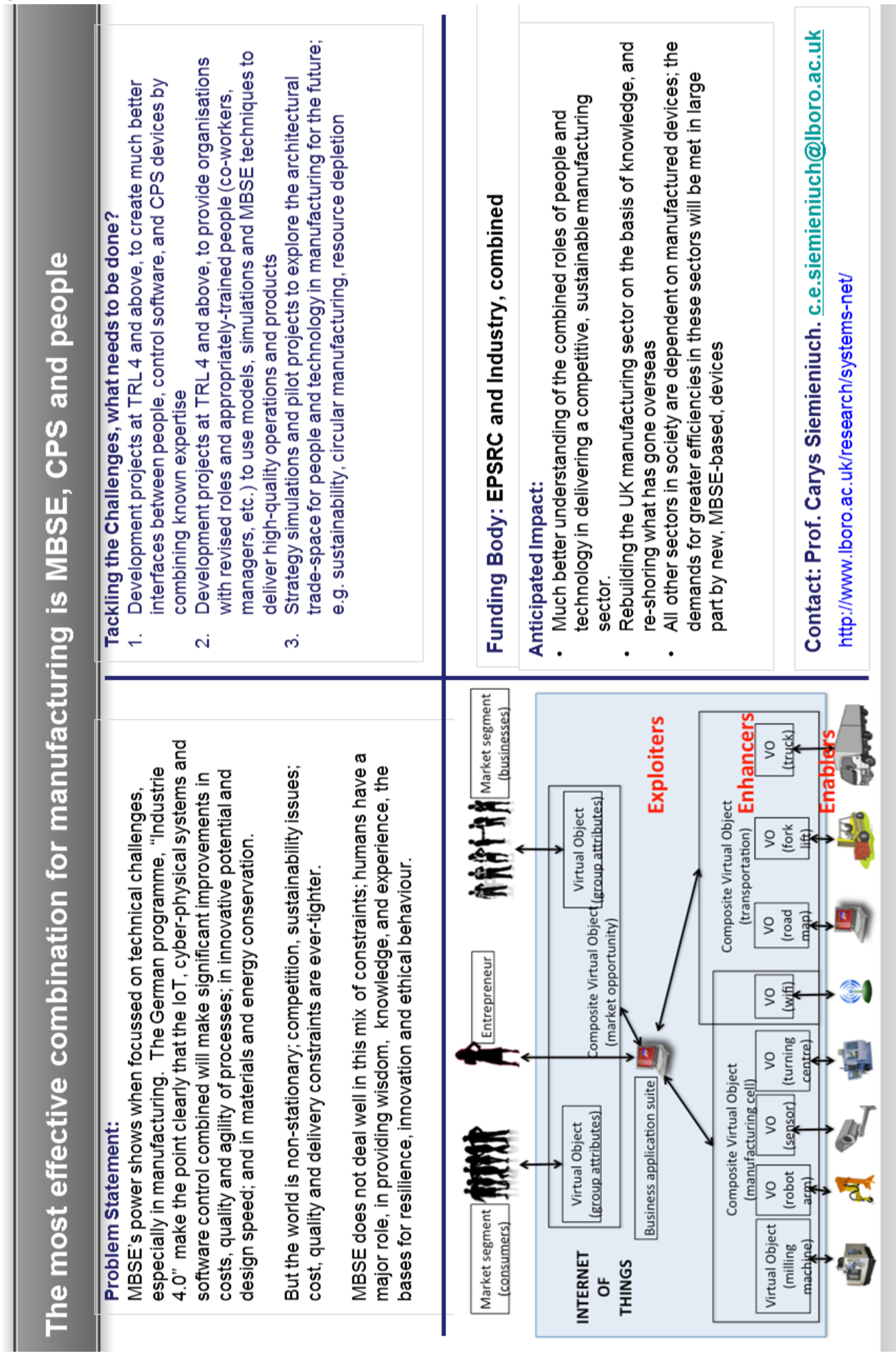
http://www.twi-global.com/capabilities/joining-technologies/welding-engineering/welding-automation/welding-systems-integration/

5.- **"Continuous Adaptation of Work Environments with Changing Levels of Automation in Evolving Production Systems" – Carys Siemieniuch, Loughborough University**



The most effective combination for manufacturing is MBSE, CPS and people

Problem Statement:

MBSE's power shows when focussed on technical challenges, especially in manufacturing. The German programme, "Industrie 4.0" make the point clearly that the IoT, cyber-physical systems and software control combined will make significant improvements in costs, quality and agility of processes; in innovative potential and design speed; and in materials and energy conservation.

But the world is non-stationary; competition, sustainability issues; cost, quality and delivery constraints are ever-tighter.

MBSE does not deal well in this mix of constraints; humans have a major role, in providing wisdom, knowledge, and experience, the bases for resilience, innovation and ethical behaviour.

Tackling the Challenges, what needs to be done?

1. Development projects at TRL 4 and above, to create much better interfaces between people, control software, and CPS devices by combining known expertise
2. Development projects at TRL 4 and above, to provide organisations with revised roles and appropriately-trained people (co-workers, managers, etc.) to use models, simulations and MBSE techniques to deliver high-quality operations and products
3. Strategy simulations and pilot projects to explore the architectural trade-space for people and technology in manufacturing for the future; e.g. sustainability, circular manufacturing, resource depletion

Funding Body: EPSRC and Industry, combined

Anticipated Impact:

- Much better understanding of the combined roles of people and technology in delivering a competitive, sustainable manufacturing sector.
- Rebuilding the UK manufacturing sector on the basis of knowledge, and re-shoring what has gone overseas
- All other sectors in society are dependent on manufactured devices; the demands for greater efficiencies in these sectors will be met in large part by new, MBSE-based, devices

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Appendix C – Workshop Process

The Workshop was divided so as to dedicate the first part of the morning to workshop Session 1, "Developing an Initial Set of Top Challenges"; this was followed by Quad Chart presentations and then the session 2 of the workshop as in Figure 1.

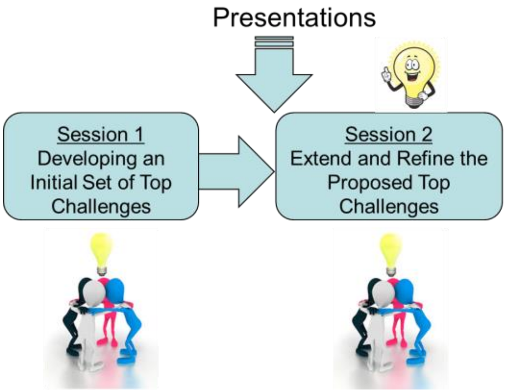

Figure 1 Workshop process to identify the top Grand Challenges for MBSE in Industry 4.0 and IoT

Workshop Session 1 - Developing an Initial Set of Grand Challenges

This session was about polling opinions from all the participants as to what they consider to be the top issues in modelling the next generation MBSE for Industry 4.0 and IoT to allow scalability and add end to end value; this was carried out through discussion between 7 participants at each table, taking into account the following questions:

1. What do we see as the top challenges/ issues/ problem areas?
2. What is the current state of play of any technologies / techniques/ processes/ body of knowledge vs item 1?

Each challenge was written down in a template to record a definition of the Top Challenge proposed, Context, Potential impact, and Perceived difficulty. Reaching consensus was not an easy task given that the area of specialisation of each participant was in most cases very different from many others; however the motivation to formulate a list of issues that are common across many areas resulted on several challenges proposed totalling 11. See Appendix A for the actual scanned copies of the challenges proposed. This session was followed by a series of six presentations on related research.

Workshop Session 2 – Reviewing the Grand Challenges

Following the last presentation all the participants gathered together to discuss the 11 challenges proposed in session 1. The participants were asked to review and refine the set and select the challenges that were most representative or simplified them if there was repetition. This resulted in 9 Challenges that were then submitted to a voting process in which each delegate placed up to five blue star markers on a Top Challenge to indicate their relevance.