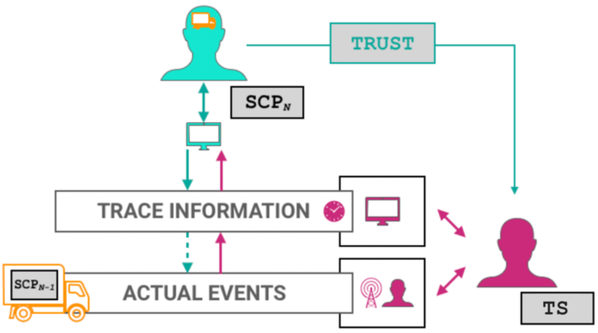
product certification paperwork [16]; tampered IoT sensors [17]; cloned RFID tags [18].

Figure 2: Trust in Traceability Information and the Cyber Physical Bond



3 Contrasting current AECO traceability practice with other sectors

The automotive, agriculture and pharmaceuticals sectors are seen to have developed a comparatively mature traceability practice [3,19]. Its development in the AECO sector, as with many areas of innovation [20,21], lags behind these industries [22,23]. Whilst some low–tech voluntary initiatives exist to encourage the responsible sourcing of raw materials such as timber [24–26], there is no industry–wide scheme to facilitate the traceability of construction products through their entire lifecycle [23]. The general state-of-the-art of product traceability in the sector is summarised by an industry spokesperson *“From government, down to small sub–contractors, we suffer from a shocking lack of data. Traceability technology exists, but we understand little about our supply chains below tier 1”* [27, p.6].

The very nature of the sector introduces barriers to being more proactive in this area; its significant degree of fragmentation, project–basis, separation of activities, poor information management and adversarial relationships [28–31]. These all conspire to further entrench information in silos that stifle traceability [4].

4 Traceability Drivers and Incentives

Despite the apparent inertia, several factors point to the increasing importance of improved product traceability in construction:

- $4.8 billion is spent each year by US building owners verifying operations and maintenance data for buildings. A further $613 million is spent to rekey the information into a different format or system [32].
- The incidence of counterfeit and fraudulent products in general is increasing globally (over $1 trillion annually in 2003 [33]); and a high proportion of construction projects become victims (almost a third, according to [19]).
- Significant issues in the transfer of product information in construction projects can directly and severely affect occupant safety [34].

Despite evidence of the growing need for improved traceability in AECO, its currently established initiatives (e.g. CARES, FSC) tend to entail a narrow focus on responsible sourcing, ostensibly concerning the extractive industries [26]. The comparator industries, however, demonstrate a plethora of drivers beyond this in three broad areas (legal, economic and social drivers) with application areas of traceability spanning the extremities of the supply chain. These include: regulatory compliance, product recall facilitation, fraud/security, quality and safety management, counterfeit prevention, business efficiency, inventory control, financial analytics, waste prevention, transparency, and the supporting of origin claims; to say nothing of emerging business models which are penetrating the psyche of these industries (discussed in section 4.2). The aforementioned application areas convey a sense of being a *push* or *pull* incentive, or both [1–3,13,35–45]. This is to say that businesses in comparator industries willingly engage in some application areas (pull), whilst in others they are forced (push) to do so by external agency, such as governmental bodies or pressure groups [2].

Whilst the majority of application areas seem to be driven by the self–interests of businesses (pull), Borit and Santos [13] note that, in general, regulatory compliance mechanisms tend to induce the initial application of traceability in a sector (push). Though these levers are yet to fully materialise in AECO, recent events may mean that the sector is forced to develop traceability systems by future regulation [23,34]. This external agency may catalyse progress in the industry, but the burden it places on a sector known for its backward relationship with technology could place substantial strain on existing sub-optimal information systems [46] with consequences for the resultant information assurance.

4.1 A Paradigm Shift in Traceability Objectives

Sterling *et al.* propose that traceability ‘best–practice’ delivers business benefits in the four areas of compliance, risk mitigation, market access, and operational efficiencies [47]. Charlebois *et al.* [45] along with [47] and [3] concur that a more proactive stance to traceability is beneficial, with the latter stating that *“adopting traceability for strictly compliance reasons can markedly limit the value that businesses derive from implementing traceability systems.”* [3, p.396].

These and other more recent work denote a paradigmatic shift from an historic reactively orientated approach that has not sought out or exploited business opportunities beyond regulatory compliance towards a faster, more reliable and cost–effective approach to traceability designed to *“capture data proactively for use to commercial advantage”* [47]. This shift, from push to pull, can be analogised as a transition from a compliance centric ‘must do’ activity to an opportunistic 'can do' activity with incentives sufficiently attractive that SCPs voluntarily overcome the profusion of cost, complexity and collaboration barriers which bedevil TS adoption [2,6,48–50]. The new approach seeks to unlock new value streams and business benefits – as in the case of Amazon, a company labelled by many business commentators as predominantly a data company (as opposed to retail, its inaugural classification) due to the value it extracts from the collection and exploitation of data in new value propositions and data driven business enhancements [51,52]. This shift is in the spirit of observations made by Teece *et al.* over 20 years ago, who argued that *"knowledge, competence and related intangibles have emerged as the key drivers of competitive advantage in developed nations. This is not just because of the importance of knowledge itself, but because of the rapid expansion of goods and factor markets, leaving intangible assets as the main basis of competitive differentiation in many sectors"* [53, p.76]. Accordingly, Hartmann *et al.* [54] defined six types of data-driven business models which are anchored to the principle of the exploitation of information, alluding to the clear proliferation and maturation of the new paradigm.

4.2 Potential Development of Traceability in AECO

To envisage what such a shift in traceability in AECO could look like, one can examine the transformation underway in the manufacturing industries of developed economies; these are undergoing rapid digitalisation and innovation in a quest to remain competitive and relevant in the global marketplace [55–57]; rallying under the colloquial term of *Industry 4.0* [56,58]. The espoused benefits of the Industry 4.0 movement include more responsive and resilient supply chains, improved operational efficiency, enhanced customer value propositions, and reduced waste [58–60]. In some cases technology is enhancing the facilitation of existing approaches, in others it is catalysing the genesis of entirely new ones [61]. Far from being the mere overlaying of novel technologies on existing practices, entirely new business models are emerging based on the innovations. Three such innovations include: servitisation, cyber physical systems, and digital twinning [56,62–69]. These concepts are also discussed in the emerging AECO literature, with a major underlying driver of improved productivity in a sector commonly lambasted for its poor performance in this area. Product traceability, spanning each stage of the supply chain and throughout the full lifecycle of a product, is a key enabler of these innovations. It would also directly lead to financial and social benefits by solving the three problems identified in section 4 whilst contributing to improvements in counterfeit elimination and environmental credentials. Finally, the flow of in-use construction product data could lead to a panoply of other valuable benefits for stakeholders: manufacturers could optimise designs based on real usage data, orders of magnitude richer than laboratory-based test results; whilst facilities managers could receive predictive maintenance and product-recall alerts, driven by fresh data.

5 The Potential Role of DLT in Traceability

A central tenet to many such innovations is their wholesale reliance upon the flow of information throughout supply chains in complex sociotechnical systems. Alongside the development of technologies in areas such as robotics, sensors, internet of things, geolocation, space, and materials; the soaring dependence on information flow has arguably catalysed the accelerated development of an entirely new area within the information management field, blockchain, and a broader category termed Distributed Ledger Technology. Widely popularised by Bitcoin (its first major application), blockchain has rapidly become a poignant topic of conversation across a spectrum of academic and business literature. It is arguably one of the most novel technological and sociological developments in recent times.

There are two types of blockchain: *permissionless* (like Bitcoin or Ethereum) which is fully decentralised with no central authority, and fully accessible to anyone to participate; or *permissioned* where a central actor must grant access and permissions for someone to participate [70,71] (like Corda). In general, a blockchain can be conceptualised as a distributed append–only database [72] made up of interlinked blocks of data which contain records of the transactions made in the system between nodes (participants) since the last block was added. The blocks of transactions are confirmed and added to the existing chain by mutually mistrusting [73] 'writers' called validators [74], leading to the descriptor 'trustless' [75], since no trusted centralised third-party is needed to facilitate the effective functioning of the system.

The writers come to an agreement on the validity of the transactions communicated in the system via a self–propagating consensus algorithm [71]. Each new block that is appended to the chain references the previous block via a one–way cryptographic hash function [71], essentially a fingerprint ID of the previous block, which prevents data from validated blocks from being tampered with. Furthermore, the information within a blockchain system may hide in plain sight, sitting securely behind the protection of "very big numbers" [76] and within a small space, due to optimising Merkle Tree hashing–functions [77] whilst indefinitely preserving the integrity of historic transaction data. These features mean that blockchain systems are generally accepted to possess five key attributes, as noted in Table 2 below.

Table 2. Purported Attributes of DLT Systems

Attribute	Comment
Auditable	Provides an unbreakable audit trail of all transactions all the way back to the first (genesis) block, which can also be conceived as transaction traceability [78].
Disintermediative	There is no reliance on a third 'trusted' party to execute transactions, it is peer to peer (and information is also directly accessible) [70].

Transparent (with/without pseudonymity)	The information within blockchains is viewable by all participants [...] Users can choose to remain anonymous or provide proof of their identity to others [71]
Secure	Expensive computational algorithms create disincentives to 'hack' the system [72], and blockchains' distributed and encrypted nature makes them difficult to hack. [70,71]
Immutable	Existing data in public systems is extremely hard (and economically unfeasible) to change [77,79].

There is growing consensus in the literature that blockchain can lead to enhanced traceability in supply chains due to its novel approach to information management. An extensive body of literature asserts a degree of support for the notion that blockchains are especially well placed for the enhancement of traceability of physical artefacts in supply chains. Cole *et al.* [80, p.471] provides a succinct synthesis of the emerging consensus: *"immutability of the data means that agreed transactions are recorded and not altered. This provides provenance of assets, which means that for any asset it is possible to tell where it is, where it has been and what has happened throughout its lifetime."* Outwith the academic literature, prominent industry bodies such as IBM, Deloitte, and Oracle tend to sympathise with this stance [81].

6 Open research problems

6.1 Distributed Ledger Technology

There is no notable opposition to claims that blockchain can prove the provenance of data created within a blockchain system due to its advances over older technologies (namely. immutability). That being said, two erroneous propositions pervade the nascent argument that blockchain by itself will enhance traceability of non-informational artefacts. These are as follows:

- The conflation of the guarantee of the provenance of traceability information received with the validation of the claims made within the traceability information received.
- The conflation of the provision of traceability information with the utility of the traceability information provided – e.g. asserting that the presence of traceability information is tantamount to achieving traceability of a physical artefact.

For example:

> *"With improved visibility, each participant in the supply chain will be able to see the progress of goods as they move through the supply chain."* [82, p.72]

> *"This improved visibility provides an auditable trace of the footprint of a product, which is particularly attractive to industries where the provenance of a product is crucial."* [71, p.223]

> *AI augmented verification technology can help determine material provenance, while blockchain can provide real–time provenance visibility to reduce tampering and counterfeiting."* [81, p.5]

Viewed through the lens of the information assurance considerations (section 2.3), the issue of the potential weaknesses of the Cyber Physical Bond must be accounted for in the development of a balanced view of the potential utility of blockchain in traceability applications. Considering a case where the RFID tag of a physical artefact is tampered with, thus sending erroneous signals to a receiving TS, shows clearly that blockchain alone cannot guarantee the truth of information pertaining to that item.

Whilst it is plausible that blockchain could safeguard information in a TS, the safeguarding of the creation of the information is not accounted for by the current literature. Two open information assurance phenomena face blockchain-based traceability applications:

- Garbage In Garbage Out (GIGO) – the quality of the informational output of a system can only be as good as the quality of the input, which is subject to fraud and error.
- The Oracle Problem (TOP) – an oracle is the interface between real–world events and the blockchain ecosystem. For example, a reporting observer, RFID tag or third-party data feed could be oracles because they create the information that blockchains process.

An established approach to overcoming the traceability information creation dilemma could be to appoint a third-party authority over the TS. Although firstly this would place a potentially unsustainable financial burden on the supply chain. Secondly, it does not necessarily eliminate SCP animosity towards the TS. Thirdly, the introduction of a central authority with ultimate control over information creation and management in the TS may undermine of the practical or philosophical arguments for the inclusion of blockchain in the TS. The resultant research challenge is thus to seek out a solution to the assurance of the information creation process; without reliance on a single authoritative actor and whilst maximising utility of the information, solving for the stakeholder incentive dilemma elucidated by agency theory.

6.2 Traceability in AECO

To date, product-level traceability in AECO has received scant attention from academia, compounded by the fact that existing traceability initiatives predominantly focus on the extractive industries. The rising importance of product-level traceability as established in section 4, in tandem with the opportunistic paradigm of traceability emanating from the Industry 4.0 movement, converge to invite research into entirely new approaches to achieving product traceability in AECO. This invitation is consolidated further by the potential opportunities presented by nascent blockchain technology research, which lays out the possibility for the creation of entirely novel decentralised business models.

The resounding issue of SCP incentives and motivations in TSs remains one of the key issues, however. No research, specifically addressing the issue of SCP incentives in AECO TSs, has been found to date.

6.3 Future Research Direction

The amalgamation of these issues provides several interesting avenues of enquiry which could lead to novel contributions to knowledge.

SCPs' incentives (perceived benefits) and disincentives (perceived risks) to participate in AECO traceability systems will be investigated through interviews with SCPs in the supply chains of selected focal products. A 'lifecycle perspective' will be adopted, taking into account the information created through the full life of a product, as well as the various stakeholders at different lifecycle stages in the AECO process.

Data will be gathered from DLT experts to garner further insight into the problems (GIGO and TOP) facing blockchain in the context of traceability applications; as well as the potential of a specific area of DLT which is not obviously considered in the blockchain-based traceability literature: token-based incentive mechanisms. These might feature cryptocurrencies and smart contracts within a decentralised business model.

The two streams of knowledge will be combined to develop a conceptual design of a TS based on a decentralised business model which features new 'pull' incentives to align the interests of AECO SCPs in order to overcome the incentive dilemma, and achieve enhanced traceability to unlock transformative benefits in AECO. This could explore the commercial exploitation of the potentially valuable data which would be contained in an AECO based TS.

7 Conclusion

The case for product-level traceability in AECO has been firmly established, taking into consideration a diverse set of drivers and mounting industry concerns. Yet the challenging structure and adversarial culture of AECO is known to stifle the proliferation of innovative technologies, and traceability systems universally are known to falter in the absence of participant buy-in. However, a paradigmatic shift in thinking towards data-driven business models and the emergence of DLT with its associated decentralised business models could hold the key to an entirely new approach to traceability in AECO which is much needed to underpin its transformation. Although the apparently unfettered support for DLT is not empirically justifiable and the two key problems of GIGO and TOP remain, it seems that it could have a potential part to play in the assurance of traceability information by facilitating an entirely new approach. The solution to traceability in AECO hinges on the degree to which it can integrate incentives which attract SCPs into willing participation and mutually beneficial alignment, based on the benefits they will receive which must outweigh the perceived risks, rather than forcing participation through external agency. The utility of DLT for product traceability in general has yet to be examined from this perspective. One exciting area for future research is the potential use of token-based incentives in traceability systems.

The achievement of product-level traceability in AECO with wholesale buy-in could release new levels of productivity by solving pertinent operational issues, whilst underpinning radical improvements in many other areas which will benefit society as a whole.

Acknowledgements

This research forms part of a PhD programme "The potential of Distributed Ledger Technologies to improve product traceability assurance in the construction industry" funded by Loughborough University and the BRE Trust. The support of these parties is gratefully acknowledged.

References

[1] Marshall, D., McCarthy, L., McGrath, P., and Harrigan, F., 2016, "What's Your Strategy for Supply Chain Disclosure?," MIT Sloan Management Review, **57**(2), pp. 37–45.

[2] Househam, A., Bombis, E., and Liew, D., 2014, "A Guide to Traceability: A Practical Approach to Advance Sustainability in Global Supply Chains."

[3] Bhatt, T., Cusack, C., Dent, B., Gooch, M., Jones, D., Newsome, R., Stitzinger, J., Sylvia, G., and Zhang, J., 2016, "Project to Develop an Interoperable Seafood Traceability Technology Architecture: Issues Brief," Comprehensive Reviews in Food Science and Food Safety, **15**(2), pp. 392–429.

[4] Olsen, P., and Borit, M., 2013, "How to Define Traceability," Trends in Food Science & Technology, **29**(2), pp. 142–150.

[5] Kang, Y. S., and Lee, Y. H., 2013, "Development of Generic RFID Traceability Services," Computers in Industry, **64**(5), pp. 609–623.

[6] Dai, H., Ge, L., and Zhou, W., 2015, "A Design Method for Supply Chain Traceability Systems with Aligned Interests," International Journal of Production Economics, **170**, pp. 14–24.

[7] Storøy, J., Thakur, M., and Olsen, P., 2013, "The TraceFood Framework – Principles and Guidelines for Implementing Traceability in Food Value Chains," Journal of Food Engineering, **115**(1), pp. 41–48.

[8] Mohan, G., 2018, "Could Blockchain Have Solved the Mystery of the Romaine Lettuce E. Coli Outbreak?," latimes.com [Online]. Available: https://www.latimes.com/business/la-fi-blockchain-ecoli-20180527-story.html. [Accessed: 22-Jan-2019].

[9] Grossman, S. J., and Hart, O. D., 1983, "An Analysis of the Principal-Agent Problem," Econometrica, **51**(1), pp. 7–45.

[10] Moe, T., 1998, "Perspectives on Traceability in Food Manufacture," Trends in Food Science & Technology, **9**(5), pp. 211–214.

[11] Rowley, J., 2007, "The Wisdom Hierarchy: Representations of the DIKW Hierarchy," Journal of information science, **33**(2), pp. 163–180.

[12] Bocij, P., Greasley, A., and Hickie, S., 2008, *Business Information Systems: Technology, Development and Management*, Pearson education.

[13] Borit, M., and Santos, J., 2015, "Getting Traceability Right, from Fish to Advanced Bio-Technological Products: A Review of Legislation," Journal of Cleaner Production, **104**, pp. 13–22.

[14] Verdouw, C. N., Beulens, A. J. M., Reijers, H. A., and Van Der Vorst, J. G. A. J., 2015, "A Control Model for Object Virtualization in Supply Chain Management," Computers in Industry, **68**, pp. 116–131.

[15] Li, S., and Lin, B., 2006, "Accessing Information Sharing and Information Quality in Supply Chain Management," Decision Support Systems, **42**(3), pp. 1641–1656.

[16] Minchin, R. E., Walters, R., Issa, R. R. A., Gaurav, S., and Lucas, E. D., 2016, "Counterfeiting in the Construction Industry: Analysis of Sino-American Differences in Perception," Journal of Legal Affairs and Dispute Resolution in Engineering and Construction, **8**(4), p. B4516002.

[17] Haddud, A., DeSouza, A., Khare, A., and Lee, H., 2017, "Examining Potential Benefits and Challenges Associated with the Internet of Things Integration in Supply Chains," Journal of Manufacturing Technology Management.

[18] Kamaludin, H., Mahdin, H., and Abawajy, J. H., 2018, "Clone Tag Detection in Distributed RFID Systems," PLoS One, **13**(3).

[19] Naderpajouh, N., Hastak, M., Gokhale, S., Bayraktar Mehmet, E., Iyer, A., and Arif, F., 2015, "Counterfeiting Risk Governance in the Capital Projects Supply Chain," Journal of Construction Engineering and Management, **141**(3), p. 04014084.

[20] Hernández, H., Tübke, A., Christensen, J., Vezzani, A., Hervás Soriano, F., European Commission, Directorate-General for Research, European Commission, Joint Research Centre, and Institute for Prospective Technological Studies, 2013, *EU R&D Scoreboard the 2012 EU Industrial R&D Investment Scoreboard.*, Directorate-general for Research, European Commission, Luxembourg.

[21] Farmer, M., 2016, "The Farmer Review of the UK Construction Labour Model," Construction Leadership Council.

[22] Glass, J., 2011, "Responsible Sourcing in Construction Projects - Can Anything Be Learned from FT.Pdf."

[23] Watson, R., Kassem, M., and Li, J., 2019, "Traceability for Built Assets: Proposed Framework for a Digital Record," Budapest, Hungary, pp. 496–501.

[24] BRE, 2009, "GreenBook Live: BES 6001: The Framework Standard for Responsible Sourcing," GreenBook Live [Online]. Available: http://www.greenbooklive.com/search/scheme.jsp?id=153. [Accessed: 23-Jan-2019].

[25] Dowdell, D., Page, I., and Curtis, M., 2017, *Electronic Traceability of New Zealand Construction Products: Feasibility and Opportunities*, SR365 [2017], branz, Porirua.

[26] Katenbayeva, A., Glass, J., Anvuur, A. M., and Ghumra, S., 2017, "Conceptual Framework for Traceability in the Construction Sector," *Proceedings of the 33rd ARCOM Conference 4-6th September 2017*, A, Cambridge.

[27] Mclelland, J., 2018, "Closing the Circularity Gap with BAMB," Raconteur, **Future of Construction 2018**(#0561), p. 16.

[28] Dainty, A. R. J., Briscoe, G. H., and Millett, S. J., 2001, "Subcontractor Perspectives on Supply Chain Alliances," Construction Management and Economics, **19**(8), pp. 841–848.

[29] Harty, C., 2005, "Innovation in Construction: A Sociology of Technology Approach," Building Research & Information, **33**(6), pp. 512–522.

[30] Gambatese, J. A., and Hallowell, M., 2011, "Enabling and Measuring Innovation in the Construction Industry," Construction Management and Economics, **29**(6), pp. 553–567.

[31] Fulford, R., and Standing, C., 2014, "Construction Industry Productivity and the Potential for Collaborative Practice," International Journal of Project Management, **32**(2), pp. 315–326.

[32] Gallaher, M. P., O'Connor, A. C., Dettbarn, Jr., J. L., and Gilday, L. T., 2004, *Cost Analysis of Inadequate Interoperability in the U.S. Capital Facilities Industry*, NIST GCR 04-867, National Institute of Standards and Technology, Maryland.

[33] Minchin, E., Pan, J., Walters, R. C., and Fang, D., 2011, "Counterfeit Construction Products from Low-Cost Sourcing Countries," *Management and Innovation for a Sustainable Built Environment*, Amsterdam.

[34] Hackitt, D. J., 2018, *Building a Safer Future: Independent Review of the Building Reguatlions and Fire Safety : Final Report*.

[35] Jansen-Vullers, M. H., van Dorp, C. A., and Beulens, A. J. M., 2003, "Managing Traceability Information in Manufacture," International Journal of Information Management, **23**(5), pp. 395–413.

[36] van Dorp, K., 2002, "Tracking and Tracing: A Structure for Development and Contemporary Practices," Logistics Information Mngt, **15**(1), pp. 24–33.

[37] Agrawal, R., Cheung, A., Kailing, K., and Schonauer, S., 2006, "Towards Traceability across Sovereign, Distributed RFID Databases," *2006 10th International Database Engineering and Applications Symposium (IDEAS'06)*, pp. 174–184.

[38] Murthy, K., and Robson, C., 2008, "A Model-Based Comparative Study of Traceability Systems," *Proceedings of the International Conference on Information Systems, Logistics and Supply Chain (ILS)*, Citeseer.

[39] Dabbene, F., Gay, P., and Tortia, C., 2014, "Traceability Issues in Food Supply Chain Management: A Review," Biosystems Engineering, **120**, pp. 65–80.

[40] Pizzuti, T., and Mirabelli, G., 2015, "The Global Track&Trace System for Food: General Framework and Functioning Principles," Journal of Food Engineering, **159**, pp. 16–35.

[41] Alonso-Rorís, V. M., Álvarez-Sabucedo, L., Santos-Gago, J. M., and Ramos-Merino, M., 2016, "Towards a Cost-Effective and Reusable Traceability System. A Semantic Approach," Computers in Industry, **83**, pp. 1–11.

[42] COGNEX, 2017, "Expert Guide: Traceability for the Automotive Industry."

[43] Diallo, T., Henry, S., and Ouzrout, Y., 2018, "Towards a More Efficient Use of Process and Product Traceability Data for Continuous Improvement of Industrial Performances," arXiv:1810.13141 [cs].

[44] Cheung, H. H., and Choi, S. H., 2011, "Implementation Issues in RFID-Based Anti-Counterfeiting Systems," Computers in Industry, **62**(7), pp. 708–718.

[45] Charlebois, S., Sterling, B., Haratifar, S., and Naing, S. K., 2014, "Comparison of Global Food Traceability Regulations and Requirements," Comprehensive reviews in food science and food safety, **13**(5), pp. 1104–1123.

[46] Heiskanen, A., 2017, "The Technology of Trust: How the Internet of Things and Blockchain Could Usher in a New Era of Construction Productivity," Construction Research and Innovation, **8**(2), pp. 66–70.

[47] Sterling, B., Gooch, M., Dent, B., Marenick, N., Miller, A., and Sylvia, G., 2015, "Assessing the Value and Role of Seafood Traceability from an Entire Value-Chain Perspective," Comprehensive Reviews in Food Science and Food Safety, **14**(3), pp. 205–268.

[48] Barnett, J., Begen, F., Howes, S., Regan, A., McConnon, A., Marcu, A., Rowntree, S., and Verbeke, W., 2016, "Consumers' Confidence, Reflections and Response Strategies Following the Horsemeat Incident," Food Control, **59**, pp. 721–730.

[49] Sarpong, S., 2014, "Traceability and Supply Chain Complexity: Confronting the Issues and Concerns," European Business Review, **26**(3), pp. 271–284.

[50] Olsen, P., and Borit, M., 2018, “The Components of a Food Traceability System,” Trends in Food Science & Technology, **77**, pp. 143–149.

[51] Goldman, J., 2018, “How Companies Like Amazon and Google Turn Data Into a Competitive Advantage -- and How You Can Too,” Inc.com [Online]. Available: https://www.inc.com/jeremy-goldman/how-companies-like-amazon-google-turn-data-into-a-competitive-advantage-how-you-can-too.html. [Accessed: 25-Feb-2020].

[52] Kelion, L., 2020, “Amazon: How Bezos Built His Data Machine,” BBC News.

[53] Teece, D. J., 1998, “Capturing Value from Knowledge Assets: The New Economy, Markets for Know-How, and Intangible Assets,” California Management Review, **40**(3), pp. 55–79.

[54] Hartmann, P. M., Zaki, M., Feldmann, N., and Neely, A., 2016, “Capturing Value from Big Data – a Taxonomy of Data-Driven Business Models Used by Start-up Firms,” Int Jrnl of Op & Prod Mnagemnt, **36**(10), pp. 1382–1406.

[55] Müller, J. M., Kiel, D., and Voigt, K.-I., 2018, “What Drives the Implementation of Industry 4.0? The Role of Opportunities and Challenges in the Context of Sustainability,” Sustainability, **10**(1), p. 247.

[56] Barreto, L., Amaral, A., and Pereira, T., 2017, “Industry 4.0 Implications in Logistics: An Overview,” Procedia Manufacturing, **13**, pp. 1245–1252.

[57] Lu, Y., 2017, “Industry 4.0: A Survey on Technologies, Applications and Open Research Issues,” Journal of Industrial Information Integration, **6**, pp. 1–10.

[58] Kagermann, H., Wahlster, W., and Helbig, J., 2013, *Recommendations for Implementing the Strategic Initiative INDUSTRIE 4.0.Pdf*, acatech – National Academy of Science and Engineering, Munich.

[59] Brusset, X., 2016, “Does Supply Chain Visibility Enhance Agility?,” International Journal of Production Economics, **171**, pp. 46–59.

[60] Rüßmann, M., Lorenz, M., Gerbert, P., Waldner, M., Justus, J., and Harnisch, M., “Industry 4.0: The Future of Productivity and Growth in Manufacturing Industries,” p. 14.

[61] Hofmann, E., and Rüsch, M., 2017, “Industry 4.0 and the Current Status as Well as Future Prospects on Logistics,” Computers in Industry, **89**, pp. 23–34.

[62] Porter, M. E., and Heppelmann, J. E., 2014, “How Smart, Connected Products Are Transforming Competition,” Harvard business review, **92**(11), pp. 64–88.

[63] Rymaszewska, A., Helo, P., and Gunasekaran, A., 2017, “IoT Powered Servitization of Manufacturing – an Exploratory Case Study,” International Journal of Production Economics, **192**, pp. 92–105.

[64] Royal Academy of Engineering, 2015, *Connecting Data: Driving Productivity and Innovation*, ISBN: 978-1-909327-22-1, Royal Academy of Engineering, London.

[65] Bordel, B., and Alcarria, R., 2017, “Building Enhanced Environmental Traceability Solutions: From Thing-to-Thing Communications to Generalized Cyber-Physical Systems,” p. 17.

[66] Jeschke, S., Brecher, C., Meisen, T., Özdemir, D., and Eschert, T., 2017, “Industrial Internet of Things and Cyber Manufacturing Systems,” *Industrial Internet of Things: Cybermanufacturing Systems*, S. Jeschke, C. Brecher, H. Song, and D.B. Rawat, eds., Springer International Publishing, Cham, pp. 3–19.

[67] Uhlemann, T. H.-J., Lehmann, C., and Steinhilper, R., 2017, “The Digital Twin: Realizing the Cyber-Physical Production System for Industry 4.0,” Procedia CIRP, **61**, pp. 335–340.

[68] Deloitte, 2017, *New Technologies Case Study: Data Sharing in Infrastructure*, Deloitte, London.

[69] Bolton, A., Butler, L., Dabson, I., Enzer, M., Evans, M., Fenemore, T., Harradence, F., Keaney, E., Kemp, A., Luck, A., Pawsey, N., Saville, S., Schooling, J. M., Sharp, M., Smith, T., Tennison, J., Whyte, J., Wilson, A., and Makri, C., 2018, *Gemini Principles*, CDBB, Cambridge.

[70] Wüst, K., and Gervais, A., 2017, “Do You Need a Blockchain?,” IACR Cryptology ePrint Archive, (i), pp. 1–7.

[71] Wang, Y., Han, J. H., and Beynon-Davies, P., 2019, “Understanding Blockchain Technology for Future Supply Chains: A Systematic Literature Review and Research Agenda,” Supp Chain Mnagmnt, **24**(1), pp. 62–84.

[72] Min, H., 2019, “Blockchain Technology for Enhancing Supply Chain Resilience,” Business Horizons, **62**(1), pp. 35–45.

[73] Christidis, K., and Devetsikiotis, M., 2016, “Blockchains and Smart Contracts for the Internet of Things,” IEEE Access, **4**, pp. 2292–2303.

[74] Baralla, G., Pinna, A., and Corrias, G., 2019, “Ensure Traceability in European Food Supply Chain by Using a Blockchain System,” p. 8.

[75] Bahga, A., and Madisetti, V. K., 2016, “Blockchain Platform for Industrial Internet of Things,” Journal of Software Engineering and Applications, **9**(10), pp. 533–546.

[76] CRI, 2014, “Bitcoin 101 - Quindecillions & The Amazing Math Of Bitcoin’s Private Keys.”

[77] Bocek, T., Rodrigues, B. B., Strasser, T., and Stiller, B., 2017, “Blockchains Everywhere - a Use-Case of Blockchains in the Pharma Supply-Chain,” *2017 IFIP/IEEE Symposium on Integrated Network and Service Management (IM)*, pp. 772–777.

[78] Wu, H., Li, Z., King, B., Ben Miled, Z., Wassick, J., and Tazelaar, J., 2017, “A Distributed Ledger for Supply Chain Physical Distribution Visibility,” Information, **8**(4), p. 137.

[79] Aste, T., Tasca, P., and Matteo, T. D., 2017, “Blockchain Technologies: The Foreseeable Impact on Society and Industry,” Computer, **50**(9), pp. 18–28.

[80] Cole, R., Stevenson, M., and Aitken, J., 2019, “Blockchain Technology: Implications for Operations and Supply Chain Management,” Supp Chain Mnagmnt, **24**(4), pp. 469–483.

[81] IBM, 2018, “Orchestrating Tomorrow’s Supply Chain.”

[82] Hald, K. S., and Kinra, A., 2019, “How the Blockchain Enables and Constrains Supply Chain Performance,” International Journal of Physical Distribution & Logistics Management.