



Thèse en cotutelle avec
l'Université de Borås (Suède) et l'Université de Soochow (Chine)

Contribution to development of a secured traceability system for textile and clothing supply chain

Contribution au développement d'un système de traçabilité sécurisé pour la chaîne d'approvisionnement textile et habillement

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pour obtenir le grade de Docteur de l'Université de Lille

Discipline: Automatique et Productique

Soutenue le 14/06/2019 devant la commission d'examen

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Contribution to development of a secured traceability system for textile and clothing supply chain

Doctoral dissertation by

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in the partial fulfillment of Erasmus Mundus Joint Doctorate programme: *Sustainable Management and Design for Textile*

Jointly Organized by

Université de Lille, France

University of Borås, Sweden

Soochow University, China

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for textile and clothing supply chain

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© Tarun Kumar Agrawal, 2019
Cover image: by JNT Visual/Adobe Stock
Printed in Sweden by Stema

ISBN 978-91-88838-31-5 (printed)
ISBN 978-91-88838-32-2 (pdf)
ISSN 0280-381X, Skrifter från Högskolan i Borås, nr. 95

Electronic version: <http://urn.kb.se/resolve?urn=urn:nbn:se:hb:diva-15957>



Abstract

Contribution to development of a secured traceability system for textile and clothing supply chain

Secured traceability implies not only the ability to identify, capture, and share required information on product transformation throughout the supply chain (SC), but also the ability to ensure the security of the traceability data. Due to information asymmetry and lack of transparency, textile and clothing (T&C) industries often face challenges in implementing and maintaining sufficient traceability. The SC actors find it difficult to identify and track the suppliers and sub-suppliers involved. Additionally, the opaque and largely untraceable structure of the SC has enabled the easy intrusion of counterfeits. Hence, a secured traceability system is imperative to ensure that the required traceability data are captured and shared among SC actors, thereby allowing the tracking and tracing of the products in the SC. Further, a secured traceability system helps organizations in various decision-making processes and protects customers from counterfeits.

This thesis contributes to the development of a secured traceability system for the T&C sector. It examines traceability at product and information levels, based on the system-of-systems approach. At the product level, the thesis introduces a secured traceability tag that can be printed on the textile surface. The secured tag is hard to copy and is durable enough to withstand normal textile use, thus providing sufficient security besides product tagging for traceability implementation. At the information level, the thesis explores and classifies traceability data that can be shared at business-to-business and business-to-customer levels for the implementation of secured traceability. Subsequently, a blockchain-based traceability framework is proposed for the T&C supply chain to systematically capture and share data in the supply chain network. The proposed framework demonstrates the applicability of shared data infrastructure to traceability without a central authority and develops technology-based trust among the supply chain actors. It relies on no central authority, and has customized data privacy and accessibility rules, thus providing a unique opportunity, flexibility, and authority to all supply chain actors to trace their supply chains and create transparent and sustainable supply chain networks.

Keywords: Traceability, Textile and clothing, Supply chain, Secured tag, Blockchain

Résumé

Contribution au développement d'un système de traçabilité sécurisé pour la chaîne d'approvisionnement textile et habillement

Une traçabilité sécurisée implique non seulement la possibilité d'identifier, capturer et partager des informations requises concernant la transformation du produit tout au long de la chaîne d'approvisionnement, mais aussi d'assurer à la cyber-sécurité des données liées à la traçabilité. En raison de l'asymétrie des informations et du manque de transparence et du manque de solutions peu coûteuses, simples, sécurisées et efficaces à mettre en œuvre, les industries du textile et habillement connaissent souvent des difficultés à adopter et maintenir une traçabilité efficace. Les agents de la chaîne d'approvisionnement trouvent difficile l'identification et le suivi de tous les fournisseurs et sous-contractants. De plus, l'opacité et le défaut de traçage dans la chaîne ont favorisé l'intrusion facile des contrefaçons. Par conséquent, le système de traçabilité sécurisé a été identifié comme étant un outil essentiel qui assure la capture et le partage des données de traçabilité nécessaires. Ceci permet le suivi et le repérage des produits dans la chaîne d'approvisionnement. En outre, le système de traçabilité sécurisé permet une organisation aux niveaux des processus de prise de décisions, protège les clients des contrefaçons, apporte une réponse aux demandes de transparence des consommateurs et anticipe les besoins grandissants pour la chaîne logistique retour et le recyclage de ces matériaux.

Cette thèse contribue au développement d'un système de traçabilité sécurisé pour le secteur du textile et habillement. La traçabilité du système est examinée sur des produits et des niveaux d'informations en utilisant une approche système-système. Au niveau du produit, cette thèse introduit une étiquette de traçabilité sécurisée pouvant être imprimée à la surface du textile. L'étiquette sécurisée est difficile à copier, résistante aux conditions d'usages textiles, et donc fournit une sécurité suffisante avec le marquage du produit pour une mise en œuvre de la traçabilité. Au niveau informationnel, cette étude explore et classe les données liées à la traçabilité pouvant être partagées entre les entreprises elles-mêmes ainsi qu'entre les entreprises et les clients, et ceci afin d'implémenter une traçabilité sécurisée. En outre, un système de traçabilité basé sur une chaîne à blocs est proposé, pour la chaîne d'approvisionnement textile-habillement, afin de capturer et partager systématiquement les données au réseau de chaînes d'approvisionnement. Le système proposé prouve la faisabilité des infrastructures des données partagées pour une traçabilité sûre, sans autorité centrale, et développe une technologie basée sur la confiance entre les agents de la chaîne. Il s'appuie sur une autorité décentralisée avec une confidentialité des données et des règles d'accessibilité personnalisées. Par conséquent, ce système fournit une opportunité unique, une flexibilité et une autorité à tous les agents pour retrouver leurs chaînes et créer un réseau de chaînes d'approvisionnement transparent et durable.

Mots clés : Traçabilité, Textile et habillement, Chaîne d'approvisionnement, Étiquette sécurisée, Chaîne à blocs.

Abstrakt

Bidrag till utveckling av ett system för säkrad spårbarhet för försörjningskedjor inom textil- och modeindustrin

Säkrad spårbarhet innebär inte bara förmågan att identifiera, fånga och dela erforderlig information gällande hur produkten förändrats genom försörjningskedjan, utan även trygga säkerheten av spårbarhetsdata. På grund av informationsasymmetri och brist på transparens, möter ofta textil- och modeindustrin problem med att implementera och upprätthålla tillräcklig spårbarhet. Aktörer inom försörjningskedjan har svårt att identifiera och spåra involverade leverantörer och underleverantörer. Dessutom har den ogenomträngliga och icke-spårbara strukturen i försörjningskedjan möjliggjort intrång i form av kopior och förfalskningar. Följaktligen har systemet för säker spårbarhet identifierats som ett viktigt verktyg – för att säkerställa att erforderlig spårbarhetsdata fångas och delas mellan försörjningskedjans aktörer –, vilket möjliggör spårning av produkter i försörjningskedjan. Därtill hjälper även systemet för säker spårbarhet organisationer i deras beslutsprocesser och skyddar kunder från förfalskningar.

Avhandlingen bidrar till utvecklingen av ett system för säker spårbarhet för textil och modebranschen. Spårbarhet på både produkt- och informationsnivå undersöks genom ett system-of-system-tillvägagångssätt. På produktnivå introducerar avhandlingen en säker spårbarhetsmärkning som kan tryckas på en textil yta. Denna säkra märkning är svårare att kopiera och tål normal hantering, därav ger den tillräcklig tillförlitlighet, förutom produktmärkning, för spårbarhetsimplementering. På informationsnivå undersöker och klassificerar avhandlingen spårbarhetsdata som kan delas mellan företag (business-to-business) och mellan företag och kund (business-to-consumer) för att implementera säker och tillförlitlig spårbarhet. Därefter föreslås ett blockchain-baserat ramverk för spårbarhet inom textil- och modeindustrins försörjningskedjor för att systematiskt fånga in och dela information mellan parterna i försörjningskedjan. Det föreslagna ramverket visar användbarheten av delad datainfrastruktur för spårbarhet utan en central myndighet och utvecklar ett tekniskt baserat förtroende bland försörjningskedjans aktörer. Eftersom det inte bygger på någon central myndighet med anpassade regler för integritet och tillgänglighet ger det en unik möjlighet, flexibilitet och befogenhet för försörjningskedjans aktörer att spåra sina försörjningskedjor och skapa ett öppet och hållbart försörjningsnätverk.

Nyckelord: Spårbarhet, textile och mode, försörjningskedja, säker märkning, blockchain

摘要

纺织品和服装供应链安全可追溯系统开发研究

安全的可追溯系统不仅意味着能够识别、捕获和共享整个供应链（SC）中有关产品转换所需信息，而且还可以确保可追溯数据的安全性。由于信息不对称和缺乏透明度，纺织服装（T&C）行业在实施和保持足够的可追溯性方面经常会面临一些问题。供应链参与者发现很难信息识别和跟踪所涉及的供应商和次级供应商。此外，购物车不透明且几乎不可追踪的结构使得伪制品很容易进入流通。因此，安全可追溯性系统可以确定为一个必要的工具，以保证所需的可追溯数据在供应链参与者之间可以获取和共享，从而允许对供应链上的产品进行跟踪。此外，安全的可追溯系统可以帮助企业在经营过程进行各种决策，并保护仿冒品进入供应链。

本论文致力于纺织服装领域安全可追溯系统的开发研究。使用系统的方法检查产品和信息级别的可追溯性。在产品层面，本文介绍了一种可在织物表面打印的安全可追溯性标签。安全标签很难复制，经久耐用，能够承受正常的纺织品使用条件。除了可以作为产品标签外，还具有足够的安全性，以实现信息的可追溯。在信息级别方面，本文在对可追溯性数据进行分析的基础上，对可追溯性数据进行了分类，这些数据可以在企业对企业和企业对客户的不同级别实现共享，以实现安全的可追溯。随后，为纺织服装供应链提出了一个基于区块链技术的可追溯系统框架，可以在供应链网络系统中实现信息捕获和共享。该框架展示了共享数据基础设施在没有中央权威的情况下可追溯性的适用条件，并在供应链参与者之间建立了基于技术的信任基础。这个系统不依赖具有定制数据隐私和可访问性规则的中央权威，从而为所有供应链参与者提供了独特的机会、灵活性和权限，可以实现供应链数据的追溯，创建透明和可持续的供应链网络。

关键词： 可追溯性，纺织与服装，供应链， 安全标签，区块链

Acknowledgments

The work presented in this thesis was carried out at ENSAIT/University of Lille, France, University of Borås, Sweden and Soochow University, China under Erasmus Mundus Joint Doctorate Programme, Sustainable Management and Design for Textiles (SMDTex). I would like to gratefully acknowledge all the universities for their generous support in the preparation and compilation of the thesis, without which it might have never been possible.

Next, I would like to express my sincere gratitude to my supervisors Prof. Ludovic Koehl, Dr. Rudrajeet Pal, Prof. Yan Chen, Prof. Christine Campagne, and Dr. Lichuan Wang for their patience, continuous support, and immense knowledge. Their guidance helped me in the research and writing of this thesis. Special thanks to Dr. Rudrajeet Pal for his valuable suggestions and insights in compiling and drawing a red thread through the thesis. In particular, I am highly grateful to Dr. Vijay Kumar, who has always been a mentor, advisor, guru, and friend, without his motivational speeches, this thesis would never have been completed. Also, I would like to thank Dr. Sebastien Thomassey, Prof. Vladan Koncar and Prof. Pascal Bruniaux for enlightening me the first glance of research. My thanks go to Dr. Tina Carlson Ingdahl, Dr. Eva Gustafsson, Prof. Xianyi Zeng and Marie Hombert for providing continuous support in academic and non-academic matters. I am grateful to Dr. Jonas Larsson and Prof. Daniel Ekwall for their generous support and valuable insights.

Next, I would like to thank all the experts from industry and academia, who participated and contributed to this research work. Special thanks to Christophe Maestripieri (Archroma, France), Bernard Moronval (CHT Bezema, France) and Myriam Slaviero (Bluestar Silicones, France) for providing the chemicals and binders. Thanks to Christian Catel, Francois Dassonville, and Hubert Ostyn for their help in the laboratory work.

I am grateful to all my fellow colleagues and friends whom I met during my Ph.D. tenure, Dr. Sohail Yasin, Dr. Parag Bhavsar, Sheenam Jain, Sweta Iyer, Dr. Rakibul Islam, Biswajeet Mohanty, Edwin Kamalha, Dr. Ke Ma, Ann Vellesalu, Sara Harper, Ida Hermansson, Tuser Biswas, Ankit Dubey, Razieh, Molla Tadesse, Rushab Chopda, Jamila Siamwalla and Petchprakai Sirilertsuwat. Thanks for the stimulating discussions and for all the fun we had in the last four years. My special thanks to Sheenam Jain for always lending an ear and offering useful advice. I would also like to thank my SMDTex batch mates Neeraj Kumar Mandlekar, May Kahoush, Melissa Wagner, Jagadish Chandra Roy and Dr. Melkie Tadesse for their consistent encouragement and fruitful discussions. I am

also thankful to Imene Ghezal and Emelie Hultberg for their help in the translation of the abstract.

I must express my very profound gratitude to my parents, Maya Agrawal and Narayan Das Agrawal, and sisters Neha Agrawal and Sweta Agrawal for all the sacrifices they made on my behalf. Thanks for providing me with unfailing support and continuous encouragement.

Last, but by no means the least, I wish to thank almighty God for making this beautiful world.

Suzhou, China / May 11, 2019

Tarun Kumar Agrawal

List of appended papers

Paper I:

Kumar, V., Ekwall, D., and **Agrawal, T.K.** (20xx) Traceability in Textile and Clothing Supply Chain: Synthesizing the Potentials and Setting the Future Agenda. *Production Planning and control (In 3rd Revision)*

Paper II:

Agrawal, T.K. and Pal, R. (2019), Traceability in Textile and Clothing Supply Chain classifying implementation factors and information sets via Delphi study, *Sustainability*, Vol. 11 No. 6, 1698

Paper III:

***Agrawal, T.K.**, Koehl, L., and Campagne, C. (2018), "A secured tag for implementation of traceability in textile and clothing supply chain", *The International Journal of Advanced Manufacturing Technology*, Vol. 99 No. 9, pp. 2563–2577.

Paper IV:

***Agrawal, T.K.**, Campagne, C. and Koehl, L. (2018), "Development and characterisation of secured traceability tag for textile products by printing process," *The International Journal of Advanced Manufacturing Technology*, Vol. 101 No. 9, pp. 2907–2922

Paper V:

Agrawal T. K., Kumar, V., Pal, R., Wang, L., Chen, Y. (20xx) Blockchain-based framework for traceability- A case example of Textile and Clothing supply chain. *Computers in Industry (Submitted)*

Earlier version published as a book chapter in:

Agrawal, T.K., Sharma, A. and Kumar, V. (2018), "Blockchain-Based Secured Traceability System for Textile and Clothing Supply Chain", in Thomassey, S. and Zeng, X. (Eds.), *Artificial Intelligence for Fashion Industry in the Big Data Era*, Springer Singapore, pp. 197–208 (Book Chapter)

* Research work related with secured tag development secured **3rd position** at the "**Prix International Théophile Legrand de l'Innovation Textile – 2019**" by Foundation Théophile Legrand (under the auspice of The Foundation of France).

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1. Introduction

This introductory chapter of the thesis presents the background of traceability and its need, both generally and in the textile and clothing (T&C) supply chain in particular. It focuses on both the technological and managerial aspects of traceability and examines its influence on the supply chain, manufacturing, and the consumer. It further discusses the problem areas and challenges associated with traceability implementation that primarily motivated the objective and research questions of this thesis. The outcome of this section paves the way for the research process and methodologies followed during the study.

1.1. Background

Information asymmetry and lack of transparency have made global supply chains largely untraceable. Although linked through a network, supply chain partners find it difficult to identify and track all the suppliers and sub-suppliers involved (Grimm et al., 2016). Ignorance and lack of a traceability mechanism have led to a series of unfortunate events in the past decade that have raised serious concerns from the public, industries, community activists, governments, and non-governmental organizations (NGO) over supply chain safety and sustainability (Campos and Míguez, 2006; Comba et al., 2013; Hoque et al., 2016; Phau et al., 2015; Sarpong, 2014). In addition, consumer interest in sustainable products is increasing; thus, they are adopting ethical buying practices. Consumers increasingly wish to know the facts related to product origin, environmental footprint, manufacturing procedures, and ethical practices (Garcia et al., 2019; Lee and Shin, 2010; Saha et al., 2019; Svensson et al., 2012). They need assurance that manufacturing and logistical conditions of the supply chain can guarantee product safety. Product deficiency makes customers restless and inquisitive and creates distrust of products offered on the market (Chrysoschoidis et al., 2009).

Additionally, opaque and untraceable supply chains enable the intrusion of counterfeits as well as Intellectual Property (IP) attacks. According to a report by IBM on the “Security trends in the manufacturing industries” (McMillen, et al., 2016), the manufacturing sector, including textile and automotive industries, are under potential threats from data attackers targeting their intellectual property and operations information. These industries are already suffering massive losses (in the form of finances and brand identity) every year due to counterfeit products. These products not only damage the brand image and economies, but cause significant physical harm and moral disgust (Amar et al., 2018; Ekwall, 2009; Moutinho and Bian, 2011). Counterfeit goods in global trade accounted for nearly \$461 billion (€338 billion) in 2013, almost 50% higher than the amount reported in

the first such study by the Organisation for Economic Co-operation and Development (OECD) in 2008 and 2009. These trades significantly impact the revenue collections and the job market (Wajzman et al., 2015). The top five high-risk sectors included food; pharmaceuticals; cosmetics; articles of leather and handbags; and clothing and textile fabrics.

In this regard, supply chain integration through traceability implementation has proven to be a useful solution to counter the abovementioned challenges (Nativi and Lee, 2012). Traceability could be a preventive measure to limit product safety scandals and facilitate recall management (Giannakis and Papadopoulos, 2016). It is a vital sub-system of quality management that can confirm the product quality and/or identify safety concerns with contaminated or potential carcinogenic products at an early stage before reaching consumers (Cheng et al., 2013; Jd, 2001; Rijswijk and Frewer, 2012). Besides, traceability can facilitate supply chain visibility, inventory management, risk management, anti-counterfeiting, recycling, trend forecasting, transparency, and product branding (Corbellini et al., 2006; Egels-Zandén et al., 2015; Gobbi and Massa, 2015; Goswami, 2014; Kumar et al., 2016a; Rijswijk and Frewer, 2012; Sarpong, 2014). Considering the direct impact of contaminated edibles on consumer health, traceability is a significantly researched and widely adopted mechanism in the food and pharmaceuticals supply chains (Abad et al., 2009; Charlebois et al., 2014; Comba et al., 2013; Dabbene et al., 2014; Mackey and Nayyar, 2017; (Nel) Wognum et al., 2011; Olsen and Borit, 2018; Storøy et al., 2013; Thakur and Donnelly, 2010). Besides, a certain level of traceability is a legal obligation for the food and pharmaceuticals supply chains operating in most parts of the worlds, including EU, United States, and Japan (Food Standards , Australia and New Zealand, 2017; General Food Law - EU, 2016; Ministry of Agriculture Forestry and Fisheries of Japan, 2007; U.S.Food and Drug Administration, 2018).

In the case of the T&C supply chain, traceability is still a voluntary measure and partially used by brands to advertise their sustainable practices. However, recent catastrophic events, for instance, Rana Plaza in Bangladesh (Marshall, 2014), the controversial cotton cultivation in Turkmenistan and Uzbekistan (Russell, 2016), Syrian child refugees working in Turkey textile industries (Johannisson, 2016), and raw cotton procurement from ISIS-captured regions (Malm, 2015) have gained significant attention internationally and drawn the attention of authorities and customers toward unethical practices and opaqueness of the T&C supply chain (Hoque et al., 2016). Additionally, T&C brands and retailers are suffering huge counterfeit-related losses due to limited, or lack of, traceability (Corbellini et al., 2006; Kumar et al., 2017a). Responding to these issues, government agencies, industries, research institutes, and NGOs are collaborating and working toward the development of domain-specific technologies, regulations, and guidelines for

traceability implementation in the T&C supply chain (Alves et al., 2014; Bindi et al., 2016; Gobbi and Massa, 2015; Kumar, 2017; OECD, 2017; Richero and Ferrigno, 2016; Strähle and Merz, 2017).

In light of the above, this PhD research focused on secured traceability implementation in the T&C supply chain. It is noteworthy that the level of traceability in a supply chain largely depends on the extent of information sharing, level of accuracy, and efficiency of product tracking and authentication (Kumar et al., 2017b; Li et al., 2017; Sarpong, 2014; Thakur and Donnelly, 2010). Thus, traceability implementation requires efficient management and synchronization of various activities, processes, and traceability sub-systems. This thesis draws upon the system-of-systems (SoS) approach (Sage and Rouse, 2009) to contribute toward the development of a secured traceability system for the T&C supply chain. Several studies in the past have utilized the SoS theory to visualize and develop complex defense systems, transportation systems, and aircraft systems. Relatively, limited research has been conducted to examine economic activity-based systems that involve human activities and material and information exchange. In view of this, the thesis aims to theoretically contribute to traceability literature by visualizing the secured traceability system through the SoS lens for better understanding of the concept, and practically develop subsystems that can be integrated to achieve secured traceability. A complex system consists of collections of a task-oriented system-of-systems (ibid), therefore, the thesis visualizes the secured traceability system at the product and information level and illustrates its configuration through an example supply chain, using three consecutive supply chain partners coded A, B, and C as shown in Figure 1-1. Partner B functions as an upstream supplier to Partner C and, at the same time, Partner B has its own supplier, Partner A, from whom Partner B receives or purchases inbound materials. To implement a secured traceability system, it is vital that, while exchanging the physical products, the supply chain partners also share related traceability information and simultaneously ensure security of the information and product. This would require two component systems; one for information capturing and secure sharing (information traceability system) and the other for physical product exchange while securing it from being copied or lost (product traceability system). These sub-systems are connected to form an aggregate system that serves the greater goal of secured traceability in the T&C supply chain. A detailed explanation and theory of the SoS approach are provided in the Frame of Reference chapter (Chapter 2).

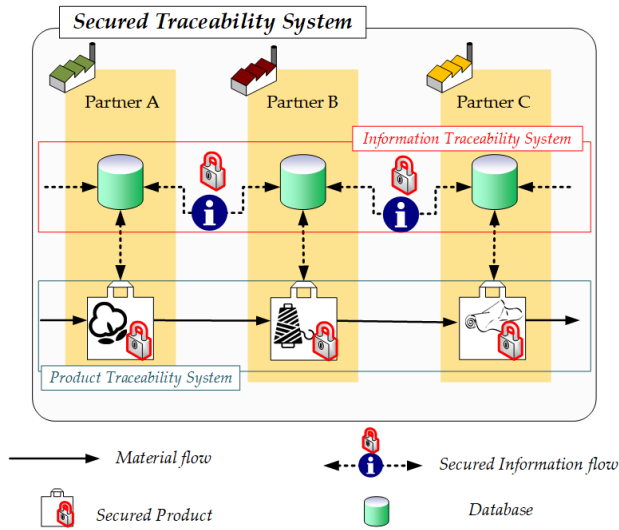


Figure 1-1: Secured traceability system

1.2. Research problem

The T&C supply chain is a complex system with numerous materials, has many possible permutations with several processes, and involves various actors. As described above, the T&C supply chain is a system-of-systems (sub-systems or interacting elements), where each sub-system contributing to the supply chain functions and interacts in the form of a network structure. The supply chain partners are usually located in different parts of the world, and the journey from the fiber to the finished product is remarkably long and complicated (Thomassey, 2010). The upstream or production segment of the T&C supply chain that is predominantly involved in the raw material generation and product manufacturing is typically located in developing countries (due to the availability of low-wage semi-skilled workers). On the other hand, most of the buyers/retailers and customers are in developed countries, with high disposable incomes. All these complexities make supply chain integration quite challenging, resulting in an opaque network with limited information exchange among the partners.

The T&C supply chain has certain unique features that differentiate it from other supply chains. For example, the T&C supply chain mostly relies on voluntary guidelines and industrial compliances; hence, they lack standards and regulatory checks, compared to the food and pharmaceuticals supply chains (Kumar et al., 2017b). This gives a free hand to the suppliers and they often follow unethical practices to reduce the production costs, which remain untraceable. In addition, it becomes difficult to identify counterfeit

products in the supply chain due to lack of product traceability. Besides, the product line changes rapidly, with typically 5-6 collections released per year. Each style is unique with different materials, silhouettes, structures, and colors, which are not usually repeated in the next fashion seasons (Gobbi and Massa, 2015). This discourages the concept of modularization in the supply chain, resulting in numerous materials, intermediate products, and distributed suppliers/sub-suppliers. Each material has different characteristics; thus, defining a granularity level and tracing each unique material is challenging. Most importantly, the T&C products are usually low-priced with variety, which deters the use of expensive ICT technologies for efficient supply chain monitoring.

These complexities are adding to the magnitude of various problems in the T&C supply chain that need immediate attention. One of the major issues is counterfeit products that are causing huge losses in the T&C industries. Counterfeits account for almost €26.3 billion direct estimated sales loss by legitimate EU industries every year, with the biggest loss being in the retail and trade sectors, which have an estimated loss of €10.8 billion in sales per year (OECD/EUIPO, 2019). The second major issue is inefficient product recalls, which are primarily caused by the lack of information about the product traceability. This results in financial losses and jeopardizes a company's reputation (Chen et al., 2009). According to the Rapid Alert System (RAPEX) for dangerous non-food products in Europe, textile, clothing, and fashion products are among the top five most notified products, contributing to almost 22% of the total recall notification between 2010-2017 (European Commission, 2018). These products not only dilute the brand's identity, but are also a serious concern for the market surveillance authorities and border customs officials who face the challenge of identifying the origin or accountable actors. Another major issue is lack of supply chain visibility and transparency, which plays a crucial role in making informed decisions, particularly in the T&C supply chain where actors are situated at distinct locations (Caridi et al., 2010; Chapman, 1995; Egels-Zandén et al., 2015). T&C production activities are usually carried out at locations with inexpensive labor (Egels-Zandén and Hansson, 2016), where the offshore suppliers often indulge in malpractices such as marginal salaries, child labor, and unhealthy working conditions. Moreover, opaque supply chains provide a certain level of autonomy to offshore suppliers to choose their policies or standards that are not visible to the buyers (Ekwall, 2009). For instance, Victoria's Secret, a famous fashion brand, has been indicted for using child labor in the organic cotton farming (Phelan, 2011), the Rana Plaza catastrophe in Bangladesh (Hoque et al., 2016), and the fire incident in a textile factory in Pakistan (Walsh and Greenhouse, 2012) were a result of the opaque supply chain.

1.3. Research gap

According to the OECD (2017) report, traceability is one of the mechanisms that can be adopted for the smooth functioning of the T&C supply chain and to address the issues mentioned above, such as product counterfeit, inefficient recall execution, and lack of visibility. However, despite its various benefits, traceability is still an evolving and less adopted mechanism in the T&C supply chain. Some of the main reasons are *lack of a dedicated and inexpensive technology* developed considering the complex T&C supply chain structure and product range, *lack of awareness and consensus* about the possible benefits of a single traceability system, and *absence of universal traceability rules and regulations* for the T&C supply chain (Richero and Ferrigno, 2016). Thus, traceability is a voluntary measure and is partially accepted by brands (Kumar et al., 2017a). Some supply chain stakeholders analyze traceability from an organizational-policy perspective and consider it as a tool that can create transparency and visibility in the supply chain, for example, in the case of Nudie Jeans and Honestby (Egels-Zandén et al., 2015; Strähle and Merz, 2017). Others consider it as a source of competitive advantage that can boost market sales and can project a positive image of the brand, which is highlighted in a study by Goswami (2014) for the T&C supply chain and by Canavari (2010) for the fruit supply chain. It is perceived as a tool to control supply chain operations by effectively tracking and tracing products when they traverse the supply chain (He et al., 2008). Due to these limitations and lack of a substantial history of promoting traceability, there are not enough comparable cases, and traceability is still a new and understudied mechanism in the T&C supply chain. Below are some of the main reasons for this:

1.3.1. *Absence of regulations and consensus for a single traceability system*

Unlike the food and pharmaceuticals sectors where traceability has a set minimum level (Alfaro et al., 2015), the T&C supply chain does not have a formal regulation for traceability, which is why it is still a voluntary measure perceived differently by different stakeholders. As a result, most of the research in the past have identified multiple traceability standards, guidelines, and initiatives with divergent approaches. All this works against the notion of a single traceability system for the T&C supply chain. Contrary to this, the development of guidelines or standards would require support and consensus among different supply chain actors, especially brands and retailers (Richero and Ferrigno, 2016). In view of this, associations such as Sustainable Apparel Coalitions (Radhakrishnan, 2015) are bringing together world leaders in T&C businesses and working toward the development of the Higg Index to measure the extent of traceability and sustainability.

1.3.2. *Data management protocols*

Data management protocols are essential to stipulate rules for data capturing, assessing, evaluation, reporting, and sharing, while at the same time handling privacy and security concerns (Manos et al., 2006). Traceability is an inter-organizational concept, and managing product transformation data is a critical component of it that requires interoperability among different production and data management systems (SCM, PLM, and ERP). However, due to the heterogeneous nature of the T&C supply chain, which involves numerous partners, each using different data systems, the absence of a standard data management protocol with common ontologies limits effective information exchange (De Sabbata et al., 2010). Furthermore, the guidelines are limited to national levels for the use of e-business messaging, such as Electronic Data Interchange (EDI). This creates issues during data interpolation and the exchange of data among the supply chain actors that are located internationally, resulting in most transactions having wrong or incomplete information (Hunter and Valentino, 1995). Previous research in this regard describes possible rules for traceability data capturing and exchange in the T&C supply chain (Bindi et al., 2018; Kumar et al., 2017b). Nonetheless, the principles of security and data privacy still need to be incorporated.

1.3.3. *Information sharing and security*

Information is a vital asset of a traceability system that needs to be adequately captured and securely shared among authorized supply chain actors (having the right to view that particular information). In the T&C supply chain (except the retailer), each partner takes the raw material as input from an upstream partner(s) and performs various operations on it to make the final product that passes to the next downstream partner. This process is replicated repeatedly until the product reaches the retailer. As a result, a significant amount of information is generated at each stage that is important for traceability data management. This information is a critical component of the supply chain, and each partner should work toward efficient data capturing, controlling its flow, and protecting its confidentiality. Presently, there is no precise classification of traceability information that needs to be shared among supply chain actors at the business-to-business (B2B) and business-to-customer (B2C) levels (Kumar et al., 2017b), which makes the realization of a complete traceability system complicated. Besides, a high level of unsecured information sharing without restriction among all supply chain partners can result in financial and legal risks (Informal Product Traceability Expert Group - Final Report (2013)) and has the potential threat of IP infringement. Additionally, the supply chain partners, especially the suppliers are reluctant to make alterations in their own information systems that can add extra costs in their manufacturing process and can potentially disclose their sensitive

information, which is a source of their competitive advantage. Thus, it can be anticipated that this requires planning, classification of the essential traceability information and development of a secure information sharing framework that can ensure traceability in the supply chain and at the same time secure stakeholders' interests, which is currently missing in the T&C supply chain (Kumar et al., 2017b; Richero and Ferrigno, 2016; UN Global compact and BSR, 2014).

1.3.4. Product traceability and security

Besides information asymmetry and security issues, product traceability and security are a serious concern in the T&C supply chain. According to a report by the European Union (EU) Intellectual Property Office Observatory, due to counterfeit products, the T&C industry loses 9.7% of sales, 26.3 billion euro of revenue per year in the sector, 362,625 direct jobs, and 8.1 billion euro of revenue by the government (Wajzman et al., 2015).

At present, the widely used mechanisms for tracking and tracing a product in the supply chain and securing it from replication are in the form of traceability tags such as quick response (QR) codes, barcodes, and radio frequency identification (RFID). These tags encode product information that is used for product identification, tracking, and information exchange. They are printed or externally attached to the product/packaging and act as a reference to record the product's footprint when it moves along the supply chain. Therefore, to realize complete traceability, it is essential that the traceability tag remains associated with the product throughout the supply chain or, ideally, throughout the product's lifecycle (Agrawal et al., 2016; Corbellini et al., 2006; Ekwall, 2009; Informal Product Traceability Expert Group - Final Report, 2013). Further, to secure the supply chain from counterfeits, the traceability tag should be unclonable and undetectable to prevent the encoded data of the original tag to be incorporated into a similar copied tag, and/or an original tag being attached to a counterfeit product. As a result, it is difficult for the consumer to distinguish genuine products from counterfeits.

Thus, the prime conditions for implementing product traceability in the T&C supply chain is an association of the product with the traceability tag and its protection from tampering or replication. Usually, off-the-shelf technologies in the form of barcodes, QR codes, and simple RFIDs are easy to copy and provide minimum security to the product. Most of them cannot withstand textile use phase mechanical agitation and are destroyed or detached from the product. On the other hand, electronic chip-based RFIDs tags affect user privacy and create problems during the recycling process (Köhler et al., 2011; Wyld, 2010) due to their long-range readability (sometimes up to 12 m).

1.4. Purpose

The purpose of this research work is to contribute toward the development of a secured traceability system for the T&C supply chain. It draws upon a suitable lens of the SoS theory and examines traceability at the product and information levels. For traceability at the product level, the thesis investigates different existing technologies and aims to introduce an integrated secured traceability tag system for T&C products. This tag should be hard to replicate, inexpensive, eco-friendly, and customer-friendly. It should be durable enough to withstand washing and abrasion during the textile use phase and can be read and validated using a smartphone camera to authenticate the textile product and trace back its history. At the information level, the thesis aims to explore and classify empirically, through a consensus of T&C supply chain experts, traceability information that can be shared at B2B and B2C levels and to subsequently propose a secured information traceability framework for the T&C supply chain. The following is developed through experimental investigation and theoretical analysis and uses three research questions described in the next section.

1.5. Research questions

This thesis aims to understand and contribute to secured traceability in the T&C supply chain. Accordingly, three research questions have been identified that aim to broadly address the issues related to secured traceability in the T&C supply chain. As shown in Figure 1-2, research question 1 (RQ1) focuses on the overall secured traceability system, research question 2 (RQ2) focuses on the product traceability system, and research question 3 (RQ3) focuses on the information traceability system. Thus, this thesis visualizes secured traceability systems through the SoS lens and contributes to the development of two sub-systems for information traceability and product traceability.

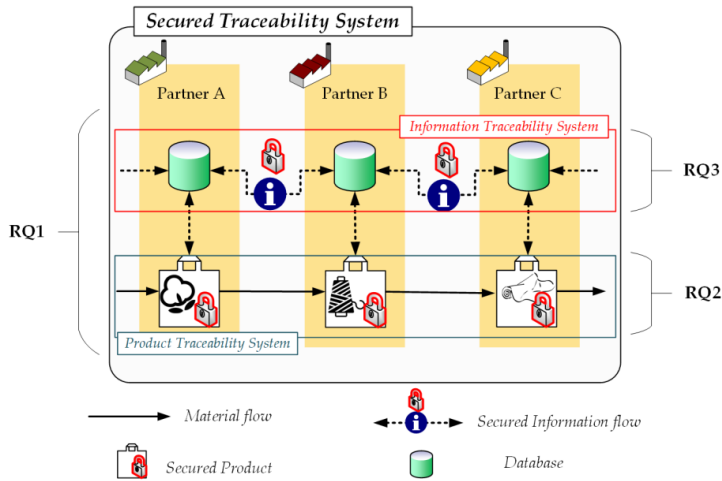


Figure 1-2: Secured traceability system and link with the research questions

RQ1. What are the different factors influencing traceability in the T&C supply chain?

As explained under Section 1.3.1, with regard to the research gap, there is a lack of consensus among T&C supply chain stakeholders regarding the potential benefits of single traceability in the T&C supply chain. In this context, as an initial step toward the development of a secured traceability system, RQ1 focuses on exploring and ranking the key factors that influence higher management decisions for adopting a traceability system for the T&C supply chain. These factors are essential and can play an important role in designing and developing a secured traceability system. They can influence the system's characteristics and act as a basis for the complete system.

RQ2. How can product traceability and security in the T&C supply chain be ensured?

As stated in Section 1.3.4, lack of dedicated product traceability technologies has made the T&C supply chain vulnerable to attacks targeting IP and intrusion of counterfeits. Off-the-shelf technologies in the form of RFIDs and barcodes can be copied (lack of a security mechanism), are expensive (in the case of unclonable RFIDs), are detachable, have low wash and abrasion resistance, and can compromise user privacy. In view of this, the thesis aims to introduce a product traceability system consisting of integrated textile tags that can overcome the drawbacks of the existing systems and ensure product traceability and security in the T&C supply chain.

RQ3. How can information traceability and security in the T&C supply chain be ensured?

To address the challenges in Section 1.3.2 and Section 1.3.3, the thesis aims to introduce and work toward the development of an information traceability system for the T&C supply chain. It empirically explores and classifies the traceability information that needs to be captured and shared among businesses and with customers through a traceability system and subsequently proposes a framework for secured information traceability in the T&C supply chain.

1.6. Research delimitations and limitations

As with all studies, there are certain delimitations that apply to this current research. Essential among these are the delimitations concerning the scope of the study that are mainly governed by the time and resource constraints. The thesis aims to contribute to the development of a secured traceability system, thus, there are certain aspects that require exploration and in-depth research to develop a complete system. Considering the fact that traceability is a broad concept that relies on technological competence, organizational policies/acceptance, government regulations, and most importantly, the motivation to adopt the system by the supply chain partners and willingness by customers to buy an authentic product, time and resource constraints somewhat forced the author to delimit the context. Thus, the thesis focuses on the technical aspects and delimits the study by excluding a focus on government regulations, supply chain partners' motivation, and customers' willingness to buy authentic products. Additionally, considering the diverse nature of the T&C supply chain, which involves various raw materials and intermediate products, this current study, related to a product traceability system, focuses mainly on the downstream part of the supply chain. Thus, it introduces and demonstrates a feasibility analysis of a secured tag system that can be integrated into the final textile product before it is passed on to the consumer. Nevertheless, at the information level, the thesis focuses on a complete supply chain and proposes an information traceability system.

1.7. Outline of the thesis

Chapter 1 provides the background of the study, focusing on the scope and practical relevance of this thesis. It presents a brief overview of supply chain traceability, its importance in general and its relevance to the T&C supply chain in particular. Also, the thesis outlines the problem areas and research gap that this study aims to address and, subsequently proposes the research questions (RQs) that are pursued in this PhD work.

Chapter 2 presents the frame of reference for the thesis. It delivers a theoretical foundation for a traceability system, starting from a broad explanation of traceability (its origin,

various definitions, and classes), followed by an explanation of its three main components. Further, this chapter explains the contribution of traceability to sustainable development and also gives an overview of the theoretical lens (in the form of the system-of-systems theory) that formed the basis of this study.

Chapter 3 brings together the methodological framework followed in this study to answer the RQs formulated in this research. It further categorizes the appended papers according to the methodology, research procedure, and the scientific reasoning behind them.

Chapter 4 presents a short overview of individual papers appended in this thesis. It also includes a summary of the five papers that form the thesis and explains their linkage to each other and to the RQs.

Chapter 5 analyzes the appended papers and answers the RQs formulated in this thesis and relates them to the frame of reference presented in Chapter 2.

Chapter 6 presents the conclusions of the thesis. An analysis is made regarding the applicability of the proposed secured traceability tags and the blockchain-based traceability system. It further highlights the theoretical contribution of the thesis.

Chapter 7 presents recommendations for future research.

2. Frame of reference

This chapter gives an insight into the relevant literature and provides a frame of reference to the thesis. Sections 2.1 and 2.2 provide a brief history of the evolution of supply chain traceability, its definitions, and types, along with the primary secured traceability definition that has been followed in this thesis. Section 2.3 lays the ground for RQ1 and provides a summary of various factors influencing traceability in the T&C supply chain. Section 2.4 and 2.5 focus on the components of the traceability system and blockchain technology and thus provides a frame of reference for RQ2 and RQ3. Finally, Section 2.6 explains the system-of-systems theory that has been followed in this research.

2.1. Supply chain traceability

According to the Asian Development Bank Institute report on food safety and ICT traceability, traceability systems trace their origin to mid-1930s Europe. They were initially used to prove the origin of high-quality food, such as French champagne. Gradually, capitalizing on the growing consumer demand for product safety assurance, marketing strategists started using traceability systems for branding. The practice is still popular and can be widely observed in the form of labeling trends, such as “fair trade,” “organic,” or “eco-friendly.” Later, with globalization and geographic expansions of supply chains in the 1990s, supply chain actors, including consumers and governments, further responded to the incentives to develop efficient and consistent traceability systems incorporating global standards and advanced technologies. It was during this phase that the International Standards Organization (ISO) 8402:1994 quality management standards defined traceability as:

[...] the ability to identify and trace the history, distribution, location, and application of products, parts, and materials (ISO, 1994).

In the past decades, traceability has emerged as a critical supply chain component in almost all sectors and is used extensively in different contexts (Goswami, 2014; Guercini and Runfola, 2009; Kumar et al., 2017a; Machado et al., 2018). It has become one of the reliable solutions for organizations looking for a mechanism to track and trace products, manufacturing activities, and collect related information in order to manage business activities and comply with government regulations. Adding a component of sustainability in this widely accepted ISO definition, the United Nations (UN) Global Compact and Business for Social Responsibility(BSR) (2014) propose a more comprehensive definition of traceability:

The ability to identify and trace the history, distribution, location, and application of products, parts, and materials (ISO, 1994), to ensure the reliability of sustainability claims, in the areas of human rights, labor (including health and safety), the environment and anti-corruption.

However, traceability applications vary according to the sectors and types of the supply chain (Shamsuzzoha and Helo, 2011). For instance, in logistic companies, traceability is more about tracking and tracing the consignments using unique traceability codes, when they traverse the supply chain (Bujak and Zajac, 2013), while, in the case of food and pharmaceuticals sectors (which directly impact consumer health), in addition to product tracking and tracing, traceability also facilitates record keeping and maintenance of information to comply with government regulations (Charlebois et al., 2014). Similarly, in the T&C sector, traceability is still a voluntary measure with brands using it to project a positive image and convey a sustainable aspect of the product to customers (Egels-Zandén et al., 2015). Regardless of its numerous applications, the core idea of traceability remains the same and is defined by Olsen and Borit (2013) as,

[...] the ability to access any or all information relating to that which is under consideration, throughout its entire lifecycle, by means of recorded identifications.

In this definition, “that which is under consideration” refers to the product or Traceable Resource Unit (TRU) that is typically a tradeable, logistics, or production unit. Often, there is a hierarchy of TRUs. It can be an individual product or box of products that can be a part of a pallet, which in turn can be a part of a container (Olsen and Borit, 2018). The form, structure, and/or specification of TRUs change and are modified throughout the supply chain (Moe, 1998). For instance, in the T&C supply chain with a woven cotton garment as the end product, the TRUs start as bales of cotton fibers that are processed and formed into cones of yarns, which are in turn weaved into rolls of fabric, and these fabrics are stitched and shaped into 3D garments that are passed on as the final TRU to the customers. Thus, traceability in the supply chain is about efficiently tracking the TRU “throughout its entire lifecycle” and capturing related information “by means of recorded identifications.”

It is clear from the above definition that a traceability system comprises two essential and inseparable component systems managing the product and its information. For efficient supply chain traceability, the traceability system should seamlessly capture and share information related to TRU transformation and related attributes with the supply chain

partners involved. At the same time, it should also assure unique identification of individual TRUs to ensure tracking and tracing of products when they move along the supply chain.

However, acknowledging security issues in supply chains in the form of information leakage (Bhargava et al., 2013; Zailani et al., 2015) and product counterfeits (He et al., 2008; Kumar et al., 2017c), recent studies suggest incorporation of security mechanisms in the traceability system (Guillermo Azuara et al., 2012; He et al., 2008). In addition to seamlessly capturing and sharing information and tracking/tracing products, the traceability system should also be secured to prevent any attack targeting intellectual property. This is also known as a “secured traceability system.” This security mechanism can be incorporated at two levels, first at the business or information level to ensure seamless and secure information sharing and, second, at the product level to prevent the intrusion of counterfeits in the supply chain.

Following the definition of Olsen and Borit (2013) and the notion of security, this thesis intends to investigate traceability systems at both information and product levels for implementation in the T&C supply chain and to conceptualize the secured traceability system shown in Figure 1-1. Besides structure, like other systems, traceability systems have different interrelated people, processes, and technologies interacting and functioning together. Some of these are as follows:

2.1.1. Role of government regulations

Government regulations are introduced mainly to address issues related to documentation/record-keeping requirements, labeling (including origin), and recall management. These regulations play an essential role in traceability system development and, to some extent, determine the traceability level of the supply chain. For example, there are traceability regulations in the food supply chain that require a certain level of traceability to track and trace product origin, processing methods, and storage conditions, and to authenticate all the processors involved (Charlebois et al., 2014). On the other hand, traceability is still a voluntary measure in the T&C supply chain due to the absence of government regulation (Richero and Ferrigno, 2016).

2.1.2. Role of buyers' requirements

In most supply chains (including T&C), the buyer is the supply chain leader and has the upper hand in determining the supply chain rules. Apart from government regulations, buyers impose the strictest traceability requirements based on their market demand perception and laws (Kumar et al., 2017b). In a competitive market, to safeguard their

interest and minimize risk, the buyer can demand any accessible information and determine the level of traceability in the supply chain. They can ask suppliers to become certified and compliant to an open standard (Comba et al., 2013). For example, open standards with traceability requirements (also applicable for the T&C sector) include GS1 Global Traceability Standards, ISO 22000, British Retail Consortium Global Standards, etc.

2.1.3. *Certification systems*

Apart from open standards, there are various certification systems, such as Fair Trade, Organic Cotton, and Carbon certificates to address ethical and sustainability concerns (Almeida, 2015). The certificate requires information documentation, process awareness, and product tracking, thus determining the extent of traceability in a supply chain. Based on the auditing, these certification systems can be divided into three categories. The first category is first party or self-claimed certification—practiced in a small or vertical supply chain (with the consumer and the supplier as the only partners)—where the consumer and the seller have a face-to-face relationship and mutual trust. The second category is second party certification, where an intermediate supply chain partner develops a close relationship with the supplier (originator) and acts as a guarantee for the product authentication and provides information to the customer—it is similar to product branding. The final category is third-party certification, in which a third party is entrusted with auditing the production process and flow in order to ensure that the product and the process abide by the standard conditions—this is very common in complex and widespread supply chains (e.g., T&C) (Meuwissen et al., 2003). Traceability requirements for such third-party certification are maximum, to record the trail and capture relevant information concerning all third-party certification at each supply chain stage.

2.1.4. *Use of information and communication technology (ICT)*

Traceability systems and ICT are closely associated and ICT acts as a facilitator of traceability (Bindi et al., 2019). ICT automates product identification, data capturing, data transfer, and data validation. Product identification requires the labeling of each TRU for secure authentication and tracking at different stages of the supply chain (Storøy et al., 2013). Data capturing involves recording and documentation of processes (including date, time, locations, and temperatures) through sensors and other devices that the product undergoes during its traverse in the supply chain (Abad et al., 2009). Data transfer or sharing requires the effective sharing of information across supply chain actors including customers, auditors, and government regulators. Finally, validation and authentication of the product and information are required to affirm the claims. These validations can be

done through a scientific test, chemical analysis of products, or by varying the trail of traceability information (Ting and Tsang, 2013).

It can be well inferred that ICTs are a crucial element of traceability, and it requires the integration of various technologies to achieve a complete traceability system. ICTs form an integral part of the food, automotive, and pharmaceuticals supply chains for traceability application (Abad et al., 2009), however, their application in the T&C supply chain are still limited. One of the possible reasons for this is the limitation of ICTs developed considering the distinct features of the T&C products and supply chain (Richero and Ferrigno, 2016). Hence, the focus of this thesis is to contribute to this area by introducing and testing technologies that can integrate the T&C supply chain and facilitate traceability implementation. The next sections discuss the components of traceability systems and the contribution of ICTs to each of them.

2.2. Types of traceability

Traceability can be divided into the following two types.

2.2.1. External or chain traceability

As the name indicates, external or chain traceability focuses on the entire supply chain level, outside of an individual business entity. External traceability is among supply chain partner-companies situated at different geographical locations and depend on the presence of internal traceability in an individual partner-company. Thus, external traceability is challenging to achieve and requires partners' integration and cooperation at all stages of the supply chain. It has many advantages, including efficient product recall, better quality monitoring, product marketing, and, most importantly, facilitation of compliance with government requirements and regulations (Liang et al., 2015; Moe, 1998; Senneset et al., 2007).

2.2.2. Internal traceability

As opposed to external traceability, internal traceability focuses on recordkeeping or capturing of information related to a product within a particular operation, company, or manufacturing facility. It relates to the collection of the data and tracking product internally, once it is received as a raw material or intermediate product from an upstream supplier, through all in-house processes, to the final product before it is delivered to the next downstream buyer. It has the advantages of productivity improvement, production monitoring, and cost reduction. Internal traceability is an essential and mandatory criterion for external traceability. In other words, in order to have external traceability, it

is vital to have internal traceability at an individual company level (Marconi et al., 2017; Moe, 1998; Rouabhia-Essalhi and Amirat, 2017).

2.3. Factors influencing traceability in the T&C supply chain

As mentioned before, despite the multiple benefits, traceability is an evolving and less adopted mechanism in TC supply chains. Thus, steps are required to develop consensus among the T&C supply chain partners for development and adoption of a complete traceability system that can facilitate seamless capturing and sharing of information at each supply chain stage. In this direction, an initial step could be to explore and rank essential factors influencing traceability in the T&C supply chain. These factors can bring out the perceptions of the practitioners and encourage traceability adoption in the T&C supply chain.

◆ Transparency and visibility

Transparency is the extent to which information is shared among the supply chain actors (including customers), and visibility implies the extent to which a buyer can trace back the details about the suppliers and sub-suppliers involved in the construction of the final product. It is a useful tool for the partners involved to make informed decisions (Chapman, 1995). Both are in high demand in the current scenario and are crucial elements for a sustainable T&C supply chain, and therefore require an effective traceability mechanism that can connect and integrate all the involved supply chain partners. The T&C supply chain has a complex and widespread network, with most of the upstream suppliers located in the developing countries (Egels-Zandén and Hansson, 2016; Gobbi and Massa, 2015). Therefore, production processes need synchronous functioning in order to reduce lead-time and meet growing market demands (Thomassey, 2010). In light of this, traceability-based supply chain visibility and transparency can help to gain insight in the production activities, synchronize its functioning, and reduce handling costs, thus leading to efficient resource utilization (Cheng et al., 2013; Guercini and Runfola, 2009; Töyrylä, 1999). For better transparency and visibility, various traceability information related to a product (e.g. origin, composition, manufacturer/supplier details, and product specifications), process (e.g., timestamps, process name, and details), quality (e.g., certification, audit reports, and tracking) and social/environmental (e.g., social audit and carbon footprints) can be shared among businesses and customers (Kumar et al., 2017b; Thakur and Donnelly, 2010). Moreover, traceability has been used by brands to convey their sustainable practices and a mechanism to answer anti-sweatshop campaigns. For example, Honestby is one of the leading brands disclosing most of the supply chain

traceability information, and Nike, Adidas, and H&M have started disclosing the names of their suppliers (Egels-Zandén et al., 2015; Strähle and Merz, 2017).

◆ **Product maintenance**

Textile product maintenance, in its use phase, especially during washing and drying, influences the durability and recyclability of the textile product. A traceability system is essential to share product maintenance aspects with the end-user, and at the same time, an active traceability mechanism can be programmed to record product use-phase data (e.g., number of washes) or automatically adjust washing/drying parameters (Kim et al., 2007; Kumar et al., 2017b; Legnani et al., 2011). Additionally, traceability data related to product maintenance and use are a crucial requirement for recycled material standards that certify the content, chain of custody, and sustainability of the recycled content.

◆ **Market surveillance**

Market surveillance by public authorities that closely observe products in the market and ensure that the products conform to the applicable law requires crucial information about the history, origin, and composition of the product/raw material and the intermediate product. Examples of such authorities are the Administrative Cooperation Group (AdCos) and the Rapid Alert System (RAPEX). A traceability mechanism connects the supply chain partners and enables tracking and tracing of a product at each stage of the supply chain. The other aspect of consumer protection includes safety from harmful products (Kumar et al., 2016a). Traceability plays an important role, as it enables easy identification of recalled products and, secondly, consumers can trace if products are recalled. Cases such as Rana Plaza in Bangladesh (Marshall, 2014), the controversial cotton cultivation in Turkmenistan and Uzbekistan (Russell, 2016), Syrian child refugees working in Turkey textile industries (Johannisson, 2016), and the raw cotton procurement from ISIS captured regions (Malm, 2015) have gained public attention internationally, and government agencies have issued guidelines suggesting traceability as an effective mechanism to counter these problems (Marshall, 2014; OECD, 2017). Moreover, research support by an informal expert group on product traceability (2013) describes traceability as an effective mechanism for market surveillance and recall management.

◆ **Reverse logistics and renting, sharing, and reuse**

Reverse logistics management involves the collection, sorting, and segregation of the used product during recycling and inventory management during remanufacturing and return. An automated reverse logistic system using traceability tags and information can

save costs and time and enable effective recycling, reuse, and renting of products (Wyld, 2010).

◆ **Quality monitoring and the recall mechanism**

Recording and sharing of quality-related information enable effective control and monitoring of product quality and recall management to identify the origin of a defect. In the case of recalls, a traceability mechanism can trace the origin of the defect and locate the responsible partner. The T&C supply chain involves numerous actors and diverse sets of raw materials with limited traceability. Taking advantage of such an opaque supply chain, suppliers often use inexpensive and banned raw materials that can affect consumers' health. Textile, clothing, and fashion products are among the top five most notified products contributing to almost 22% of the total recall notifications between 2010-2017 in the EU, as reported by RAPEX (European Commission, 2018). Moreover, in such recall cases, it is often difficult to identify the accountable partner. Therefore, it becomes essential to monitor quality at each step of the supply chain to ensure the quality of the final product (Cropper and Wang, 1995; Gobbi and Massa, 2015). For this reason, traceability can enable identification of the source of the defect and the accountable actor, thus optimizing product quality and helping in managing recall (Cheng et al., 2013; Kumar et al., 2016a). In addition to product quality, sustainability characteristics including social, environmental, and economic aspects of the supply chain are also traced through a traceability mechanism. Various certifications like organic cotton and Fairtrade can be validated through traceability (Kumar et al., 2017a; UN Global compact and BSR, 2014).

◆ **Sales forecasting and production data management**

Real-time tracking and tracing of products and product data management ensure effective and more precise sales forecasts, production planning, and control. Due to its short cycle, forecasting is one of the challenging and crucial issues for T&C businesses (Thomassey, 2010). Effective forecasting diminishes risk, helps in inventory management and in achieving high customer service (Liu et al., 2013; Thomassey, 2010). In the current dynamic market, a traceability system can enable real-time or up-to-date statistics collection related to inventory, sales, purchase orders, and the location of transit logistics in the supply chain, and helps to improve forecasting (Bindi et al., 2016; Guercini and Runfola, 2009; Kwok and Wu, 2009).

Furthermore, the declining order sizes, quick-changing fashions, and escalating global competition have pushed the manufacturers to optimize production activities and produce multiple styles with different materials and designs simultaneously (Bhardwaj and Fairhurst, 2010; Guercini and Runfola, 2009; Tyler et al., 2006). Therefore, internal

traceability is essential to track and trace material movement within the same industry for resource utilization (Bindi et al., 2016). Traceability can also help in lean manufacturing and reduce the bullwhip effect, due to its applicability in material handling, inventory management, and real-time product tracking in the supply chain (Ringsberg and Mirzabeiki, 2014; Saikouk and Spalanzani, 2012).

◆ **Product authentication and IP protection**

Product and information security are some of the critical concerns of the T&C supply chain that require secure technologies and a system for counterfeit deduction and data protection. The T&C products account for almost 5-7% of the total counterfeits traded around the globe (Beltrametti, 2009). Counterfeit production involves minimum investment and are likely to use inferior quality materials that can pose a severe health-related threat to the consumers (Ekwall, 2009). In light of this, traceability provides an opportunity for brand authentication (Choi et al., 2013).

◆ **Marketing**

In this era of fast fashion, the consumer needs more information about the product to make an ethical buying decision. Consumers are concerned about the environmental and social impact of fashion products (Goswami, 2014). Enabling the customer to trace the history of textile products through a traceability mechanism can create a positive brand image, boost sales, and act as a competitive advantage over other brands (Canavari et al., 2010). Traceability information can assure the safety and quality of the product and can build consumer trust (Clemens, 2003). Product history through traceability can help brands to take advantage of the “Made in” aspect of the product (Guercini and Runfola, 2009). Yang and Fryxell (2009) have identified a positive correlation between brand positioning and traceability.

◆ **Risk management**

Risk management in the supply chain is about implementing strategies to identify, control, detect, and mitigate risk along the supply chain with the objective of ensuring continuity and profitability and reducing vulnerability. Risk in the supply chain can be in the form of cost volatility, financial issues, supplier failures, and disasters (natural or man-made) (Jüttner et al., 2003). Traceability systems can therefore play a significant role, as they can help in the early detection of threats related to product quality, consignment delays, poor forecasts, excess/low inventory, etc. (Arienzo et al., 2008). Traceability systems can also help in supplier risk management by collecting, analyzing, and managing suppliers as well as supplies information (Giannakis and Papadopoulos, 2016).

2.4. Components of a traceability system

As defined earlier, traceability refers to the “recorded identification” of a TRU “throughout its entire lifecycle,” which requires a specific mechanism for product identification/authorization and information capturing to keep track of TRU relationships as they traverse the supply chain. Therefore, there are two broad components of a traceability system, namely, product traceability and information traceability, as shown in Figure 2-1.

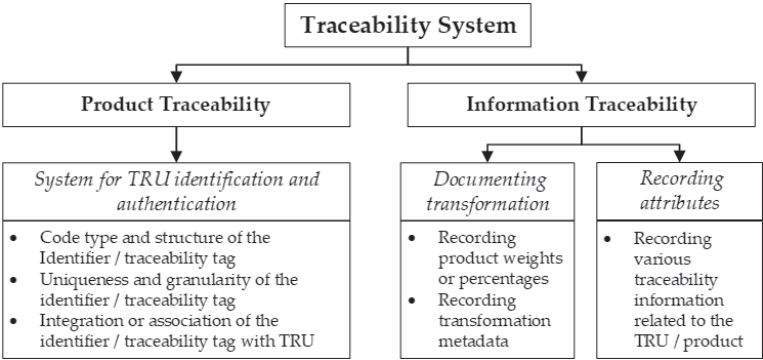


Figure 2-1: Components of traceability systems, adapted from Olsen and Borit(2018)

2.4.1. Product traceability

◆ A system for TRU identification and authentication

TRU identification requires the selection of an identifier code (also referred to as a traceability code) and structure, ensuring its uniqueness, and a method to associate this identifier with an individual TRU.

There are various methods and pre-defined standards for identifier code or structure selections. It can be alphanumeric or numeric, with a variable length that can consist of a few to hundreds of characters. The code can be sequential or structural (with each part representing a different denotation). Various global organizations (e.g., GS1) provide standards for identifier code generation to avoid accidental re-use or overlapping of numbers. They also provide guidelines for printing such codes in machine-readable formats, such as barcodes, and sharing the methods through ICTs (Storøy et al., 2013).

On the other hand, for an efficient TRU identification, it is essential to ensure its uniqueness within the context it is being used (i.e., supply chain, individual manufacturing unit, or organizational level). Organizations such as GS1 issue unique

codes for different contexts on individual TRU or sets of TRUs. It is problematic for a traceability system if a set of TRUs have the same code (i.e., if a one-to-many relationship exists between codes), which is common in many supply chains (including T&C) involving fast moving commercial goods (Regattieri et al., 2007). In such cases, a unique code does not just point to a unique TRU, thus making the TRUs indistinguishable to a certain extent (Senneset et al., 2007). However, with the development of ICTs and more extended computer-generated codes, one-to-one relationships between TRUs and codes are becoming common (Dabbene et al., 2014). Besides, a one-to-one relationship is more potent for a traceability system as it facilitates the association of new attributes for the TRU.

In addition to identifier code selection and ensuring its uniqueness, it is equally important to associate these codes with the TRUs. There are various methods to do this. One of the most widely used methods is the direct physical marking of codes on the TRU with human-readable components and/or machine-readable barcodes/QR codes (Várallyai, 2012). Physically attached tags in the form of RFIDs are also extensively used to track supply chains, mostly at the B2B level. Although they are very cheap and have a considerable amount of storage, RFIDs have some technical challenges related primarily to privacy issues due to their long-range readability (Juels, 2006).

In the past, substantial research has been conducted to develop technologies that can prevent counterfeiting and/or track and trace TRUs in a supply chain (Burnotte et al., 2006; Cheung and Choi, 2011; Ting and Tsang, 2013). The technologies are in the form of *authentication technologies* that are useful in identifying counterfeits, but they cannot trace the product in the supply chain. On the other hand, there are *track and trace technologies* that can be used for tracing products in the supply chain using unique identifiers, such as RFIDs and barcodes. However, these lack a security mechanism and can be replicated. As a result, an additional security mechanism is required in the track and trace systems for product authentication and to avoid illegal cloning of the tags (He et al., 2008). This technology is commonly known as “secured traceability” (Guillermo Azuara et al., 2012) and is mostly found in the food, pharmaceutical, cosmetic, and luxury product supply chains (Guillermo Azuara et al., 2012; Han et al., 2012; He et al., 2008). Table 2-1 provides an overview of the various TRU identification and authentication systems based on literature, including their advantages and disadvantages.

Considering the uniqueness of the T&C supply chain and products, it has special traceability requirements that cannot be addressed by the off-the-shelf technologies on the market (Richero and Ferrigno, 2016). Traceability tags for T&C products should be secured to prevent easy and unauthorized reproduction. At the same time, the tag should

be *durable* enough to withstand normal textile use. It should remain *integrated* with the T&C product to prevent disintegration. Finally, the tag should be *inexpensive*, *eco-friendly*, and *readable* by an easily available device, allowing the customer to authenticate and trace the product.

Table 2-1: An overview of various TRU identification and authentication systems (adopted from Paper III)

1. Authentication Technology		
Feature-based identification techniques are useful for differentiating the original product from counterfeits (Ting and Tsang, 2013). These are the most widely used technologies for product authentication but do not support product tracking. Moreover, most of these technologies required sophisticated and expensive equipment or an expert with a discerning eye for product validation.		
1.1. Direct Authentication	1.2. Security Features Based Authentication	
Inherited physical, chemical or visual properties, e.g. diamonds, leather goods, gems, etc. (Bansal et al., 2013), e.g. in study by Baldini et al (2015)	Externally added features (Bansal et al., 2013) that can be: a) Overt: Visible to the naked eye and vulnerable to attacks, (e.g., holograms and micro-engraving); b) Covert: Invisible to the naked eye, requires a particular device for authentication (e.g., digital watermarking and ultraviolet (UV) sensitive inks); or c) Forensic: Chemical or biological features, requires sophisticated instruments for reading and analysis (e.g., in study by Yoon et al (2013))	
2. Track and Trace Technology		
Based on the principle of unique identifiers in the form of tracking tags (Ilie-Zudor et al., 2011), track and trace technologies are used extensively for freight tracking in logistics operations. These are mature technologies with relatively low investment, high readability and a high level of standardization. However, they are extremely prone to counterfeiting or illegal reproduction.		
2.1. RFIDs	2.2. Barcodes/QR codes	2.3. Miscellaneous
Contactless electronic tags consisting of an electronic microchip for data storage and an antenna for communication (Nath et al., 2006). They are used widely due to their long-range readability, small size, low-cost, and high memory storage. However, they can easily be cloned, require a special device for reading, and are usually removed or	A machine-readable optical pattern used for data representation, printed or attached in the form of labels or stickers. They are a systematic arrangement of codes describing the associated product. They have high readability and low cost. They have used widely in the fast-moving commercial products. However, they can be easily copied and applied to	Magnetic strip cards, magnetic ink character recognition (MICR) codes, or magnetic barcodes are some of the examples of other miscellaneous technologies useful for product tracking. They are remotely sensed and decoded using magnetic sensing technologies. They are used in the packaging industries and banks and in the transportation industry

deactivated at the point of sale to prevent privacy.	counterfeit products as they lack an authentication method (Várallyai, 2012).	for metro or tram tickets (Sparavigna, 2008).
3. Secured Traceability Technology		
Technologies that can track and trace a product and can authenticate the brand or product identity without the threat of easy clonability. Presently, most of the secured technologies are relatively expensive and are used on the high-value products with more profit margins. They are also used in pharmaceutical or food products, contamination or counterfeiting of which can lead to serious health consequences.		
3.1. Secured RFIDs	3.2. Secured barcodes/QR codes	3.3. Miscellaneous
a) Watermarking and RFID based Self-validation System (WARDS): A two-factor authentication system that uses scanned watermark information from labels along with the product's identification code from RFIDs (Ting and Tsang, 2013). b) Physical Unclonable Function (PUF) based RFIDs: An RFID IC chip equipped with PUF to prevent product clonability (Devadas et al., 2008). c) Fingerprinting RFID tags: Prevent cloning by using physical attributes or features based on minimum power responses measured at multiple frequencies (Periaswamy et al., 2011). d) Other examples can be found in study by Rieback et al. (2006) and Pateriya and Sharma (2011).	a) Cryptographic barcode (Corbellini et al., 2006) for traceability and brand authentication in the textile industry. It is printed directly on the surface of the textile and tested against deformation due to the unstable textile surface. b) QR code and a digital signature (Seino et al., 2004) for fishery products. The system uses the weight of an individual fish as its digital signature. c) Microtaggant (Han et al., 2012): Lithographically fabricated to consider the QR code pattern for traceability on pharmaceutical industries.	a) Yarn-based traceability tags by Kumar et al. (2017c) use the yarn based feature in the secured traceability system. b) Permanent sub-surface tattoo (Cataldo et al., 2016), developed for leather products for traceability and counterfeits reduction. c) SigNature® T (Hurry, n.d.) protects the product using unique molecular-based tagging of each textile and clothing product.

2.4.2. Information traceability

◆ Documenting transformation

Following a system for TRU identification and authentication requires a procedure for the documentation of each transformation that occurs on the TRU during its flow through the supply chain. It is also one of the essential components of the traceability system, especially for a complex supply chain with numerous transformations involving constant

splitting and reunion of TRUs by many suppliers, which require direct (with known inputs and known outputs) or indirect (with undocumented mixing) recording of all transformations. In practice, ICTs for traceability implementation include functions that visualize the sequence of transformation in the form of a traceability tree, which is a directed graph, as shown in Figure 2-2.

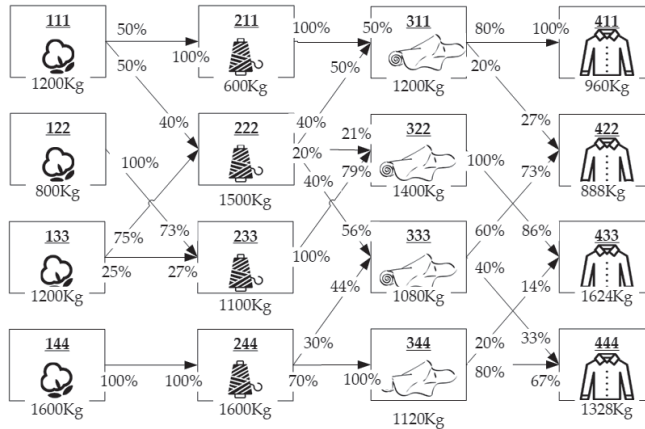


Figure 2-2: An example of a traceability tree, adapted from Olsen and Borit, (2018)

Based on the traceability model, certification scheme, and type of supply chain, different transformation recording mechanisms can be followed. There are three basic types: “product segmentation,” which keeps the separation of the certified and non-certified product during transformation; “mass balance,” which records and tracks weight or percentage mass of TRUs during transformation; and “book and claim,” which directly tracks the product based on the recorded claim book.

Along with transformation data, traceability systems should also record metadata related to each transformation, which describe the transformation. These data can be associated with duration, time, location, and/or the environmental and social parameters associated with the transformation (production).

◆ Recording attributes

The value of a traceability system is often determined by its accessibility to different TRUs’ attributes or the traceability information. The above two mechanisms are simply means to an end; the main concern lies in the TRU attributes that a traceability system records throughout the lifecycle. The notion of a TRU’s attribute is well described by Olsen and Borit, (2018, p. 147) as follows:

The traceability system facilitates information flow in much the same way that a system of railroad tracks and carriages facilitates material flow; in this analogy, the carriages contain recorded data rather than physical products. The mechanisms related to identifiers and transformations in a traceability system may be likened to the railroad track that connects everything together, whereas the attributes recorded may be likened to the carriages that move on the tracks. The traceability mechanisms (the railroad track) is what ensures that data once recorded (the carriages) are connected, and can be moved from place to place without loss. If the necessary mechanisms are in place (the railroad track), adding more attributes (carriages) is fairly trivial, and, from a system perspective, there is no limit to the number of attributes that can be linked to a given TRU.

In general, one of the essential requirements and a motivation for investment in a traceability system is to get access to the TRU's attributes (information) in the given supply chain system and tracing its ancestors. Table 2-2 summarizes important traceability information sets (TRU attributes) based on the literature, which can be recorded and shared through the traceability system. However, for an efficient information traceability system, it is not important to record and share all TRU attributes with other actors, including customers, as this might make the system cumbersome and slow down the processing. In the case of the T&C supply chain, very little has been explored in past studies about opinions related to traceability or consumers' or businesses' preferences for traceability information. Therefore, it is necessary to segregate important traceability information for the optimum sharing and functioning of the information traceability system.

Table 2-2: Essential traceability information sets / TRU attributes, adopted from Paper II

Information sets	References	Sub-category	Description
Product Information	(Jansen-Vullers et al., 2003; Kumar et al., 2017b; Lumsden and Mirzabeiki, 2008; Siu Keung Kwok and	Origin	Origin of the final product, components, sub-components, and raw materials utilized in the production of the final product.
		Composition	The composition of final product, components, sub-components, and raw materials utilized in the production of the final product.
		Manufacturer/supplier details	Information about all the manufacturers, suppliers and sub-suppliers involved throughout the lifecycle of the product.

	Kenny K.W. Wu, 2009; Strähle and Merz, 2017; Thakur and Donnelly, 2010)	Inbound material specifications	A detailed description of the design and product/material specification that is procured from supplier/upstream actor.
		Outbound product specifications	A detailed description of the design and product/material specification of the finished product that is transferred to the next downstream actor.
		Costing data	Information related to the cost of the final product, raw materials, and the entire intermediate product.
		Lot numbers	A unique series of the number provided to a bundle or lot of the product to facilitate batch traceability.
		Sales data	Real-time data related to product sales in different retail channels.
Quality Information	(Kumar et al., 2017b; Strähle and Merz, 2017; Thakur and Donnelly, 2010)	Audit reports	Various quality audit reports done throughout the lifecycle of the product.
		Test procedures and reports	Various quality audits, test procedures, and test reports done throughout the lifecycle of the product.
		Quality Certification Data	Various quality certification related to raw materials, intermediate product, and final product throughout the lifecycle of the product.
		Tracking data of surplus or damaged material/product	Tracking data of each product and the damaged or discarded product/intermediate product and raw materials in the supply chain.
Process Information	(Kumar et al., 2017b; Strähle and Merz, 2017; Thakur and Donnelly, 2010)	Process names/details	Information and details about all the manufacturing processes involved throughout the lifecycle of the product.
		Machine IDs	The IDs of the machines involved in the product's processing throughout its lifecycle.
		Timestamps	Time stamps of all the important events and processes throughout the lifecycle of a product.
Social-Environmental Information	(Kumar et al., 2017b; Phau et al., 2015; Ritch, 2015; Strähle and Merz, 2017)	Social audit-report / certification	Various social audit reports and certification associated directly or indirectly with the product.
		Environmental audit-report / certification	Various environmental audit reports and certification associated directly or indirectly with the product.
		Carbon footprint data of products	Complete carbon footprint data of the final product throughout its lifecycle.

2.5. Blockchain technology

Blockchain is a shared, immutable ledger that facilitates the process of recording transactions and tracking assets in a business network. An asset can be tangible (a house, a car, cash, land) or intangible (intellectual property, patents, copyrights, branding). Virtually anything of value can be tracked and traded on a blockchain network, reducing risk and cutting costs for all involved (Gupta, 2018).

Introduced by Haber and Stornetta (1991), blockchain technology gained its popularity from the launch of the Bitcoin (a cryptocurrency application of blockchain) released in January 2009 (Nakamoto, 2008). Blockchain consists of a series of blocks that are connected in the form of a chain, with each block containing a set of the transactions (encoded through a hash function), timestamp, hash of the previous block, a block ID, and a nonce (proof of the consensus mechanism) (Saber et al., 2018), as shown in Figure 2-3. These blocks are recorded on a shared distributed ledger as per the consensus rules agreed on by the network partners. Due to their immutable characteristics, blocks are hard to modify or forge by an individual partner. Blockchain technology provides an efficient mechanism to build consensus for secure and uninterrupted information sharing without data tampering (Viriyasitavat and Hoonsoon, 2018). It generates technology-based trust among a group of parties with trust issues, interacting in an unreliable and decentralized network with no centralized authority (Swan, 2015).

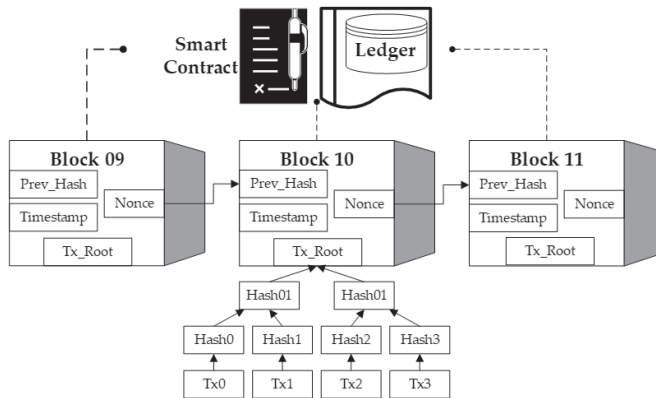


Figure 2-3: A typical blockchain structure

The critical element of blockchain technology that guarantees network security and makes the shared ledger immutable is the use of a hash function to encrypt each block and connect it with the previous block. This hash function is a cryptographic function (e.g.,

SHA-256 in the case of Bitcoin) that generates a value of a fixed length (e.g., 256 bits for SHA-256) for any arbitrary input. For each input value, there is a fixed pseudo-random output (hash value) that is hard to predict but easy to evaluate (Antonopoulos, 2014). Two identical inputs will always generate the same and unique hash, but a slight variation changes the output hash value significantly. Therefore, any alteration in the transaction data of the already registered block will alter the hash of all the subsequent blocks (Gupta, 2018).

2.5.1. *Key characteristics of the blockchain*

Below are the key characteristics of blockchain:

◆ **Decentralization**

Unlike the centralized transaction system where an individual transaction is validated through a trusted central agency (e.g., bank), blockchain maintains a decentralized database over a distributed network and a consensus algorithm (such as proof of work, proof of stake, etc.) is used to ensure data consistency (Swan, 2015). Consensus mainly involves voting or the validation of a transaction (affecting the global state of the ledger) by the majority of network participants to ensure its credibility (Mougayar, 2016).

◆ **Persistency and immutability**

The process of transaction validation is quick and it ensures the detection of fraudulent transactions and the protection of the ledger from invalid entry. Moreover, due to the immutable nature of the shared ledger, it is almost impossible to delete or modify a transaction once it has been registered on the blockchain (Nofer et al., 2017). Thus, the participant can be sure about the history and reliability of the record.

◆ **Anonymity and security**

By using the generated address, participants can protect their identity by interacting anonymously or with a customized level of identity disclosed, based on the blockchain type. Moreover, information stored on the blockchain includes a timestamp and a cryptographic hash of the previous block, which prevents data tampering, unauthorized modification of information, and anonymous trading on the network (this is required in a public network) (Hileman and Rauchs, 2017). Timestamping has the added advantage of giving various time-based competitive information related to perishability concerns, lead-time, and delivery dates (Ølnes et al., 2017). The decentralized structure of blockchain also adds to its security through information verification and validation by network partners according to consensus rules.

♦ **Auditability and transparency**

One of the most significant advantages of a blockchain is the auditability of the stored data on the shared ledger. Blockchain follows standard transaction validation algorithms, for example, the Unspent Transaction Output (UTXO) model in the case of Bitcoin, and keeps a digital trail of transactions related to all assets being traded on the blockchain and a trail of transactions by the participants (Antonopoulos, 2014). This mechanism ensures easy validation and traceability of assets. It also addresses the growing demand for transparency in business.

♦ **Smart contracts**

These are automatically executable computer codes containing contract terms and business rules. Smart contracts verify the pre-defined rules agreed on by blockchain participants and trigger the related action. The terms of the contracts are approved by the network participants and are self-executable, thus limiting human intervention (Luu et al., 2016). As required in traditional contracts, the role of intermediaries (centralized trusted parties) can be reduced through smart contracts, thus improving business efficiency and profitability. Smart contracts check the transactions' validation rules and, accordingly, add them to the shared ledger.

2.5.2. *Taxonomy of blockchain systems*

Primarily developed for financial applications, the unique features of blockchain have encouraged more extensive use of the technology in the various markets, including non-financial applications in the supply chain, government, healthcare, energy, and real estate (Kouhizadeh and Sarkis, 2018; Markets and Markets, 2018; Sikorski et al., 2017). Depending on the application and type of participants involved, a blockchain can be public or private. A public blockchain is usually permission-less, such that any individual with access to the internet can participate anonymously, trade, and/or view all the transactions on the ledger. Due to the involvement of anonymous participants and lack of trust among them, the security and reliability requirements of a public blockchain are very high. By contrast, business blockchains are usually private and commissioned networks with access to restricted, predefined participants with a certain degree of trust. To ensure privacy and security in such private blockchains, a membership provider usually provides a customized level of accessibility to the participant, based on their role and contribution in the network (Zheng et al., 2017). The main differences between public and private blockchain are summarized in Table 2-3.

Table 2-3: Differences between public and private blockchains (Zheng et al., 2017)

Property	Public blockchain	Private blockchain
Determining Consensus	All miners* (*interconnected node/pool of systems using their computing power to validate the transaction.)	Only a selected set of nodes or even a single node representing an organization
Permission	Public	Customized accessibility depending on the role and authority in the network
Immutability	Almost impossible to tamper	Could be modified
Efficiency	Low	High
Centralized	No	To a certain extent
Consensus process	Permission-less	Permissioned

2.5.3. Blockchain-based traceability in the supply chain

Blockchain technology within the context of supply chain traceability is still developing and evolving. Unlike the cryptocurrency based blockchain applications that are usually public, blockchain-based traceability systems in supply chain networks need to be private and to be granted permission, with limited authorized participants. The accessibility level of each participant is determined initially through digital key-based access to maintain information security and privacy. Figure 2-4 illustrates the transformation of a conventional supply chain into a blockchain-based supply chain. As indicated in Saberi et al. (2018), four key participants play a significant role in the blockchain-based traceability system for supply chains: first, a *registrar or ordering service provider* who defines the accessibility of each network participant through a unique digital key; second *organizations for standardizations* that set the traceability and supply chain standards, policies, and technological requirements; third, *certifiers*, who provide participation certifications to supply chain partners; and fourth, *actors*, who supply the chain partners, including manufacturers, buyers, and consumers who participate in the blockchain network. It is noteworthy that only a range of traceability information can be collected on the shared ledger of the blockchain-based traceability network (Tian, 2016). Besides, as shown in Figure 2-4, each participant can be connected to multiple blockchains at the same time, each having a different ledger and governed by a different smart contract. Based on the accessibility rules, smart contract agreement, and consensus, only certain actors can initiate a trade with another partner and can generate and record new traceability information. The transaction data is validated and updated automatically based on the validation rules (Abeyratne and Monfared, 2016). Blockchain facilitates product and

information traceability throughout the supply chain and ensures technology-based trust among the actors.

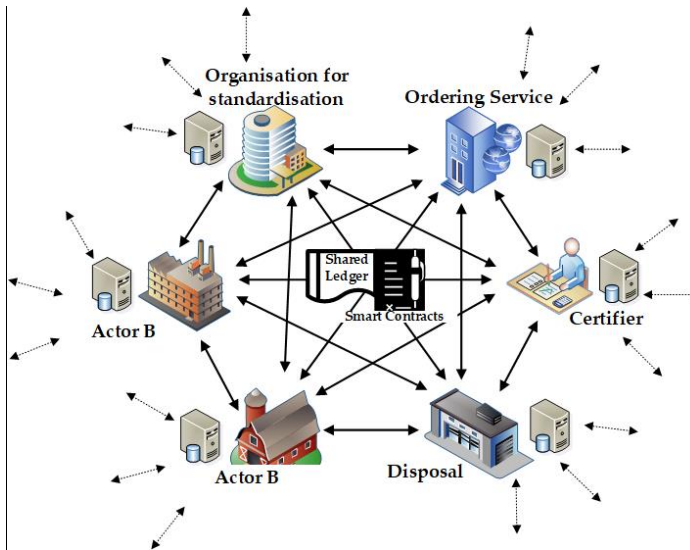


Figure 2-4: Blockchain-based supply chain

In terms of applications, blockchain is an innovative and emerging technology with unique qualities such as automaticity, pseudonymity, immutability, and auditability that can facilitate unparalleled reliability, efficiency, and traceability in the supply chain (Treiblmaier, 2018). It influences product cost, quality, speed, supply chain dependability, and risk reduction and increases sustainability and supply chain flexibility. Blockchain increases accountability and transparency in the supply chain. A blockchain-based traceability system in the supply chain can provide better assurance of human rights and ethical working and practices (Adams et al., 2018). For example, a traceable record of product history on the auditable shared-ledger can assure customers regarding product safety, involved supply chain partners, and product verification as being produced ethically. Smart contracts can be customized to track product transformations automatically and control sustainable terms and regulatory policies governing appropriate corrections. Through blockchain technology, important traceability data can be captured, stored, secured, and managed without requiring a central trusted party. Trust, transparency, reliability, and security among supply chain partners can exist in a technological context (Abeyratne and Monfared, 2016). Once integrated with product traceability systems such as RFIDs and barcodes, the complete blockchain technology-based traceability system can help in real-time product tracking and tracing required as traceability regulations in the specific supply chain (Tian, 2016). It can also help in

counterfeit detection and reduction in the supply chain, as traceability information can only be recorded by authorized supply chain partners. Blockchain can also affect the economic performance of the supply chain. Through blockchain adoption, traceability data modification can be shared with all supply chain partners instantly, allowing instant processing and product modification or deployment, while reducing transaction time and human error.

The use of the cryptographic function and chain structure ensures data immutability in the blockchain, making it secure against deliberate alteration of data or IP infringements and reducing supply chain risk. Blockchain allows secure and symmetric information sharing among supply chain partners, thus increasing the transparency and visibility of the supply chain. This can be realized as a competitive advantage that can increase consumers' trust and loyalty toward the product and brand (Kshetri, 2018). A private blockchain can detect and restrict fraudulent partners and helps with sustainability by assuring human rights, fair trade, and safe work practices. Blockchain technology can facilitate quality monitoring by tracking substandard products accurately to reduce, rework, and manage product recalls (Saber et al., 2018). It can also help in tracing the carbon footprint of products that can determine the carbon tax of a company and facilitate the customer to make an ethical buying decision (Jabbour et al., 2018). IBM and Energy Blockchain Labs Inc. in China are working toward the development of a green assets blockchain-based platform that can aid in tracking and measuring the carbon footprint of the product, fulfill the Carbon Emission Reduction (CER) quotas, and enable carbon asset production and trading. Secured and up to date traceability information on the blockchain can provide an opportunity for businesses to efficiently trade their carbon assets in the green assets market. Moreover, blockchain-based traceability can improve the recycling process. It can help in the sorting and segregation process and can encourage consumers and organizations to participate in recycling activities.

2.6. Toward the development of a traceability system: A system-of-systems approach

The thesis draws upon the theoretical lens of the system-of-systems and visualizes a secured traceability system as a complex system consisting of multiple sub-systems or component systems (in this case, the information traceability system and product traceability system). These component systems can coexist independently with limited individual functionality. However, when integrated together, they produce functionality that is greater than the aggregate functionality of the systems.

2.6.1. *System-of-systems theory*

System engineers and managers are increasingly acknowledging the necessity to integrate technical, organizational, and social challenges from different aspects of lifecycle activities, which are intended to result in the deployment and support of systems. Moreover, due to IT globalization, they are facing various amounts of dysfunctionality and distributed organizational difficulties. In response, canonical management concepts are extending to facilitate international coalition development, management, and integration of widely distributed systems, resulting in the development of complex adaptive systems (Stacey et al., 2000). Some of the main characteristics of such large and complex systems are that they are often formed from multiple sub-systems or component systems that are potentially customized from existing off-the-shelf commercial systems or newly engineered from a matured custom system. Such systems are often referred to as “system-of-systems” (SoS) (Sage and Cuppan, 2001) and the theory behind their development is known as the system-of-systems theory.

According to Sage and Cuppan (2001), “There is no universally accepted definition of these ‘super systems’. What distinguishes a system-of-systems from other systems does not, at this point, have a definitive answer. In a formal sense, almost anything could be regarded as a system of systems.” Although the SoS is a relatively new concept, the SoS theory has been in existence for a long time (Ackoff, 1971; Jackson and Keys, 1984). In literature, the SoS theory predominantly focuses on examining huge military, transportation, and infrastructural systems. However, comparably little has been done on exploring and analyzing the economic activity based systems that involve human activities and behaviors (Choi et al., 2018; Choi and Shen, 2016; Czerwinski, 1998; Stacey et al., 2000). Although the SoS has its unique features, researchers have identified some crucial elements and rules of the SoS theory that apply to most SoSs. One of the main advantages of the SoS approach is that it aims to achieve better performance of an economic activity-based SoS by promoting and developing new thinking related to technology interaction, economics, and various SoS rules.

2.6.2. *Characteristics of system-of-systems*

The SoS is based on the concept that modern systems have dynamic needs that keep changing and updating with technological development. The SoS is not monolithic and cannot be developed using the grand design approach (based on the “waterfall” model). Some of the critical characteristics of the SoS are as follows (Carlock and Fenton, 2001; Krygiel, 1999; Maier, 1998):

◆ **Operational independence of the component systems**

This characteristic implies that in order to be qualified as an SoS, all the individual component systems, when disassembled from the SoS, would be able to exist independently and perform useful operations without depending on other component systems.

◆ **Managerial independence of the component systems**

This characteristic implies that component systems do not only possess operational independence. However, they do operate independently with their own managerial governance to achieve the intended purpose. Even when integrated into the SoS, the component system still maintains a continuing operational existence as a self-contained system that is autonomous from the SoS.

◆ **Geographic distribution**

This characteristic implies that the SoS is complex and large, and the component systems are widely distributed along substantial geographical distances.

◆ **Emergent behavior**

The SoS is used to achieve goals and perform functions that cannot be achieved through the component system independently. In other words, the component system cannot perform the ultimate function and exhibit the same behavior as the whole SoS. These behaviors are new features of the complete SoS acquired by combining all the component systems.

◆ **Evolutionary development**

This is one of the critical characteristics of the SoS that distinguish it from the monolithic systems. According to this characteristic, the SoS is never “fully formed” or complete. Its development is evolutionary, with the addition, modification, or removal of functions, structures, and purposes, and other issues experienced over time.

2.6.3. System-of-systems theory and secured traceability system development

As explained by Choi et al. (2018), the complex T&C supply chain is in fact a system-of-systems (sub-systems or interacting elements), each contributing to the supply chain function and interacting in the form of a network structure. For example, these systems can be in the form of an operations management system, inventory management system,

auditing system, strategic management system, marketing and sales system, etc. (Badillo et al., 2011). Based on the supply chain layout and partners' interaction, there can be multiple such systems and sub-systems interacting and coordinating together to meet the objectives of the complex supply chain system. There are several reasons for following the SoS theory and approach in developing a traceability system for the T&C supply chain. Some of these reasons are stated below:

- The SoS approach is appropriate for the development of relatively large systems with limited central control and authority. These systems are decentralized and operate with a coalition of partners working toward a common goal (Sage and Lynch, 1998). In a similar way, an ideal supply chain traceability system is decentralized and distributed. There should be no individual partner leading or controlling the supply chain activities and, in turn, the traceability system.
- The SoSs are usually specially purpose-built, that is, they are tailored from a mixture of custom-developed and off-the-shelf commercial technologies (Sage and Rouse, 2009). Similarly, and also one of the shortcomings indicated in the previous studies, the development of a traceability system, especially for T&C, needs customization of off-the-shelf technologies (in the form of RFIDs, barcodes, or blockchain technology) as well as the custom building of new technologies to cater to the particularities of the T&C supply chain.
- The SoS integrates systems across communities of partners, situated at various locations, and managed by more horizontally-organized structures, such as the Integrated Product and Process Development team, which facilitates conflict management resulting from political, business, and competition for interest. Likewise, as the T&C supply chain is widely distributed, with multiple partners around the globe who have differences in political and business interests, an SoS approach is deemed appropriate to develop a traceability system, considering the associated challenges.
- Unlike the traditional monolithic system, SoS engineering and management requires transdisciplinary research and development (Sage and Cuppan, 2001). In the same way, the development of a complete traceability system requires understanding and modification of various organizational, regulatory, and technological systems.
- The SoS consists of several component systems capable of operating independently. Similarly, complete traceability is a combination of multiple systems, each responsible for certain operations. For example, product security

and traceability systems track and trace the product in the supply chain and protect it from being counterfeited. Information security traceability systems ensure information symmetry across the supply chain and prevent IP infringement.

- Most importantly, as one of the main characteristics of SoS, the development of traceability systems is evolutionary, with a compelling need and requirement to modify and evolve over time, influenced mainly by technological developments.

However, as explained by Gorod et al., (2008), a system should fulfill five requirements: “A,B,C,D,E,” in order to qualify as an SoS. These are Autonomy (A), which refers to the ability of a system to make independent choices; Belonging (B) or the right and ability of individual systems to choose their belongingness to the SoS; Connectivity (C), the ability to connect to all other systems in the SoS; Diversity (D), when connected, the SoS should have diverse capabilities, in addition to limited individual capabilities; and Emergence (E), the ability to be dynamic and formulate new properties with changes.

3. Methodological framework

This thesis is a compilation of five appended papers, each of which followed a relevant methodological consideration. This chapter gives an overview of the scientific approach followed and the reasoning that lay the foundation of this thesis. It describes the research methodology framework, which includes the data collection procedure, data processing, analysis, and interpretation, followed by an overview of the chronology of the research process.

3.1. Research procedure

The Merriam-Webster English Dictionary defines research as *investigation or experimentation aimed at the discovery and interpretation of facts, revision of accepted theories or laws in the light of new facts, or practical application of such new or revised theories or laws*. It is a systematic investigation procedure employed in order to enhance or revise current knowledge by discovering new facts (Kothari, 2004). Research (based on outcomes) can be divided into two general categories: “basic research,” also known as fundamental or pure research, which aims to make a contribution to knowledge or increase scientific knowledge and “applied research,” which aims at utilizing basic research to solve problems or develop new products, technologies, or processes (Collis and Hussey, 2013). Designing a research plan involves the interaction of philosophy, specific methods, and strategies of inquiry (Creswell, 2014). To plan a study, researchers must think about and view the problem through a philosophical lens that they bring to the study, the strategy of inquiry that relates to their paradigm, and specific methods or procedure that interpret the approach into practice. These criteria for selecting a research plan is highly influenced by the researchers’ personal experience and training, the research problem or issue that needs to be addressed, funds, and the audiences that would accept or refer to the research (Bryman and Bell, 2011).

In general, research approaches can be categorized into three broad classes: qualitative, quantitative, and mixed methods (Creswell, 2014). The qualitative approach aims to explore and understand the individual or group attributes of a human or social problem, with a general emphasis on words rather than numerical data (Denzin and Lincoln, 2008). It is mainly an inductive approach with an emphasis on generating new theories rather than exploring the relationship between theory and research (Soiferman, 2010). On the other hand, quantitative research aims to test objective theories and examine relationships among variables using numbers and statistical tools (Denzin and Lincoln, 2008), predominantly a deductive approach that incorporates the practices and norms of positivism and the natural science model (Soiferman, 2010). While quantitative and

qualitative research approaches represent different strategies with striking differences in terms of epistemological issues, ontological concerns, and the role of the theories, the distinction is not fixed. Studies with broad characteristics of one research approach might have characteristics of the other. With a more pragmatic lens toward a problem, significant research in the past has focused on combining qualitative and quantitative approaches, showing that a wedge need not be driven between the two methods. This gave birth to triangulation of data sources—seeking a merger of qualitative and quantitative methods, which is commonly known as a mixed methods approach (Jick, 1979).

While this research adds to the fundamental knowledge and improves the understanding of traceability, especially in the context of T&C, it is primarily driven by specific industrial problems (in the form of, but not limited to, counterfeits, information asymmetry, and low transparency). Therefore, this study, to a greater extent, can be classified as applied research. With this consideration, a pragmatism paradigm has been adopted that arises out of actions, situations, and consequences, rather than antecedent conditions. Instead of focusing on a specific method, this study focuses more on the problem and utilizes different research approaches to understand the problem and propose solutions. Accordingly, the proposed research questions were addressed using a mixed methods approach, that is, both qualitative and quantitative methods were followed in different papers. This provides freedom of choice, and different data collection techniques were used. Paper I, being a literature review, is more of an exploratory research that focuses on secondary data collection and therefore does not follow a specific research method. The methods followed in other appended papers are explained in the following subsections.

3.1.1. *Experimental research approach*

In this approach, one of the factors/variables (which influenced the case under study) is deliberately varied to discover its effect on the other factors/variables or to examine the results of presumed causes (Christensen, 2007). It is a widely practiced approach by both scientists and non-scientists to identify causal relationships and correlations between dependent and independent variables. It can be divided into two categories: laboratory and field experiments (Tierney, 2008). For ease of replication (that would not usually occur in everyday life), laboratory experiments are conducted in an artificial setting with the advantage of being able to control the confounding variables. However, it has some limitations. For example, generalizations of findings in the real-life scenario become problematic as the experiments are done under artificially controlled conditions. In contrast, field experiments take place in familiar environments or real-life settings, such as schools, clinics, and daycare centers, and have good ecological validity. Nonetheless, confounding variables are hard to control in such a setting, compared to laboratory

experiments. Thus, as a standard and well-accepted practice, the initial prototype developments are carried-out through laboratory research that is later tested and verified in the real scenarios through field experiments.

A significant part of this thesis focuses on the development and experimental validation of a secured traceability mechanism that requires control experiments. Therefore, the laboratory experimental research approach was followed for the development of a secured traceability tag in Paper III and its durability analysis in Paper IV. Both these papers are more of analytical or explanatory research. On the other hand, Paper V is largely descriptive research that proposes a blockchain based traceability framework and tests it with case examples using the experimental approach.

3.1.2. *Survey approach (including open-ended questions)*

Surveys, in general, are a quantitative method that aims to collect numerical data from a sample of subjects to identify and acquire information related to characteristics of a particular problem (Ellram, 1996). They are widely adopted in descriptive research that aims to answer the “what” questions. However, as a well-accepted modification, surveys can be designed with open-ended questions to give respondents more freedom to express additional commentary input (qualitative data). These data, to a certain degree, can provide insights on the “why” and “how” questions and are useful in enhancing the analysis of the survey responses. Paper II, which focuses on RQ1 of the study, follows a survey approach with open-ended questions. In addition, it incorporates a Delphi method to improve the quality of data and the results obtained.

Developed at Rand Corporation by Dalkey and Helmer (1963), Delphi is a widely used and accepted research method to achieve consensus on a complex and multidisciplinary problem. Based on the rationale that “two heads are better than one, or ...n heads are better than one,” it is a systematic group communication process, allowing anonymous interaction among dispersed panel experts for achieving a convergence of opinion regarding real-world knowledge solicitation. Delphi experts are limited in number and must possess appropriate knowledge and experience related to the specific issue being addressed. They should represent a variety of views. Top management decision-makers or individuals whose judgments are being sought are mostly preferred as panel members, as they can use the results of the Delphi study. These selected panel experts are questioned using a sequence of questionnaires in multiple rounds, where the responses from each round are used as input for the next rounds. After evaluations by the survey moderators, questions on which agreement or consensus can be identified are filtered out, while questions with low or no agreement are explored further in the following rounds (Okoli

and Pawlowski, 2004). This anonymous and controlled feedback method is helpful to avoid noise and the adverse effects of dominant personalities, interpersonal biases, defensive attitude, and unproductive disagreements. Moreover, panel experts are able to modify or refine their response based on the feedback anonymously, without the risk of embarrassment (Hsu and Sandford, 2007). Delphi has been adapted to numerous research fields, such as needs assessment, resource utilization, policy determination, forecasting, and program planning (Heisig et al., 2004; Ogden et al., 2005; Pal et al., 2018).

The Delphi method used in this thesis was conducted in five steps, each continuing until a consensus or agreement was formed on each question. It was followed in the Paper II study to rank factors influencing traceability implementation and classify traceability information. A brief overview of each step is discussed in Figure 3-1.

Methodology (Delphi based approach)	
Step 1	Exploring key factors and essential traceability information from literature
Step 2	Subject selection based on Delphi guidelines
Step 3	Design of semi-structured questionnaire based on results from step 1
Step 4	Survey round 1 with the selected subjects (Researchers and Industry experts)
Step 5	Evaluation (survey round 1) to find degree of consensus and response with low-agreement, followed by survey round 2 (opportunity to reconsider the responses)
Step 6	Final evaluation (survey round 2) using 'Distribution analysis', 'Hierarchical clustering' and 'Optimal leaf ordering' methods.

Figure 3-1 Steps followed in the Delphi-based approach

3.2. Research chronology

The research process started in October 2015 under the framework of Erasmus Mundus Joint Doctorate Program, “Sustainable Management and Design for Textile (SMDTex),” which was funded by the European Commission. Taking into account the multidisciplinary nature of the research and precondition set by the funding agency (European Commission Education, Audio-visual and Culture Executive Agency for the European motilities, and Chinese Scholarship Council (CSC) for the Chinese motility), the research had pre-defined and fixed motilities in two European and one Chinese universities. These were: (1) Multifunctional Textiles and Processes (MTP) and Human Centered Design Department (HCD) at École Nationale Supérieure des Arts et Industries Textiles (ENSAT), University of Lille, France (18 months, i.e., October 2015 to March 2017); (2) Textile Management Department at the University of Borås, Sweden (18 months, i.e., April 2017 to September 2018); and (3) College of Textile and Clothing Engineering at

Soochow University, China (12 months, i.e., October 2018 to September 2019), with a total duration of 48 months.

It can be well inferred from the three departments involved that the thesis contributes to both engineering and management disciplines. Seeking secured traceability in T&C the supply chain is a multimodal concept. It involves technical aspects related to the development of systems for product and information security and traceability, including efficient capturing, recording, and sharing of relevant traceability information among different actors in the supply chain. It also involves organizational or managerial aspects related to the classification of traceability information and implementation of such a system in the supply chain.

The technical or engineering aspect of this research was carried out during the first mobility period of the doctoral program at ENSAIT, France. It involved reviewing literature, followed by the development and durability analysis of the secured tag. A brief plan for the second phase at the University of Borås, Sweden was also prepared before commencing the mobility. The second mobility period focused on the organizational or managerial aspect of the project and started with a Delphi-based approach to rank the key traceability factors and classify traceability information. Considering the feedback of the expert panel, the latter half of the second mobility focused on the development of a blockchain-based traceability system for the T&C supply chain, which continues until the third and final mobility at Soochow University, China.

As stated earlier, this thesis is a compilation of five research publications that were the outcome of the research studies carried out during the PhD period at different universities. A research chronology of the full PhD period is presented in Figure 3-2. Paper I is a review of literature to understand traceability, both in general and in the context of the T&C sector. It lays the foundation of this PhD research by exploring factors influencing traceability in the T&C supply chain, and then enlists the different challenges and the scope of future research related to traceability adoption. Using the Delphi-based approach, Paper II empirically ranks these key factors and, based on the factors, it further explores and classifies traceability information for the T&C supply chain. An earlier version of Paper II was presented at the “22nd International Symposium on Logistics (ISL 2017)” at Ljubljana Slovenia and the “25th International EurOMA Conference (2018)” at Budapest, Hungary, respectively. Paper III and Paper IV deal with the development of the secured tag. It describes its manufacturing, encoding, and validation algorithm, followed by the durability analysis of the proposed tag using different binders and textile substrates. An earlier version of these papers was presented at the “Uncertainty Modelling in Knowledge Engineering and Decision Making” (FLINS) conference in 2016 at Roubaix,

France and the “17th World Textile Conference” (AUTEX) in 2017 at Corfu, Greece. Finally, Paper V presents a blockchain-based traceability framework for the T&C supply chain. A shorter version of Paper V was published as a book chapter in “Artificial Intelligence for Fashion Industry in the Big Data Era” by Springer in Singapore and presented at “The 91st Textile Institute World Conference” (TIWC) in 2018, at the Textile Institute, Leeds, UK.

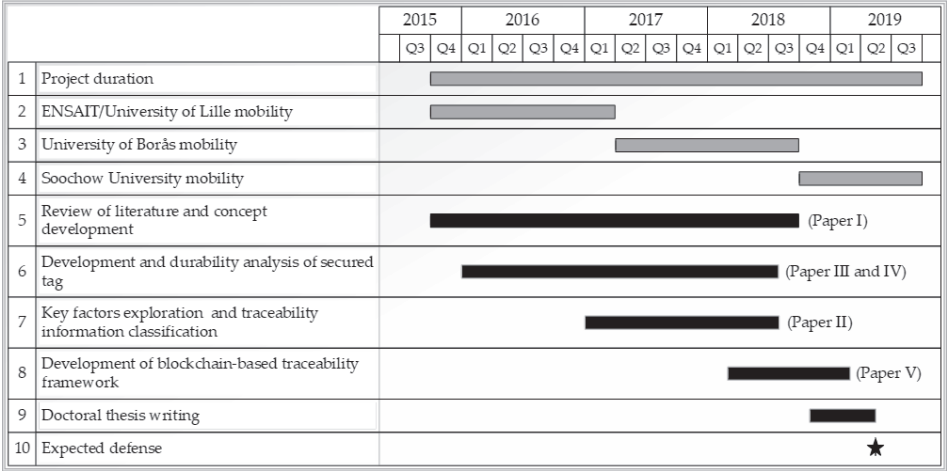


Figure 3-2 Research chronology

3.3. Scope, purpose, and methods of appended papers

Table 3-1 provides an overview of the scope, purpose, and methods used in the different appended papers. Paper I is a review of literature to understand traceability in the context of the T&C supply chain. By analyzing existing scientific and non-scientific literature, the paper explores the importance of traceability for various T&C actors, including government agencies and customers. It further lists the challenges that need to be addressed for the complete traceability implementation and scope for future research.

Table 3-1: Scope, purpose, and methods used in the appended papers

Paper #	Scope	Purpose	Main method	RQ #
I	Review of literature	To explore the need for traceability in the T&C supply chain	Desk research (secondary data)	1
II	Supply chain management	Rank key factors influencing traceability and classifying traceability information	Empirical research using the Delphi approach	1,3
III	Manufacturing secured traceability tag	Development of a secured tag for product traceability	Image processing, pattern recognition	2
IV	Manufacturing, durability analysis, secured traceability tag	Durability analysis of integrated secured tag	Image processing, textile testing, and surface characterizations	2
V	Supply chain management and security	Developing and experimental validation of a framework for information traceability	Blockchain	3

Paper II filters out the key factors influencing traceability implementation (from Paper I and other literature sources) and ranks them in order of importance based on the Delphi experts' interaction. Based on these factors, the study further classifies traceability information that can be shared among B2B and B2C actors in the T&C supply chain. Papers III and IV focus on item-centric product traceability and present a proof-of-concept for a new secured traceability tag mechanism. It explains the manufacturing, encoding, and validation method of a screen-printed secured tag and further analyzes its durability by experimentally examining binders (printing paste) and textile substrate interaction at various stages of the secured tag lifecycle (i.e., before print, after print, after wash, and after abrasion). Paper V, on the other hand, utilizes blockchain technology to develop an information traceability framework for the T&C supply chain. The proposed framework was validated and tested through a case example of the organic cotton supply chain.

3.4. Data sources

Data sources in a research study are generally divided into two categories: primary data sources and secondary data sources. Primary data sources broadly consist of all original sources for the collection of first-hand, unmediated data that are closely related to the

study. Primary data sources are mostly created using different data collection techniques, e.g., surveys, experimentation, interviews, etc. ("Primary Data Source," 2010). In contrast, secondary data sources comprise existing sources and are usually utilized for the purpose for which they were not initially intended. These sources provide second-hand or non-original data that are valuable to develop an understanding of the subject under investigation (Rabinovich and Cheon, 2011).

This thesis is built on both primary and secondary data sources. To understand the concept, requirements, and research gap related to traceability in the T&C supply chain, various scientific and non-scientific secondary data sources were explored and analyzed. In addition, latest reports from the European Commission on traceability and IP infringement (European Commission, 2018; Richero and Ferrigno, 2016; Wajzman et al., 2015) were consulted to build the foundation of this thesis. Secondary data sources were also explored to find the key characteristics of a secured traceability tag and important traceability information and to understand blockchain technology. Primary data were created through experimentation, while secondary data were used in the development and durability analysis of the secured tag, blockchain-based framework, ranking of the traceability factor, and the classification of traceability information. Besides, primary data were also collected using the Delphi approach (involving a survey and open-ended questions) to collect experts' perceptions on traceability in the T&C supply chain.

A summary of the different data sources for the appended papers in the thesis is presented in Table 3-2.

Table 3-2: Data sources for the appended papers

Paper #	Empirical data		
	Laboratory-based experimentation	Delphi-based survey and open-ended questionnaire	Literature/ conceptual
	I		X
	II	X	X
	III	X	
	IV	X	
	V		X

3.5. Data analysis

Paper I is a structured literature review to explore and filter out relevant publications using two widely used citation databases. These publications were critically analyzed to find traceability requirements in the T&C supply chain, describe challenges in its implementation, and propose future research directions. In the other four appended papers, statistical analysis (descriptive and inferential) and thematic coding were used for data analysis.

Descriptive statistics are useful in describing the essential features of the research data through a simple graphical analysis, tables, and so on. It is helpful for summarization and better communication of a large amount of data in a sensible way. Descriptive statistics are used in Paper II to summarize the key factors and information sets (in tabular form) obtained from the literature analysis and present the aggregate results of Likert-scale values for each factor given by experts during the Delphi analysis. Descriptive statistics are used in Paper III to summarize various tracking, tracing, and authentication technologies from literature and in Paper IV to describe the properties of different binders (Table 1) and the different textile substrates (Table 2), and to present a comparative summary of various experimentation results (Tables 3, 4 and 5).

Contrary to descriptive analysis, inferential statistics are used to make an inference from the data, can be helpful to reach conclusions that extend beyond the immediate data alone. The experimental research approach in this thesis utilizes many inferential statistical tools. Factor analysis using pairwise comparison has been used in Paper II to rank traceability factors from Likert-scale values, and hierarchical clustering, along with the optimal leaf ordering method (Bar-Joseph et al., 2001) is used for clustering traceability information sets. In Paper III, a pairwise comparison of difference in the membership value is used for proving the randomness of the secured tag and analyze its durability.

On the other hand, thematic coding which is a descriptive method often used for identification, analysis, and derivation of the pattern (themes) with qualitative data, is used in Paper II for analyzing the open-ended commentary inputs from the experts during the Delphi study. Paper V is a conceptual paper that proposes and validates, using a case example, a blockchain-based traceability framework, and thus does not involve any data analysis.

3.6. Research quality

This research involves both quantitative and qualitative data obtained from primary as well as secondary sources. Therefore, four conventional criteria, namely, internal validity,

external validity, reliability, and objectivity were used to establish the quality of the research (Guba and Lincoln, 1989).

3.6.1. *Internal validity*

Internal validity uses pattern matching and logical models (mostly from the secondary data sources) to explain and build the concept (Rabinovich and Cheon, 2011) and ensures that the research outcomes are replicable by other researchers. Each appended paper in this thesis presents a brief overview of the literature to explore and establish the research gap and work toward filling the gap, and then explains the contribution of the study to the research gap in the results and conclusions section. For example, in Paper I and II, data from secondary sources (literature) and primary sources (experts' perception) explaining the need, challenges, and research agenda related to traceability system, were collected and presented in their original form. The papers laid the foundation of this study and the research outcomes (from Paper III, IV, and V) were analyzed and justified with the help of pattern matching and explanation building using these data.

3.6.2. *External validity*

External validity ensures the generalizability of the research study through the statistical or analytical tool. According to Gregory, *"It is the extent to which [a test or experiment] measures what it claims to measure"* (2004, p. 117). To ensure external validity of the research, standard methods with an adequate sample size were used throughout the PhD study. Paper I follows a structured review method using a defined query on standard citation databases to ensure repeatability and validity. In Paper II, to ensure external validity, 23 experts across the globe with extensive knowledge and experience on supply chain traceability were selected following the Delphi guidelines. Paper II further followed the hierarchical clustering and distribution analysis method to classify factors and information sets. Paper III used widely accepted image-processing methods (such as Hough transformation) and fuzzy membership functions to develop algorithms for secured tag encoding and validation. Paper IV used the standard experimentation method (prescribed by ISO) to test the durability and surface characterization of the secured tag. In Paper V, the developed blockchain-based traceability framework was tested and verified through a case example to demonstrate its applicability in a practical scenario.

3.6.3. *Reliability*

According to Thanasegaran (2009), reliability is *"the degree to which measures are free from error and therefore yield consistent results (i.e., the consistency of a measurement procedure)."* For example, in the case of an instrument, its reliability is determined by verifying the

repeatability of results for the same set of inputs. In the same way, the reliability of a research work is verified by the degree to which the obtained results can be reproduced using the same methodology. For highly reliable research, results are reproducible with high consistency. It is also noteworthy that the results' consistency does not only rely on the methodology, as there are various other factors (such as test environment, conditions, and instruments), that influence the replicability of the results. Kirk and Miller suggest that the reliability of quantitative research is determined by the degree of repeatability, stability, and similarity of measurement over a given time (1986, p. 41).

All the lab-based experiments in Paper III and Paper IV were carried out in a closed environment under controlled conditions. Multiple test samples were constructed with different binders and the textile substrate, and each experiment was repeated multiple times following the standard protocol. As explained above, structured literature analysis was done in Paper I to ensure repeatability of the literature search results. The use of the multi-round Delphi method ensured the reliability of the study in Paper II and in Paper V, the proposed framework was validated for applicability using a case example.

3.6.4. *Objectivity*

To ensure that the research inquiry was free of bias and/or prejudice, various standard procedures, as defined in the literature, were followed during the study. In Paper I, to guarantee that all the relevant literature had been covered in the study, two widely used and well-acknowledged citation databases (Scopus and Web of Science) were used. Maximum precaution was taken in formulating the search query to confirm an exhaustive search of the related articles. In Paper II, to eliminate possible biases in factor and information exploration from literature, the first round of Delphi experts were asked (through open-ended questions) to review the list of factors and information to suggest additions or modifications. Moreover, Pearson's correlation coefficient was calculated between the survey responses to ensure stability and consensus in the responses. In Paper IV, standard characterization methods (as set by ISO) were followed to ensure replicability and eliminate possible biases. Paper III validates the proposed encoding and validation algorithm using several experimental analyses. Similarly, Paper V makes a small blockchain program using the proposed framework and validates it through a case example.

4. Summary of appended papers

This chapter presents an overview of the research contribution of the thesis, followed by a summary of the papers appended in this thesis report. For each paper, the purpose, an overview of the research question(s), research method, and the main finding(s) are outlined. The chapter further explains how the appended papers contribute to, and address the research questions formulated in Chapter 1.

This thesis is based on five publications to address the different research questions. Table 4-1 shows the relationship between appended papers and the proposed research questions, while Figure 4-1 highlights the focus area of each appended paper.

Table 4-1: Relationship between the appended research papers and the research questions

Paper #	RQ1	RQ2	RQ3
I	X		
II	X		X
III		X	
IV		X	
V			X

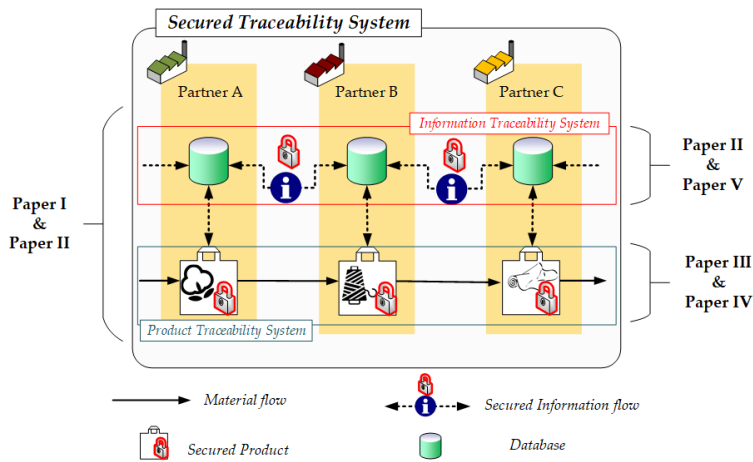


Figure 4-1: Supply chain traceability and focus areas of the appended papers

As stated before, this PhD research was conducted in three different universities under the supervision and with the help of multiple authors. Table 4-2 shows the contributions of various authors briefly in each of the appended publications.

Table 4-2: Authors' contributions in the appended papers

Paper #	First author	Second author-last author	Responsibility
I	Vijay Kumar (VK)	Daniel Ekwall (DE), Tarun Kumar Agrawal (TKA)	VK is the first and corresponding author of the manuscript. VK conceptualized the study with the help of DE and TKA. VK formulated the traceability framework and wrote the major parts of the manuscript. TKA helped VK in developing the methodology section and manuscript refinement.
II	Tarun Kumar Agrawal	Rudrajeet Pal (RP)	TKA is the first and corresponding author of the manuscript. TKA conceptualized the study with the help of RP. RP contributed to finalizing the methodology. TKA carried out the Delphi study, analyzed the results, and wrote the manuscript. RP contributed to analyzing the results and refinement of the manuscript.
III	Tarun Kumar Agrawal	Ludovic Koehl (LK), Christine Campagne (CC)	TKA is the first and corresponding author of the manuscript. TKA conceptualized the study with the help of LK (on the automation aspect) and CC (on the material aspect). All authors contributed to finalizing the methodology. TKA carried out the experimental part, analyzed the results, and wrote the manuscript. LK contributed to analyzing the results. LK and CC contributed to the refinement of the manuscript.
IV	Tarun Kumar Agrawal	Christine Campagne, Ludovic Koehl	TKA is the first and corresponding author of the manuscript. TKA conceptualized the study with the help of CC (on the material aspect) and LK (on the automation aspect). TKA carried out the experimental part, analyzed the results, and wrote the manuscript. CC contributed to analyzing the results. CC and LK contributed to the refinement of the manuscript.
V	Tarun Kumar Agrawal	Vijay Kumar, Rudrajeet Pal, Lichuan Wang (LW), Yan Chen (YC)	TKA is the first and corresponding author of the manuscript. TKA conceptualized the study with the help of VK and RP. TKA formulated the blockchain-based traceability framework and program. TKA wrote the manuscript. VK, RP, LW, and YC contributed to the refinement of the manuscript and the development of the conclusions and discussions section.

4.1. Results of the appended papers concerning research questions

This section presents a combined overview of the appended papers concerning the RQs of the thesis as presented in Chapter 1. Table 4-3 summaries the main contributions of the appended papers with respect to the RQs. Further, Chapter 5 uses the combined results of this table to formulate a detailed discussion.

Table 4-3: Results of the appended papers and the research questions

		RQ #		
		1	2	3
Paper #	I	- Exploring key factors influencing traceability implementation	-Need for product traceability and security	- Need for information traceability and security
	II	- Ranking of factors influencing traceability implementation		- Key traceability information that can be shared at the B2B level and the B2C level
	III	- Product authentication - Risk management - Market surveillance - Marketing tool	-Key features of a traceability tag -Product traceability and security using unique features based on a traceability tag -Manufacturing, encoding, and validation mechanism for a newly introduced secured tag	
	IV	- Product authentication - Risk management - Market surveillance	-Durable secured tag that can withstand T&C use phase treatments	
	V	- Risk management - Visibility - Transparency - Quality monitoring - IPR protection		-Blockchain-based framework for information traceability and security

4.2. Paper I

4.2.1. Purpose and overview

Traceability is the ability to trace and access all information related to a product throughout the lifecycle of the product. It is one of the primary requirements of the quality management standards set by ISO 9000 (Kvarnström and Bergquist, 2012; Rizzi and Zamboni, 1999). According to Kumar et al. (2009), as a common perception, a company

needs to have traceability in order to track and trace its products while they traverse the supply chain. This is required to handle issues such as product recalls and inventory management. It has emerged as a requirement in practically all supply chains, including the textile and clothing (T&C) industry, and is widely used in different contexts (Abad et al., 2009; Goswami, 2014; Guercini and Runfola, 2009; Informal Product Traceability Expert Group - Final Report, 2013; Solanki, 2015; Zhang and Kraisintu, 2011).

Traceability in T&C has been seen as a possible solution to integrate supply chain actors for synchronous functioning and make the supply chain transparent and visible. It has potential application in anti-counterfeiting, brand authentication, consumer safety, product development, production, and quality optimization (Alves et al., 2014; Cheng et al., 2013; Choi et al., 2013; Corbellini et al., 2006; Gobbi and Massa, 2015; Guercini and Runfola, 2009; Jansen-Vullers et al., 2003; Sun et al., 2014; Terzi et al., 2007; Töyrylä, 1999). In the past, very little work has been done to explore the need and benefits of traceability in the T&C supply chain. In this direction, this paper explores the factors influencing traceability in the T&C supply chain from various perspectives (including industrial, consumers, and monitoring agencies) based on various literature sources. Further, the paper discusses the challenges associated with the implementation of traceability in the current industrial scenario and sets up the agenda for future research.

4.2.2. *Paper research questions (PRQs)*

The study formulates, and explores two specific paper research questions (PRQs) through an analysis of literature:

PRQ 1: What are the potentials and implementation challenges of traceability in the T&C supply chain?

4.2.3. *Research method*

To understand the relevance of traceability holistically, the study reviewed literature to collect and analyze available secondary data. Scientific publications between 1900 and 2017 were explored using two citation databases: Web of Science and SCOPUS. The following queries were used:

Web of Science: TS = (traceab* AND (textil* OR cloth* OR garment*))

Scopus: TITLE-ABS-KEY (traceab* AND (textile* OR cloth* OR garment*))

Here, “*” represents the “wildcard” that finds words containing zero or more characters in place of the asterisk-character. For example, “traceability” might appear as “traceable” or

“traceability” in literature. Thus, a wildcard with the term “traceab” will extract all words that start with “traceab” in the database.

Additionally, “AND” and “OR” signify the Boolean operators that merge the keywords. For the preliminary analysis, only English language literature from scientific journals, conferences, and books was considered. The initial search generated 43 results in WoS and 72 results in Scopus. However, further analysis of the abstracts, based on their purpose, methods, findings, and focus area of the research, showed that there were only 27 unique publications (13 journals, 13 conference articles, and one book chapter) related to traceability in the T&C supply chain directly or indirectly. To gain a broader understanding, the search also included other non-indexed publications. The work aimed to compile literature to organize the diverse schools of thought. It provides a “launch pad” for future concept development and research.

4.2.4. *Main findings*

To answer RQ1, the paper explores and describes various applications of traceability in the T&C supply chain from literature, including traceability requirement to trace product origin and the importance of traceability information during product recycling. The paper advocates the significance of traceability by refereeing and acknowledging its benefits for the T&C supply chain from literature sources. The study discusses traceability requirements from various perspectives (including industry, consumers, and monitoring agencies) and the key findings are summarized in the following paragraphs.

Consumers require traceability to trace the history of a product to know its origin and inquire about the ethical manufacturing practices and the product’s carbon footprint. Traceability information allows the customers to make ethical buying decisions considering the sustainability aspects of the product. Considering this, several brands (e.g., Honestby, Nike, and H&M) have started sharing names of their first-tier and second-tier suppliers. However, brands and other supply chain partners still need to implement traceability to make the complete supply chain transparent and visible. Traceability is also crucial for safety assurance and maintenance of a product during its use phase.

With regard to the industrial perspective, the most important applications of traceability are: to check intrusion of counterfeits in the supply chain, to manage product recall, to identify the origin of defects, to ensure visibility in the supply chain, product sorting at the recycling phase, product marketing, and efficient forecasting. Similarly, for monitoring agencies, traceability is useful to check and authenticate products when they cross international borders. Traceability can also track and trace harmful products on the market and is useful in handling cases of product recalls.

Additionally, the paper identifies various challenges in implementing traceability in the T&C supply chain. These are mainly due to lack of dedicated product traceability technology for the T&C supply chain. Existing off-the-shelf technologies are usually cloneable, detachable, expensive, or may not withstand wash and abrasion during the textile use phase. The other major challenge is the lack of a data management protocol and secure information sharing system. This results in information asymmetry in the supply chain.

To address these issues, this paper highlights multiple aspects and suggests future research direction such as standardization of technology, semantics, and systems. The role of policymakers and government regulation, which play a vital role in introducing or bridging different regulations at global as well as local levels for traceability implementation, is highlighted.

4.3. Paper II

4.3.1. *Purpose and overview*

This work is a continuation of Paper I and focuses on RQ1 and RQ3. Considering various factors that were explored and explained from the literature analysis, the paper further ranks them empirically in order of their importance to answer RQ1. The study further explores and classifies (based on importance) essential information that a traceability system needs to be recorded and shared at business-to-business and business-to-customer levels in the supply chain. Thus, it lays a foundation for information traceability system development and works toward answering RQ 3.

4.3.2. *Paper research questions (PRQs)*

The study formulates and empirically explores two specific paper research questions (PRQs):

- *PRQ 2.1: What are the key factors influencing traceability in the T&C supply chain?*
- *PRQ 2.2: What essential traceability information needs to be recorded and shared among various T&C supply chain stakeholders?*

4.3.3. *Research method*

Considering the research questions that aimed to rank the key factors of traceability in the T&C supply chain and essential traceability information sets, the Delphi-based survey method was followed. Developed at Rand Corporation by Dalkey and Helmer (1963),

Delphi is a popular technique to achieve consensus on a complex and multifaceted issue. It is a systematic group communication process, allowing anonymous interaction among dispersed panel experts. These selected panel experts are questioned by a sequence of questionnaires in multiple rounds, where the responses from each round are used as input for the next rounds. After evaluations by the survey moderators, questions on which agreement or consensus can be identified are filtered out, whereas questions with low or no agreement are explored further in the following rounds (Okoli and Pawlowski, 2004). Moreover, panel experts can modify or refine their responses anonymously, based on the feedback, without the risk of embarrassment (Hsu and Sandford, 2007). The Delphi technique reported in this study was conducted in five steps, each continuing until a consensus or agreement is met on each question. The final panel consisted of a total of 23 experts (12 research practitioners and 11 industry experts). All the industrial experts held major C-suite positions in various multinational T&C companies and the research practitioners were academicians and investigative journalists researching intensively on T&C supply chain traceability and related issues. To test consensus, Pearson's correlation coefficient along with p-value, were calculated between the survey responses from different rounds and between the different groups of respondents within the same round. Pearson's correlation coefficient values range from -1 to 1, where -1, 1, and 0 indicate a perfect negative, a perfect positive, and no correlation, respectively. In addition, a lower p-value indicates strong evidence against the null hypothesis. The information types were clustered using hierarchical clustering and arranged using the optimal leaf ordering method (Bar-Joseph et al., 2001).

4.3.4. *Main findings*

A Delphi-based survey was conducted in two rounds to collect qualitative and quantitative data in order to identify and prioritize various factors that influence traceability adoption in T&C supply chains. Based on these factors, the study further explores, classifies, and suggests information that can be recorded and shared for complete traceability among T&C supply chain actors, both business-to-business and business-to-customer.

A deductive model of various factors and information sets obtained from literature is presented in Figure 4-2. "Risk Management" and "Recycling data" were added to Level 1, Factor 14 and Level-2 (Social-environmental information) respectively, based on commentary input from panelists after the first round of the Delphi analysis.

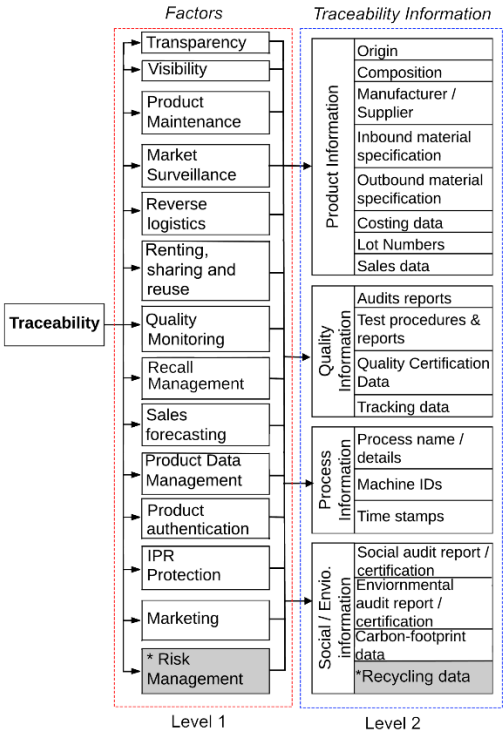


Figure 4-2: Summary of different traceability factors and information

◆ **Traceability factors**

During the Delphi rounds, experts were asked to rate each traceability factor on a Likert scale. The mean and standard deviation (SD) values of the Likert scale responses were calculated for each factor, and then a pairwise comparison of the SD values was made to compute the consensus. After Round-2, a general consensus among the panelists' responses was observed, with a low SD value corresponding to each factor and a Pearson correlation coefficient ρ ($\rho = 0.66$) ($p\text{-value} < 0.01$). Figure 4-3 shows the aggregate results for each factor obtained after Round-2, arranged in terms of their relative ranking of mean values on a Likert scale.

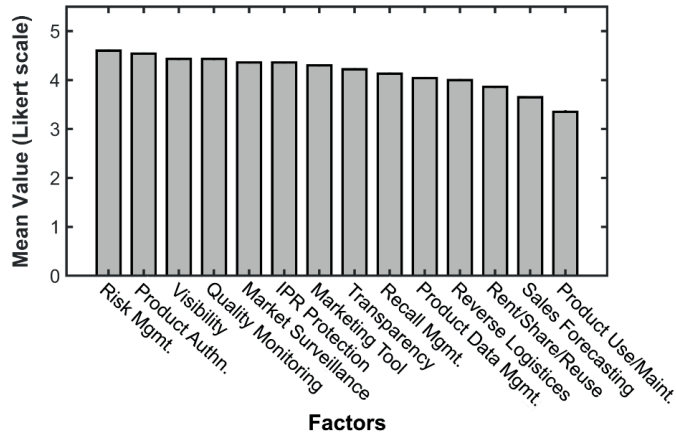


Figure 4-3: Bar-plot of aggregate results corresponding to traceability factor after survey round 2, in descending order of importance

◆ Traceability information

After ensuring consensus and stability in the responses, mean values from Round-2 were clustered through hierarchical clustering and the resulting dendrogram was optimized through the leaf ordering algorithm to arrange the data in logical order. Besides, exactly three clusters were obtained in the whole dendrogram at a threshold level of ~ 1.10 . Elements in cluster one (C-1) had the highest rank, followed by cluster two (C-2), and then cluster three (C-3). Figure 4-4 shows the dendrogram from the clustering of response data on traceability information at the B2C and B2B levels. At the B2C level, information related to the origin, composition, manufacturer/supplier details, and product sustainability is in C-1 and the first half of C-2, thus becoming the most important. At the B2B level, manufacturer/supplier details, product specifications, quality certification data along with composition, and origin-related information are in C-1, thus placing these information among the crucial ones. Composition, origin, and manufacturer/supplier information are among the most crucial information, while process-related information, such as machine ID, time stamps, and sales and cost data are among the least important ones for both B2B and B2C levels.

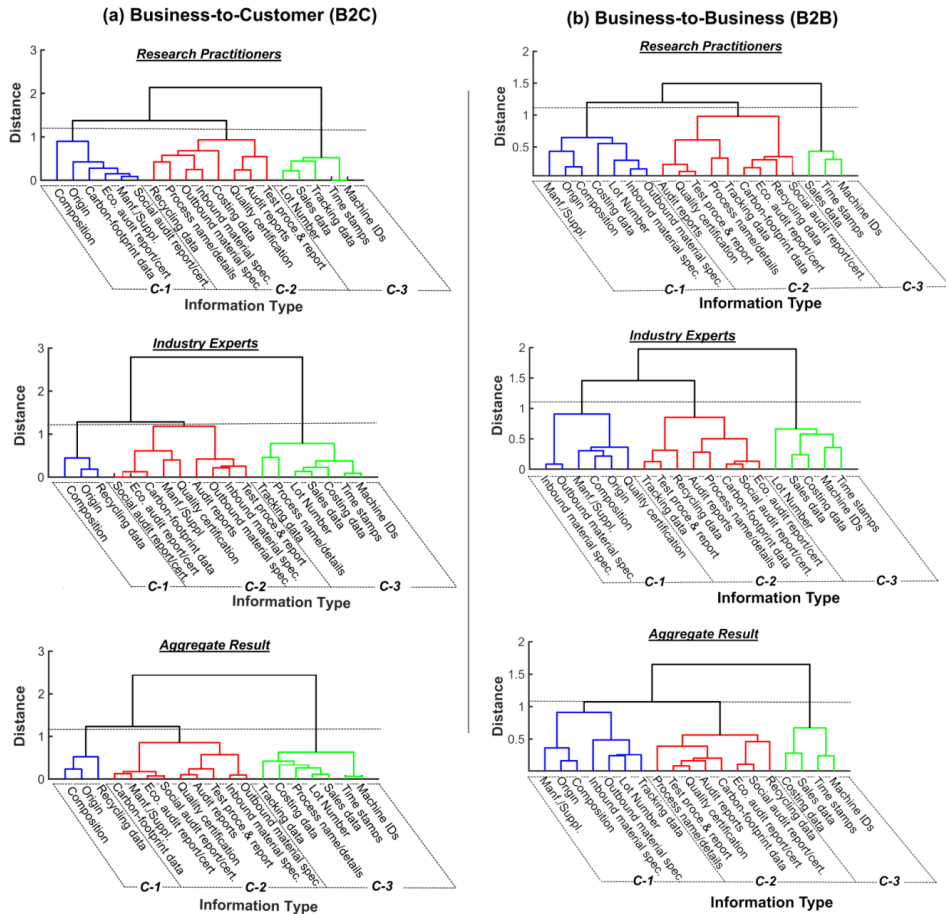


Figure 4-4: Information that can be recorded and shared at B2C and B2B levels

4.4. Paper III

4.4.1. Purpose and overview

The paper aims to contribute toward the development of a secured tag for product traceability in the T&C supply chain. Considering the needs of T&C products, which face certain challenges while using off-the-shelf tracking technology such as Radio Frequency Identification (RFID) and Quick-Response (QR) Code/Bar code, the study proposes the use of an integrated secured tag that is printed on the surface of the textile product. Inspired by the concept of Physical Unclonable Function (PUF), the secured tag is difficult to replicate and can be manufactured using inexpensive screen-printing technology. This

tag acts as a unique identifier linking each authentic product to the product database and helping in effective information exchange among various stakeholders located worldwide. The unique tagging of the product can help in realizing the concept of the Internet of Things (IoT), where the tag can be used to connect the user with the product information database. The smartphone-readable secured tags can virtually remove the geographical barrier between the user and the manufacturer by directly connecting the user to the manufacturer's database by merely scanning the tags.

The paper starts by exploring its prime focus, which is to develop an integrated secured tag for textiles that can be read and validated by smartphones to authenticate the product and connect to the product database. With this tag, information related to history and composition of the product can be easily accessed and can be useful in the recycling process. To realize the functionality as mentioned above, PUF, in the form of pseudo-random distribution, is explored to prevent easy cloning of the tag. Moreover, existing technologies are explored and utilized to develop a new solution to minimize the implementation cost.

4.4.2. *Paper research questions (PRQs)*

The study formulates, and empirically explores, two specific paper research questions (PRQs):

- *PRQ 3.1: What are the characteristics of a secured tag for a T&C product and how can conventional manufacturing methods be used to construct a secured tag?*
- *PRQ 3.2: How can image processing tools and pattern recognition algorithms be employed to read, encode, and validate a secured tag printed on the surface of the textile?*

4.4.3. *Research method*

To create random distributions on the textile surface, a printing paste, comprising micro particles (glitters) and binders in a fixed ratio, was screen printed on the surface of a textile of 3x3 cm² area as shown in Figure 4-5. An automatic magnetic table was used to control the metallic squeegee pressure. The particle randomness obtained was extracted and characterized using image processing tools and encoded using a fuzzy membership function as described in Figure 4-6. A detailed explanation of each algorithm step can be found in Paper III, appended in this thesis. The code thus obtained acts like a secure key to authenticate the product. To evaluate the tolerance of the proposed algorithm and verify its applicability, a sequence of experimental analyses was conducted and the results were discussed.

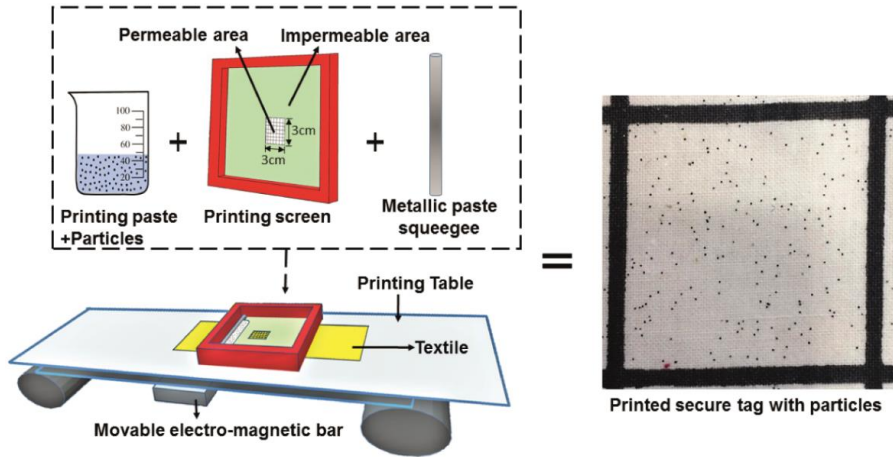


Figure 4-5: Representation of the magnetic table and screen-printing setup used in the current study

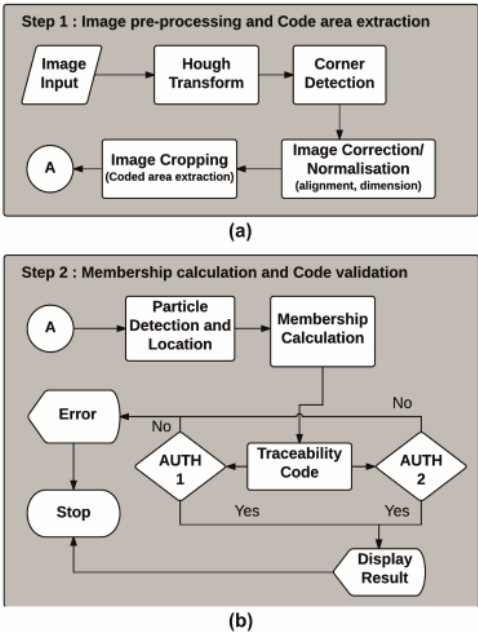


Figure 4-6: Flow chart for tag encoding and validation mechanism: (a) Steps for image pre-process and code area extraction; (b) Steps for extracting the features, calculating the membership, and validating the code

4.4.4. Main findings

A secured traceability tag for textiles should be durable enough to withstand normal textile use. It should be secured against unauthorized reproduction, remain integrated to the flexible textile product throughout its lifecycle, be low-cost (developed with an inexpensive method), be eco-friendly, and be readable by a readily available device.

Considering these characteristics, the paper introduces a secured tag that can be printed on a textile surface using an inexpensive screen-printing technology. The tag was encoded using image processing and pattern recognition algorithms, such as Hough transformation, inter-mode threshold, projective transformation, and Delaunay triangulation, followed by defining a decision support system using the fuzzy membership function. A detailed explanation of this can be found in Paper III, appended in this thesis. A sequence of experiments was performed to show that (1) the secured tag distributions are random and unique and (2) the developed algorithm can validate an original tag, even after certain deformations in the tag. The difference in the membership values was calculated between the original tag and a dissimilar or unlike tag for secured tag verification. It was observed that there was no significant change in the membership difference value of an original secured tag, even after the addition or removal of around 20% of the particles, as shown in Figure 4-7. Also, the membership difference did not increase (within the authentic tag), even after shape distortion due to stretching (up to 20%). For detailed results, refer to Paper III.

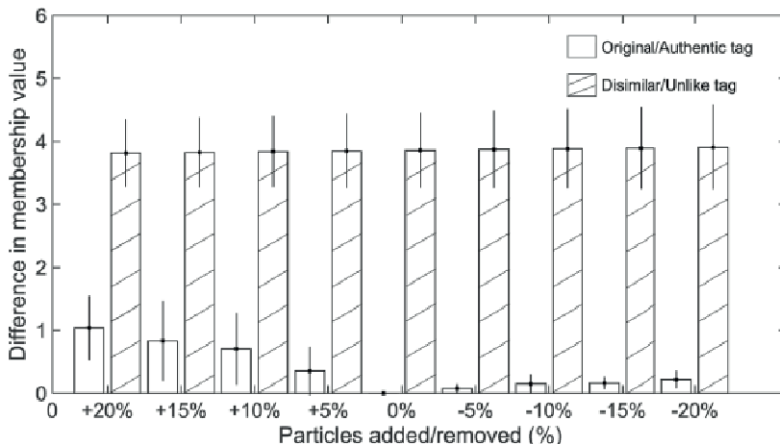


Figure 4-7: Difference in membership value when particles are added or removed

4.5. Paper IV

4.5.1. Purpose and overview

Product security is one of the major concerns in the textile industry. Every year, fashion brands suffer significant losses due to counterfeit products. To address this problem, the paper introduces a secured tag for traceability and security of textile products. The proposed tag is unclonable and can be manufactured using conventional screen-printing processes. Further, it can be read using a smartphone camera to authenticate the product and trace its history, thus providing additional functionality to the textile through surface modification. To validate its applicability, the study experimentally investigated the durability and readability of the developed secured tag using three different binders on polyester and cotton textile substrates. A comparison is presented with an in-depth analysis of the interaction of surfaces and binders at different stages of the secured tag’s lifecycle, that is, before print, after print, after wash, and after abrasion cycles. The methodology and findings of the study can also be useful for other manufacturing domains dealing with printing processes.

4.5.2. Paper research questions (PRQs)

The study formulated, and empirically explored, one specific paper research questions (PRQs):

- PRQ 4: How can a secured tag be printed to ensure its durability during the textile use phase?

4.5.3. Research method

Figure 4-8 presents the research methodology followed to address the PRQ.

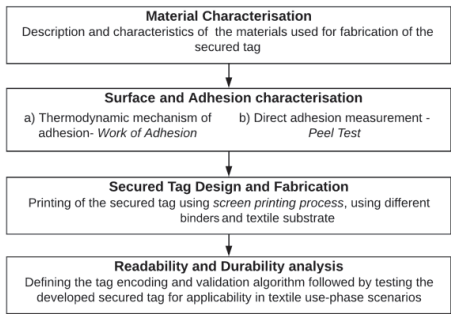


Figure 4-8: Research methodology followed in Paper IV

4.5.4. *Main findings*

The study presents a new secured tag for textile product authentication and traceability in the T&C supply chain. The secured tag is realized by printing randomly distributed micro-particles on the textile surface through an uncontrolled screen-printing mechanism. The randomness thus obtained is unclonable and acts like a unique signature for each product. Besides, this secured tag can be easily read and verified using a smartphone camera, thereby providing additional functionality to the textiles. The study systematically explains the development process of the secured tag (including design, fabrication, and encoding/validation algorithm), followed by an in-depth investigation of different raw materials (three binders and two textile substrates) and their interaction. Tests such as abrasion and wash resistance have also been performed to examine the durability and readability of the tag during the textile use phase. Finally, all the results were compared to determine the optimum combination. For experimental validation, three binders - Binder 1 (vinyl acrylic copolymer), Binder 2 (silicones), and Binder 3 (styrene acrylic copolymer); two textile substrates – Cotton (100% cotton) and Polyester (100% polyester); and two screens with 10 threads/cm and 24 threads/cm, were used. Figure 4-9 and Figure 4-10 show the results of the washing test and abrasion test on different samples. On the vertical axis is the number of particles (in percentage) that were eroded during the test and the horizontal axis is the number of test sequences. In addition, samples printed using a screen with the 24 threads/cm size on the cotton substrate are represented as “Cotton 24.” Similarly, “Cotton 10,” “Polyester 10,” and “Polyester 24” represent the type of textile substrate and screen size. It was observed that secured tags printed with Binder 1 (vinyl acrylic copolymer) performed best in all the different tests, while Binder 2 (silicones) performed better in wash resistance. On the other hand, Binder 3 (styrene acrylic copolymer) did not prove appropriate for the secured tag fabrication. Since the performed tests simulated the real-use condition of garments, it is anticipated that the fabricated tags can sustain the various use conditions of the textile.

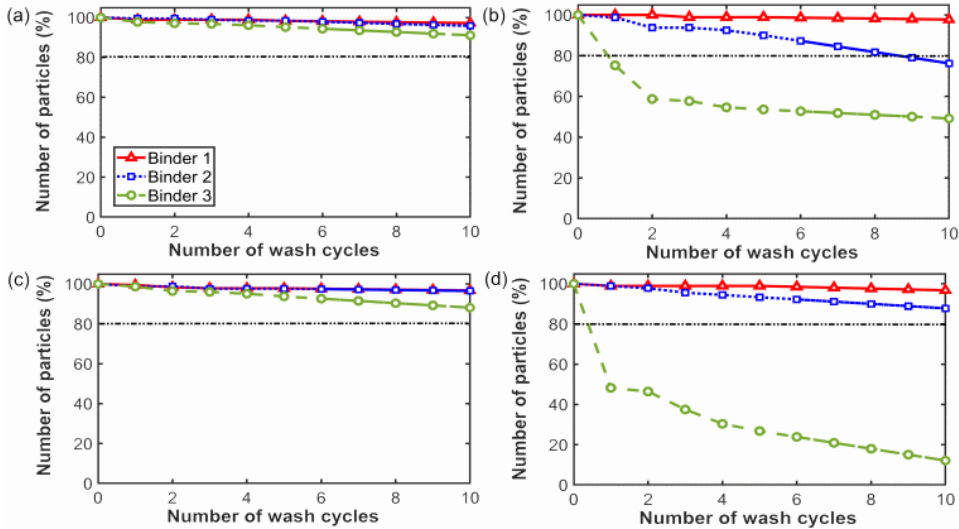


Figure 4-9: Washing test results: (a) Cotton 10; (b) Cotton 24; (c) Polyester 10; (d) Polyester 24

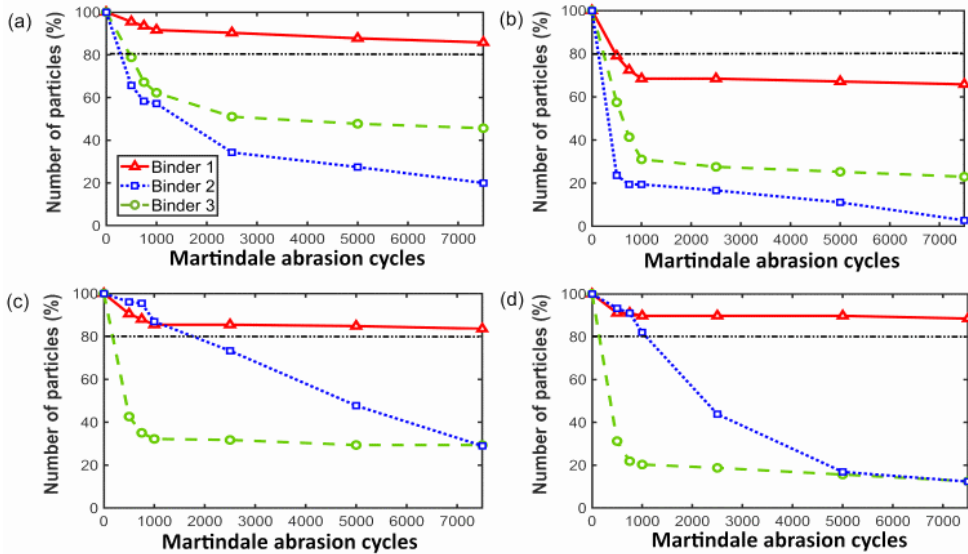


Figure 4-10: Abrasion resistance test results: (a) Cotton 10; (b) Cotton 24; (c) Polyester 10; (d) Polyester 24

4.6. Paper V

4.6.1. *Purpose and overview*

The paper presents a blockchain-based traceability framework for the supply chain with a case example of the textile and clothing (T&C) industry. It provides an overview of the T&C supply chain and blockchain technology, followed by a detailed framework for information/material exchange, supply chain partners' interaction, distributed ledger arrangement, smart contract development and information/material traceability and security in a commissioned or private blockchain network with restricted access to the supply chain partners, based on their roles and responsibilities. To support the proposed framework, the paper further develops and demonstrates an example blockchain with customized smart contract and ledger-updating rules for the T&C supply chain. The example is an initial step for customized blockchain development and can be further complicated by adding more interaction and network rules. It can be noted that, although the blockchain framework has been developed for the T&C industry, it can be incorporated for any supply chain with some modifications.

4.6.2. *Paper research questions (PRQs)*

The study formulated, and empirically explored, one specific paper research questions (PRQs):

- *PRQ 5: How can information traceability and security be ensured in the T&C supply chain using a blockchain-based traceability framework?*

4.6.3. *Research method*

This is a conceptual paper that follows a systematic approach to develop an information traceability framework using blockchain technology. It designs and explains the network structure at organization level and a mechanism for recording product transformation at operational level. Further, it uses mass balancing concepts to develop an example blockchain to demonstrate traceability data exchange between the partners in an organic cotton supply chain.

4.6.4. *Main findings*

The paper proposes a private blockchain network for supply chain traceability, as shown in Figure 4-11 (detailed explanation in Paper V). It explains the network configuration and partners' interaction at the organizational level. The unique feature of the network is that

it can ensure data privacy, network efficiency, and security. The figure shows a simple network with two channels, each for a particular set (cluster) of supply chain partners including the retailer (RE). In this example retailer is the focal firm that initiate the blockchain and host multiple channels for various clusters of supplier. Each cluster of supply chain partners - trading in a particular asset - interact on an individual channel (Channel 1 and Channel 2). Partners' interaction on channels are governed by the individual channel rules (C1 and C2) and by common channel rules (CN). There are multiple peer systems (e.g. P1a and P1b for Channel 1 and P2a and P2b for Channel 2) associated with single channel that can host single smart contract and ledger (e.g. P1a hosting S1 and L1) or multiple smart contracts, and multiple ledgers (e.g. PC hosting S1 and L1 at the same time S2 and L2). A1a and A1b are applications to access Channel 1; similarly, A2a and A2b to access Channel 2. AC on the other hand can access both channels and ACus is application for customer.

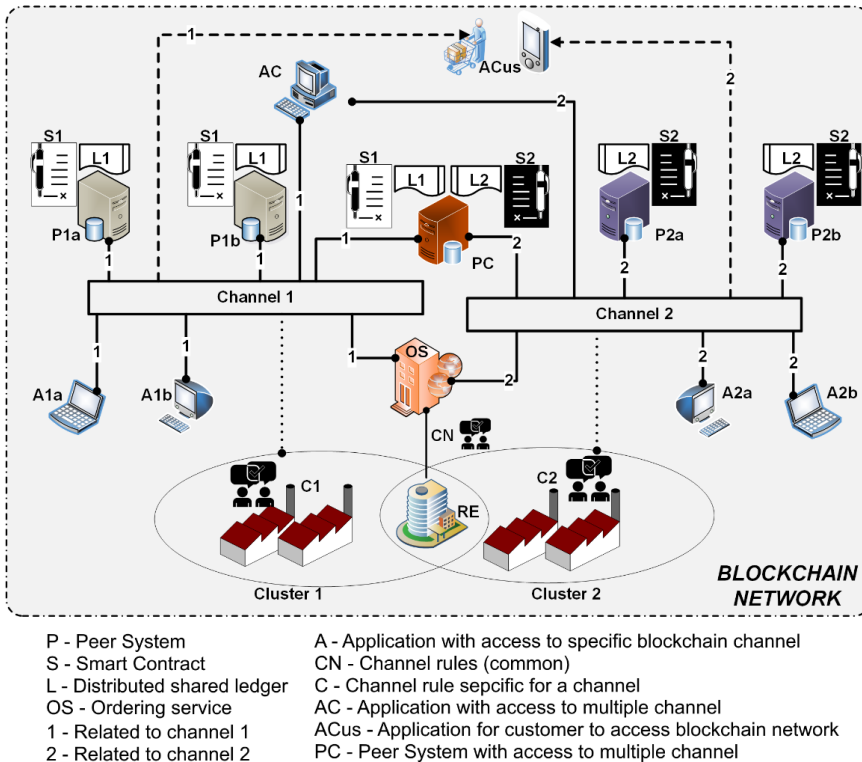


Figure 4-11: Commissioned blockchain at the organizational level

Further, the paper describes the framework at an operational level and explains the method for efficient recording and sharing of product transformation data for information traceability and security. To prove the applicability of the proposed framework, it demonstrates a case example of an organic cotton supply chain, as shown in Figure 4-12. For a detailed explanation, refer to Paper V, appended in this thesis.

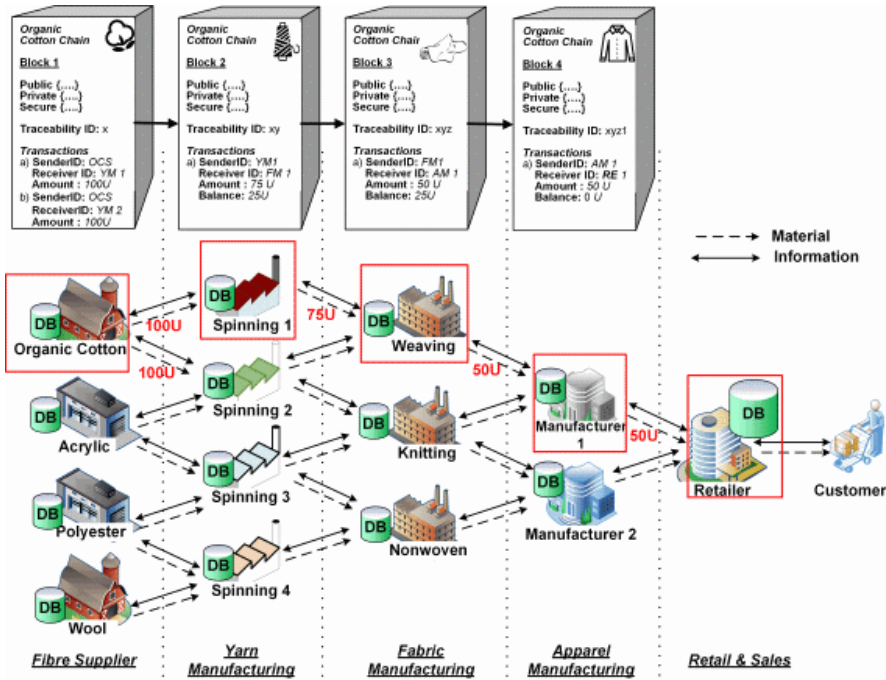


Figure 4-12: A typical T&C supply chain network with a marked partner involved in the simulated scenario

4.7. Interconnection between the appended papers

The appended papers cover different perspectives of traceability in the textile sector and are directly or indirectly interconnected with each other. Table 4-4 briefly describes the interconnection between the different appended papers.

Table 4-4: Interconnection between the papers				
	Paper II (Classification of the traceability factor and information)	Paper III (Manufacturing, encoding and validation mechanism of the secured tag)	Paper IV (Durability analysis of the secured tag)	Paper V (Blockchain-based traceability framework)
Paper I (Review of literature)	Identify factors influencing traceability implementation in the T&C supply chain	Printed secured tag can address traceability challenges related to product identification and security	Printed secured tag can address traceability challenges related to product identification and security	Blockchain-based traceability can address traceability challenges related to information asymmetry and security
	Paper II (Classification of the traceability factor and information)	Traceability information that can be linked with secured tag	Traceability information that can be linked with secured tag	Traceability information that can be shared at B2B and B2C levels
		Paper III (Manufacturing, encoding, and validation mechanism of the secured tag)	Binder and printing mechanism that can ensure the durability of the secured tag during textile use-phase	Secured tag can be integrated with blockchain technology to ensure both product and information traceability
			Paper IV (Durability analysis of the secured tag)	Durable secured tag with blockchain technology can ensure traceability during product use-phase

5. Analysis

This chapter presents the analysis of the results in consideration of the frame of reference presented in Chapter 2 to answer the research questions. The discussion in this chapter elaborates the results from the appended papers, based on the points aggregated in Figure 5-1 and how these results answer the RQs.

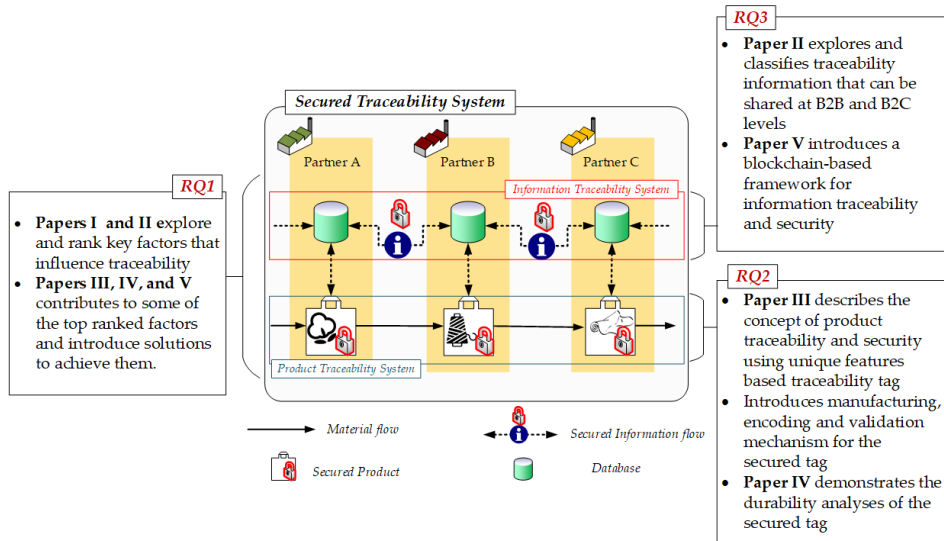


Figure 5-1: Contribution of each appended paper to the development of the secured traceability system

5.1. RQ1: What are the different factors influencing traceability implementation in the T&C supply chain?

Traceability has been a significant concern in various industrial sectors. RQ1 seeks to explore different factors that influence traceability in the T&C supply chain and further rank them based on experts' perceptions. PRQ 1 and PRQ 2.1 were formulated to address RQ1. The following section describes the findings from the appended papers relating to the above-stated question.

♦ Exploring and ranking key factors

Paper I (PRQ 1) examines, based on literature, the potentials and implementation challenges of traceability in the T&C supply chain. Summarizing the findings from Paper

I, Paper II (PRQ 2.1) enlists different factors that influence traceability and empirically ranks them based on experts' perceptions, using the Delphi method. The results of the analysis are shown in Figure 4-3.

Risk management ranked highest, as traceability implementation can directly contribute to risk management in a T&C supply chain dealing with various threats that cause delays and disruptions. Traceability has also been supported by Chaudhuri et al. (2015) for the food supply chain. One of the panelists said, "Main need for traceability is about - risk assessment and enabling brands to assess whether they will get the product on time with expected quality." In previous literature, Giannakis and Papadopoulos (2016) also support the need for supply chain traceability (including T&C) for risk management and stress its importance in identifying and eliminating potential sustainability-related risks that can result in losses. *Product authentication* ranked as the second most influential factor, as lack of dedicated traceability technology in the T&C supply chain makes the intrusion of counterfeit products easy. According to a panelist,

[...] most of the [traceability] solutions until now are hard to realize in the production systems [...]. Example [...] RFID, which is very hard to produce in a large quantity [...]. The cost of a durable, washable tag is very high, and the programming is complicated. The label printers that effectively can produce RFID or Barcode tags cannot print and program the durable tags because of their size and thickness. The barcodes and 2D codes that are easy to reproduce are also very easy to counterfeit or copy.

Supply chain *visibility* emerged as the third most influential factor. In agreement, another panelist reiterated, "Traceability implementation can increase visibility also of in-shored/re-shored production. It provides the opportunity to better monitor supply chain actors and their activity." A traceability system can further enable effective *quality monitoring* and assure the claims of quality certifications (like eco-labels and organic certification etc.). It confirms the reliability of the certificates by capturing each step of the product lifecycle and it "ensures that certification schemes are independent and applied in an equal manner globally" as indicated by a panelist.

Market surveillance was ranked fifth, and one of the panelists said "due to lack of traceability mechanism, border surveillance authorities and customs find it challenging to verify origin and genuineness of products when they cross borders." Additionally, in situations of recalls, due to lack of a traceability system in the T&C supply chain, it is difficult for market surveillance authorities, such as RAPEX, to trace the origin of defects or the accountable stakeholder (Kumar et al., 2017a).

After market surveillance, *IP Protection* was on the sixth rank and, due to the absence of a secured information traceability system, it is an emerging concern for the T&C supply chain according to the IBM security report (2016). Highlighting its importance, a panelist working on blockchain technology added,

Traceability ensures that information is controlled at various levels of the supply chain with restricted access to authorized actors only. All information [in the survey] plus even more should be available and accessible. [...] I am a strong believer of the future [...] of blockchain technology-based traceability systems. A [...] spot where traceability and transparency come to a collision.

In the seventh, eighth and ninth positions were factors related to marketing, transparency, and product recall. Traceability information can act as a *marketing tool* “to showcase sustainability concern of a brand, create a positive image and act as a competitive advantage,” as mentioned by a panelist. *Transparency* can aid in gathering information on the origin of materials, in order to measure social welfare, animal welfare, and environmental impact, as mentioned by a panelist, which has been supported in literature (Doorey, 2011; Egels-Zandén et al., 2015; Kumar, 2017). Moreover, traceability information can facilitate product recall by identifying early warning signs, tracking recalled products, and monitor customer reaction. *Product data management* and *sales forecasting* received tenth and thirteenth positions respectively, and one of the panelists mentioned that traceability systems facilitate production data management “by real-time tracking and tracing of material in stock exchange - trading the total quantity sales for each product/color, location or the factory address and name, and traceability code for the manufacturing mapping.”

Factors related to supply chain circularity and share economy, namely, *reverse logistics*, *rent/share/reuse*, and *product use/maintenance* got the lowest ranking and obtained the eleventh, twelfth, and fourteenth positions respectively. A panelist gave a supporting reason for such low ranking:

[Traceability] information is not relevant during the use and maintenance of the product, but during the purchasing decision making. Traceability is more necessary at the post-sales level, for the collection of relevant data and information on consumers' behavior [...] set of elements that could give customers the traceability of their footprint while using/not using, maintaining/not maintaining, re-cycling, up-cycling/discharging their textile products. To apply to the sharing business, the tag [traceability mechanism] should have its recording system that harvests the number of washes,

mistreatment, etc., while the garment is being shared. Aftersales traceability information of the kind [...] is crucial for recyclability reasons.

As highlighted and aggregated in Figure 5-1, along with Papers I and II (which are aimed at exploring and ranking traceability factors), Papers III, IV, and V also contribute to RQ1. With the aim to develop a secured traceability system for the T&C supply chain, these papers (III, IV, and V) advocate some of the top-ranked factors influencing traceability and introduce solutions for their implementation in the T&C supply chain.

◆ **Product authentication**

The T&C supply chain is highly affected by counterfeit products that account for significant losses (Corbellini et al., 2006). During the Delphi study in Paper II, counterfeit products were ranked the second most important factor influencing traceability in the T&C supply chain. Owing to the inability to differentiate between authentic and counterfeit products, a large portion (by volume as well as value) of textile products is confiscated by border customs officials of various countries every day, which disrupts the sales (Amar et al., 2018). Presently, the customers rely on brand names, logos, or tags to distinguish original products from counterfeits (briefly discussed in Paper III). However, these identifiers can be easily replicated and thus act as an easy break-in point to introduce and mix counterfeit products in the market. Product traceability can play a significant role in product authentication. Traceability implementation requires product mapping with traceability tags that act as a unique identifier for each product in the complex supply chain (Olsen and Borit, 2018). In this regard, Paper III introduces a printed secured tag based on random particle distribution that can be used for product tracking and authentication. Random distribution achieved through the screen printing process, with uncontrolled particle positioning, makes it almost impossible to replicate this secured tag, which is also supported by Gennaro (2006). Further, the proposed secured tag system was tested for durability by exploring the best combination of binder and textile substrate that can withstand washing and abrasion during the textile use phase (discussed in Paper IV).

◆ **Quality monitoring**

The T&C supply chain involves multiple stages of operation, starting from fiber production to the manufacturing and distribution of final textile products; thus, one crucial challenge is to maintain and monitor product quality throughout the supply chain. To prevent possible contamination, it is vital that supplies are carefully inspected and recorded at different stages of transformation (Dabbene et al., 2014). As explained under Section 4.5 and elaborated in Paper V, blockchain-based traceability can be incorporated as a useful tool for information traceability to keep track of supplies, their quality, and

their quantity, as they flow along the supply chain. This is also recommended by Saberi et al., (2018). Further the case example in Paper V demonstrates how the tracking of product transformations through a mass-balancing algorithm on the blockchain can help in reducing potential contamination (because of low quality or fake raw material) or fraudulent transactions. It can trace back to the origin of the defect to identify the accountable actor, and preventive measures can be taken at the source.

◆ IP protection

As discussed in Chapter 2 and as one of the highly ranked factors in Paper II, IP protection is an important challenge in the manufacturing sectors, including T&C. Timestamped ledger entries, along with the public-private key pair in a blockchain-based traceability system (as discussed in Paper V), can be an effective tool to prove the association of IP with the rightful owner. This has also been demonstrated in the work of Ølnes et al.(2017). Moreover, the hash-based encryption of immutable records in blockchain can enable IP enforcement systems to monitor and trace the partners using the IP.

◆ Other factors

Other than the above-discussed factors, risk management, market surveillance, transparency, and visibility are some of the highly ranked factors (according to the Paper II study) that have been considered while developing the traceability system proposed in Papers III, IV, and V. Risks associated with counterfeit products or fraudulent transactions can be reduced significantly with the use of a secured tag and a blockchain-based traceability system, which is also advocated in literature (Tian, 2016). The proposed traceability system would facilitate market surveillance authorities and border customs officials to identify fake or harmful products and the accountable supply chain partner. As products can be identified individually in the T&C supply chain through the secured tag, the information exchange can be distinct for each individual product and, subsequently, it can offer enhanced control and transparency in the supply chain. It would reduce the information asymmetry among the supply chain partners that work toward shared organizational objectives and enhance visibility.

- Conclusion

The aim of RQ1 was to investigate the key factors influencing traceability implementation in the T&C supply chain. Traceability is the ability to recall information and trace back the history and origin of products; therefore, its implementation has numerous benefits that can be mutual as well as exclusive to the supply chain partners. Therefore, in this analysis, relevant factors were explored and ranked based on the consensus of a group of experts.

The study revealed some of the crucial factors for the T&C sector that were later addressed through the developed traceability system based on secured tag and blockchain technology.

5.2. RQ2: How can product traceability and security in the T&C supply chain be ensured?

Product traceability is a concept of tracking and tracing individual products (TRUs) using a unique identifier to distinguish different or similar-looking products, which acts as a reference to link product transformation information throughout the supply chain (Thakur and Hurburgh, 2009). It helps in recalling the source and history of each product (Kumar et al., 2017b). To enable these functionalities, product-traceability systems rely profoundly on traceability tags that are associated with the individual product (TRU), helps in their unique identification and acts as a link connecting the product with a product database. Due to such crucial functionality, it is equally essential to ensure the product's security and durability (Kumar et al., 2016b). As the weakest link determines the strength of a chain, an unsecured or reproducible tag acts as a porous layer enabling easy intrusion of counterfeit products in the supply chain. Hence, a traceability tag should be secured enough to prevent its cloning, durable enough to withstand mechanical agitations, and associated with a product throughout its lifecycle (as discussed in Paper III while addressing PRQ 3.1). Therefore, developing an appropriate and secured tag is the very first requirement for secured traceability. One of the possible solutions in this regard is to identify an inherent and random feature on the individual product and encode it with a unique signature code that can act as a secured tag (Devadas et al., 2008). In this way, the tag will be on the product itself and cannot be removed, thus reducing the possibility of product loss or counterfeits in the supply chain.

In this context, Paper III introduces a secured tag for T&C products, which consists of printed micro-particles. These particles are distributed randomly on the surface of the textile through an uncontrolled process. Printing integrates the traceability tag with the product and randomness acts as a unique signature for each product. The appended Paper III describes manufacturing, encoding, and validation of the secured tag in detail, based on various experiments to confirm its uniqueness to answer PRQ 3.2. Paper IV further tests its durability and explores the best binder and textile substrate combination for the secured tag to address PRQ 4.

◆ Product traceability and security using unique features of the traceability tag

Product security, in the present context, implies protecting the T&C supply chain from counterfeit intrusion and the T&C product from unauthorized modification. As the T&C

supply chain involves multiple partners located worldwide, and the products are often handled and transported by third-party logistics service providers, product replacement during the transit process is a common issue. Therefore, in such situations, product security is a major concern. Paper III describes the concept of product traceability and security using a traceability tag with inherent features. Each product (TRU) should be associated with a tag that is unique, hard to copy, and integrated with the product, and should remain associated throughout the product's lifecycle. To realize such a product traceability system in the T&C supply chain, a single type of tag would not be sufficient for different stages of the supply chain. The material lots are combined and transformed into new materials with changed physical or chemical properties; therefore, unique inherent tags must be developed for each stage as shown in Figure 5-2. A similar concept is also proposed by Kumar et al., (2016b).

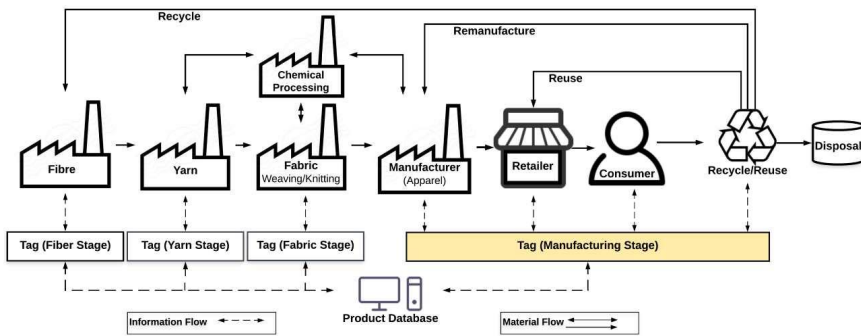


Figure 5-2: An ideal secured traceability system

These tags would be integrated with the product/intermediate product at each supply chain stage before it is transferred to the subsequent downstream partner. For instance, at the yarn stage, the traceability tag should be developed by extracting and encoding some unique features of yarn, and at the fiber stage, the tag should be based on some unique features of fiber. At each stage, these tags would link the product to the data management system and would stack product data in a time-based function, through different lifecycle stages. Thus, the unified database system would retain and include the data related to all the stages. The same concept is also supported in a study by Kumar et al. (2016b).

It should be noted that this thesis introduces secured tags that must be printed on T&C products during the garment fabrication stage before the final product is passed to the retailer and finally to the customer.

♦ **Manufacturing, encoding, and validation mechanism for a newly introduced secured tag**

Paper III introduces a particle randomness based secured tag system for product traceability in the T&C supply chain. It explains the manufacturing, feature extraction, and encoding algorithm using image processing and pattern recognition tools and further demonstrates the validation mechanism based on a defined membership function.

For manufacturing, the secured tag printing paste containing black micro-particles was screen-printed on a textile substrate (as described in Paper III). Apart from being inexpensive, the screen-printing method could not control the particle distribution on the textile surface, thus resulting in a random and unique distribution of micro-particles in each print. These micro-particles were strategically selected to enable their easy detection using smart-phone based cameras. Moreover, printing the secured tag makes it an integral component of the textile product that cannot be detached easily. It should be noted that since the position of the secured tag cannot be altered after printing, its implementation and placement location on the product would require a further well-planned investigation.

For extracting the optical features of the random micro-particle distribution, an image processing algorithm was used. This algorithm segregated the printed secured tag features from the textile background and captured the relative location of each micro-particle. These optical features were further characterized using pattern recognition tools to encode them as traceability codes. Paper III describes in detail the encoding algorithm along with a different feature that was extracted from the secured tag.

In the final stage, these features were associated with a membership function to ease the validation mechanism (to add tolerance and error handling capacity), even after the tag is distorted or destroyed to a certain extent. To prove the uniqueness of the proposed secured tag, the membership of 50 secured tags was calculated and a one-to-one comparison was done. The highest membership difference among all comparisons (except self-comparison) signifies the uniqueness of the secured tag. Further, simulated experiments were also done to test its applicability in real-life scenarios.

♦ **Durable secured tags that can withstand T&C use-phase treatments**

To ensure product traceability and security of the T&C product, it is equally important to examine the durability of the traceability tag so that it can withstand use-phase mechanical agitations in the form of washing and/or abrasion. The printing paste and micro-particles should remain intact, and the secured tag should still validate and

authenticate even after a certain degree of deformation. Therefore, to explore the best binder and textile substrate combinations, different commercially available binders and most widely used textile substrates were used to print different samples of the secured tag. These samples were experimentally analyzed through direct and indirect adhesion characterization methods and later subjected to a wash and abrasion cycle. It was observed that some of the best combinations revealed promising results and can be used for secured tag development in the actual manufacturing scenario.

- *Conclusions*

RQ2 investigated how product traceability and security can be ensured in the T&C supply chain. It targeted some of the drawbacks of the off-the-shelf and widely used externally attached tags in the form of RFIDs and barcodes and introduced a secured traceability tag system for T&C products. The secured tag transfers the encoded information onto the textile product itself, since it is printed directly on the surface, thus reducing reliance on the external tag. The secured tag is hard to replicate and is durable against washing and abrasion, proving its applicability in the textile use phase. Nonetheless, the secured tag must be placed and printed systematically on the product during the production process with advanced analysis, as post-printing adjustments will not be possible.

5.3. RQ3. How can information traceability and security in the T&C supply chain be ensured?

Based on the factors influencing traceability, this RQ aimed to identify important traceability information and a framework for its secured documentation, management, and exchange with other supply chain actors for seamless information. Information is a crucial component for the effective functioning of a supply chain. According to Štorga et al. (2011), businesses work rigorously to obtain relevant information from various sources, which can facilitate decision making and act as a competitive advantage. Although in the T&C supply chain, actors are interdependent with regard to raw material supplies and synchronized functioning, yet they act as independent units. Each actor has its administrative limitations, and seamless information sharing would require efficient supply chain integration. In this situation, products or services connect the supply chain actors for their mutual functioning, and implementing an information traceability system would extend the informational boundaries of a supply chain actor. Information traceability implementation implies capturing, sharing, and securing essential data related directly or indirectly to product transformation throughout the supply chain. As mentioned before, the T&C supply chain involves multiple operations, each of which involves product modification or transformation. These steps generate large data (from

several perspectives such as product properties, process, quality characteristics, sustainability, etc.) that need to be adequately captured for internal traceability, and shared (to a certain extent) with other supply chain partners for external or complete traceability. This added traceability information might be useful and crucial for other downstream supply chain actors or regulatory requirements. Nevertheless, a first step toward traceability system development would be to classify information that should be recorded and shared at B2B and B2C levels, as presented in Paper II. Further, Paper V describes a blockchain-based framework to share and manage the important traceability information in a linked manner, such that product transformation and related information can be traced at any point in the T&C supply chain. Additionally, the blockchain mechanism provides a systematic and secure means for information storing and sharing, while retaining the link, even if the related products are transformed.

◆ **Key traceability information that can be shared at the B2B level and the B2C level**

In Paper II (to address PRQ 2.2), a Delphi-based survey was conducted with 23 experts across the globe with extensive experience in supply chain traceability in the T&C supply chain, to classify traceability information sets (using hierarchical clustering and the optimal leaf-ordering method) that should be recorded and shared at the B2B level and the B2C level.

The analysis found that information concerning the “origin” and “composition” of the product was always in the first cluster and among the most important ones. As a mandatory government regulation (e.g., EU’s T&C legislation), this information is already shared with end-customer and surveillance authorities, albeit lacking correspondence with all tiers of the supply chain. Following this is the information related to manufacturer/supplier details and social-environmental sustainability (like “recycling data,” “social audit report/certifications,” “environmental audit report/certifications,” and “carbon footprint data”). As is evident from Figure 4(a), research practitioners consider this information very important and ranks it among information that should be shared with customers along with origin and composition details. One research practitioner even said,

Traceability relevant information is not only about sourcing locations, but also about the environmental and social footprint of raw material sourcing, i.e., agricultural method of production, soil regenerative performances of the plantation (e.g., best fibers used in agricultural rotation cycles, water consumption in case of organic cotton, pesticides, and fertilizers used in

conventional agricultural systems), as well footprint of virgin oil extraction referred to synthetic materials.

The researchers believe that these sustainability aspects are often ignored and not communicated properly to the customer. Another researcher added,

[...] raw material and production footprints, as well as social and economic footprints of the tiers' 'deeper depth' (for example the tier with chemical manufacturers), are too often the blind spots of any social and environmental assessment today. Customers [...] should not only be informed about carbon-emission but on all the relevant factors that represent the negative and/or positive environmental and social footprint. Carbon-emissions during transportation [...] starting from raw material to the consumers purchasing location, all should be part of traceability information shared at B2C level.

On the other hand, the industry experts are of the view that recycling-related information is more important than any other sustainability information. They added,

Recycling data related to recyclability and where to send the product at the end of the usage [...] would be key for both B2C and B2B. [...] closing the loop of the material is the most important objective of being transparent. Moreover, disposal information can be a component of traceability information which can help the consumers at the end of a product's life.

Despite differences in opinion, information in the two clusters (C1 and the first half of C2) are close to each other in the aggregate results and among the most important ones.

In the latter half of C2 is information related to product quality and specifications such as, "quality certification," "audit reports," "test procedure/reports," and "inbound and outbound product specifications," which are ranked among the vital information. Based on the level of traceability and information storage capacity of the traceability system or tag, brands or retailers can choose to share this information with customers and end-users.

Finally, in the last cluster and among the less important traceability information for customers is information related to "costing," "tracking," and process-related aspects like "machine ID," "timestamp," "sales," and process details. One of the panelists said, "Customers do not require timing, tracking and sales data. It can be important for B2B sharing purposes."

It is evident from Figure 4(b) that at the B2B level, along with traceability information related to manufacturer and supplier details, origin, and composition (which were also

among the most important ones for B2C), “inbound and outbound material specification,” “quality certification/audit,” “lot number,” and “tracking data” are considered very important to be recorded and shared. Previous studies have also emphasized the importance of this information in order to have better visibility, accountability, and control over the supply chain activities (Egels-Zandén et al., 2015; Kumar, 2017; (Nel) Wognum et al., 2011). Traceability information related to all the suppliers across tiers (i.e., tier 2 and even tier 3) should be recorded and shared with all supply chain partners. Moreover, as stated by one of the panelists, “incomplete or improper specification leads to quality issues and problems in production.”

Product quality and social-environmental sustainability were clustered in C2. As mentioned before, based on the traceability level, supply chain actors can choose to share this information with all other supply chain actors. It was observed that information related to social and environmental sustainability falls in the second significant cluster rather than the most important one, like in the B2C level.

Finally, in the last cluster and among the least important ones, information related to businesses is almost the same as that in the B2C level. This consists of information related to “product costing,” “sales data,” and processes related to “machine ID,” “timestamp,” “sales” and process details. Usually, businesses find it unsafe to share such sensitive data, especially related to costs and sales, in order to maintain their competitive advantage (Canavari et al., 2010).

◆ **Blockchain-based framework for information traceability and security**

The T&C supply chain is exclusive in the sense that it comprises numerous actors dealing with specialized raw materials and located in specific locations where they can provide the product at a competitive cost with more efficient services. A typical T&C supply chain consists of fiber manufacturing units, yarn manufacturers, weaving/knitting units, chemical processors, apparel producing companies, and retailers or buyers, along with the logistic partners. At each supply chain stage, inbound materials are mostly mixed to form new outbound product lots with altered physical or chemical properties. Therefore, for effective supply chain traceability, a link should be stabilized among materials at different supply chain levels and, consequently, the information that needs to be mapped with respective outbound materials and supply chain stages (Kumar et al., 2017b; Olsen and Borit, 2018). Considering this, in Paper V (to answer PRQ 5), a blockchain-based traceability system is proposed that records, secures, and verifies product transformation. A simulated case example of the T&C supply chain for 100% organic cotton products demonstrates how the system can efficiently trace the products moving in the supply

chain, while ensuring accountability, security, and transparency. Figure 5-3 is a screenshot of the developed blockchain structure, which highlights the critical features of the proposed system.



Figure 5-3: Screenshot of blockchain simulation from Paper V

Ensuring the basis of information traceability that is able to map, record, and communicate the traceability information from/with other involved supply chain actors, the system has the provision of recording private sharable information, sharable public information, and secure information (also supported in traceability framework by Kumar et al. (2017b) and Thakur and Donnelly (2010). Depending on the type of accessibility (based on digital address), individual supply chain partners can access this information to maintain the privacy and security of crucial information.

Since traceability information originates in each supply chain stage, managing multiple databases and ensuring collaboration to share the data is a practical concern. It requires a strong integration of individual databases from all partners. In this situation, a distributed shared ledger backed by blockchain technology (as demonstrated in Paper V) can handle all traceability data at a single location, with data security and privacy. The framework also provides an information apprehension and exchange method that is easily customizable to meet government regulations and/or enforce supply chain strategies. On the other hand, a distributed network is favorable when the supply chain controls and manages the supply chain partners involved.

- *Conclusions*

RQ3 aimed to develop an information traceability system for the T&C supply chain that can manage and secure crucial information from multiple supply chain actors at various production stages. Implementing traceability in the T&C supply chain requires collective action from all the supply chain actors involved. These actors collaborate on the desired level of traceability and information management and exchange. Each actor acts as an essential link in the traceability chain and shortcomings on the part of any actor would negatively affect the traceability implementation. In this regard, as a prime requirement for implementing traceability, this research aimed to collect important traceability information that needs recording and sharing at an intra-organizational level. Further, it proposes and demonstrates (through a simulated example) a blockchain-based traceability system that can recall the traceability information from each level of the supply chain. It includes the organizational and operational level networking structure and data capturing and management rules that can ensure security, accountability, auditability, and persistence.

6. Conclusions: summary and contribution

This chapter concludes the thesis and presents its implications to industry and academia. While in Chapter 5, the discussion was focused on the research questions proposed in this thesis research, this chapter describes the contributions from a general perspective.

6.1. Summary

Supply chain traceability is an inter-organizational concept that involves several partners; depends on multiple aspects such as a regulatory system, organizational policies, and technical competencies that record, store, and share information systematically and logically. As indicated by Johansson and Månsson (2013), “traceability is an internal practice of sharing information among supply chain members concerning materials and methods (for example toxins usage and use of child labor) to improve noneconomic chain performance and reduce risks.” For supply chains dealing with food and pharmaceutical products, traceability is a priority because of the direct impact of the product on end-users- which can be fatal- specially in the case of contaminated, unsafe, or bad quality products. Considering the risks, these supply chains have strict regulations and a certain level of mandatory traceability expected from supply chain partners in order to operate and conduct business (Goswami, 2014). In this context, the T&C supply chain does not have a long history of promoting and implementing traceability with their partners (Johansson and Månsson, 2013). In recent times, the need for traceability in the T&C supply chain has been fueled by a series of unfortunate events, and growing IP infringements. Customers’ demand for sustainable fashion products and increasing concern to know the origin, history, and social/ecological impact of products have aligned the T&C sector to adopt traceability mechanisms. In light of this, this thesis contributes to the development of a secured traceability system for the T&C supply chain. It explores and priorities key factors influencing traceability in T&C supply chain (Paper I and Paper II). Considering these factors (for instance, risk management, product authentication, quality monitoring and IP protection), the study introduces two component systems of a secured traceability system as shown in Figure 6-1.

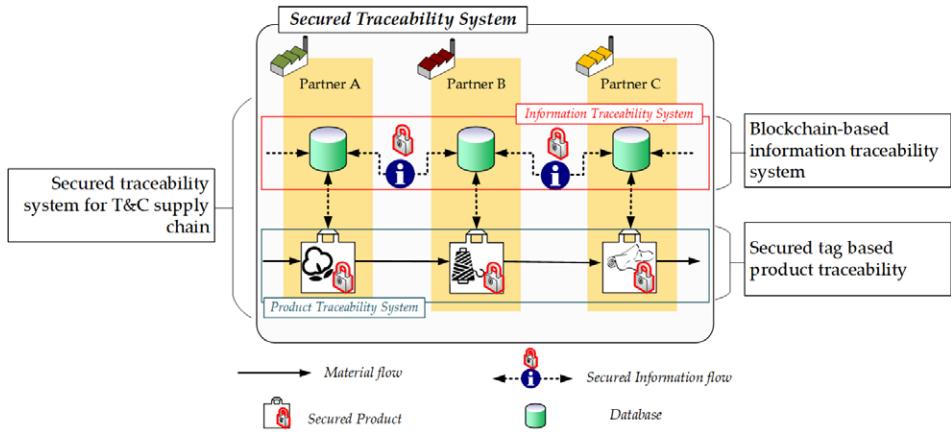


Figure 6-1: Supply chain traceability with component systems

Traceability, in the general sense, is the ability to recall the history of a product using some traces (or traceability markers/tags), which substantiate the product among the same or similar products. These traceability tag is the only link between traceability information and the physical product. The integrity of the traceability tag with the product and its security from replication are particularly necessary for the successful realization of product traceability (Informal Product Traceability Expert Group - Final Report, 2013). Therefore, to ensure product traceability and security the thesis introduces a secured tag that is hard to replicate and integrated on textile surface through printed process (Paper III and Paper IV). Further to secure information collection/sharing mechanism and prevent fraudulent transaction it proposes a blockchain based framework for information traceability and security in T&C supply chain (Paper V).

6.2. Contributions

6.2.1. Theoretical contribution

The thesis contributes to traceability literature, primarily for T&C supply chain. The research is among the few that visualizes and contribute to development of a complex secured traceability system with the SoS perspective. In past studies, the SoS approach is mainly used to examine and develop complex defense and transportation systems, however, limited work has been done to apply SoS approach for economic systems development. Thus, the thesis explains some of the crucial characteristics of the SoS theory and systematically explores their value for working toward the development of a secured traceability system for the T&C supply chain. It explains the motivation for SoS selection in section 2.6.3 and the qualifying criteria of the SoS theory for traceability

system visualization and develop in Table 6-1 using the “ABCDE” criteria (Choi et al., 2018; Gorod et al., 2008).

Table 6-1: ABCDE criteria for SOS and the satisfaction of these by the traceability system

Criteria	Traceability system features, related to criteria, as perceived from the research	Satisfied?
Autonomy (A)	Systems for information traceability and product traceability can co-exist independently and with the ability to make independent choices. However, for a complete traceability system, they need to perform synchronously.	Yes
Belonging (B)	Systems for product and information of traceability can choose to be part of the global or complete traceability system (SoS). For example, information sharing and traceability using the blockchain-based system are possible with or without the use of a secured tag or unique identifier.	Yes
Connectivity (C)	Product traceability system can be easily integrated with the information traceability system.	Yes
Diversity (D)	Traceability system at product level can track, trace, and secure the product when it moves in the supply chain. Similarly, at information or business level, it ensures information security and information symmetry. However, a combination of both systems will have enhanced capabilities and complete traceability of the supply chain.	Yes
Emergence (E)	With technological advancement, subsystems of traceability are evolving and transforming into a more advanced system, with better functionality.	Yes

Moreover, as an initial step toward bridging the research gap that demands consensus among T&C supply chain actors for adoption of a traceability system, the thesis empirically explored and classified (through experts’ perceptions and concerns) different factors influencing traceability and traceability information sets that need sharing and recording in the T&C supply chain at B2B and B2C levels in Paper I and Paper II. Based on these results, the thesis further introduced a random-particle based secured tag and a blockchain-based traceability framework for a secured traceability system for the T&C supply chain. All these contributions not only attempt to bridge the research gap, but also provide a better understanding of various technological aspects like blockchain, cryptography, traceability tags and their application in T&C supply chain. The thesis further develop insight regarding the values of the traceability system and understanding of the managerial aspects related to a system-of-systems theory, supply chain integration, information management, and supply chain management. Most importantly, it

contributes to developing the knowledge and know-how regarding different technological and managerial aspects that can be incorporated in the T&C supply chain, considering its uniqueness in terms of structure, products, and functionality.

Most past studies have focused on the product traceability using generic tags, like RFIDs and barcodes, which are externally attached to the product and usually help in tracking and tracing application. These tags are detached and deactivated at the point of sale (POS) and do not serve the purpose of after-sales traceability applications, such as product recall management. This thesis presented the concept of secured tag-based product traceability and security for the T&C supply chain. Inherent and random product features related to intermediate products (at different supply chain stages) can be encoded into a traceability marker that are hard to replicate. It further presents a secured tag algorithm by encoding random particle distribution printed on the textile surface at the apparel production stage. Although developed for the T&C products, the secured tag system can easily be incorporated in other manufacturing domains using the screen-printing method.

This thesis can be a reference point for policy makers in drafting traceability related rules and regulations. Top management can benefit in determining the traceability level in their respective supply chain, traceability related decision-making, or developing a blockchain based business model.

6.2.2. *Practical contribution*

The main practical contribution of this thesis is as follows:

◆ **Secured tag**

A secured traceability tag developed for T&C products and constructed using conventional screen-printing method. The secured tag is integrated on the textile surface, hard to replicate, and durable against wash and abrasion. The main novelty of this work is in the following: (1) the concept and design of a secured tag is specially manufactured for the T&C supply chain considering its particularities; (2) value generation from the existing conventional printing technology and material with low capital investment; (3) selection and encoding of distinct features that complement each other and lead to a high probability of true positive validation of the secured tag; (4) in-depth examination of different binders and textile substrates for optimum combination to construct a durable secured tag; and (5) traceability information that can be linked to the secured tag and shared with customers.

♦ **Blockchain-based traceability framework**

A blockchain-based traceability framework for the T&C supply chain that provides a detailed outline for information/material exchange, supply chain partners interaction, distributed ledger arrangement, smart contract development, and information/material traceability and security in a private blockchain network, with a restricted access to the supply chain partners, depending on their roles and responsibilities. To support and verify the proposed framework, the study further developed and demonstrated an example blockchain with customized smart contract and ledger-updating rules for the T&C supply chain using the concept of mass-balancing. It should be noted that, although the example blockchain was developed for the T&C industry, it can be incorporated in any supply chain with certain modifications.

7. Future research recommendations

This chapter highlights the future research directions considering the limitations of the present research work and suggests research perspectives to which the thesis can contribute and/or act as an initial stepping-stone.

Recalling the theoretical backdrop of this thesis, it is noteworthy that system-of-systems exhibits emergent behavior and is an evolutionary development.

The system-of-systems does not appear to be fully formed, its development and existence are evolutionary, with functions and purposes added, removed, and modified with experience and need. Moreover, the system performs functions and carries out purposes that do not reside in any component system. These behaviors are emergent properties of the entire system-of-systems and cannot be localized to any component system. The purposes of the system-of-systems are fulfilled by these behaviors.

Similarly, developing a complete and secured traceability system is a broad, comprehensive, and evolving process. It requires the development of new, as well as modification of existing technological, industrial, organizational, and regulatory systems. This thesis contributes initially by realizing the concept of secured traceability in the context of the T&C supply chain and, further, by introducing technological systems considering the T&C supply chain particularities. It presents a secured tag that acts as a unique signature for each product for product traceability and security and addresses the issue of information asymmetry and security. For information traceability and security, the thesis proposes a blockchain-based framework for the T&C supply chain. Traceability is a chain concept, and the implementation of these proposed systems would require direct and indirect contribution from each supply chain partners in terms of investments, process modification, employee training, information capturing, system maintenance, and policy modification. Thus, certain areas require further investigation and contribution to achieve a complete system.

According to Bechini et al. (2008),

designing and implementation of traceability systems need preliminary investigations to point out problems and solutions at different abstraction levels. The foundation for any possible discussion about the development of this kind of systems is represented by the adoption of a generic data model for traceability.

Moreover, the latest EU report on traceability in T&C highlights the need for developing consensus among organizations and the benefits of traceability as an initial step for implementing traceability. In this direction, this thesis explored and classified traceability implementation factors and information from the experts' perspective and advocated its importance in information and product management with regard to how it can be achieved for the T&C supply chain and its effect on the supply chain partners. It should be noted that the "why" questions were not addressed with regard to detailed explanations of the ranking and classification of individual factors and information. In future research, the results from Paper II can be used to do in-depth qualitative research through interviews of the experts to address these "why" questions.

Considering the notion of an ideal secured traceability system and referring to Figure 5-1 that explains the requirement of different traceability tags for each supply chain stage. Future research, where this thesis can act as a reference point, can be undertaken toward developing integrated tagging for the upstream stage of garment manufacturing. For instance, Kumar et al (2016b) propose the yarn-based integrated tag for traceability in T&C supply chain. Similarly, to assure traceability in the complete supply chain using secured and integrated tagging, it is vital to cover all other supply chain stages. In general, a secured tag should possess certain unique features, as explained in Paper III. Therefore, this research can act as a guideline for future research that focuses on different stages of the textile supply chain and on how random features can be encoded as traceability tags.

The proposed secured tag system is a feasibility study; thus, future research can be in the direction of realizing and accommodating it in the actual manufacturing and designing scenario that was not explored in this thesis. The placement of a secured tag on the garment is one of the important issues that need further analysis. The type of textile product would largely influence secure tag location. It can be placed externally, making it an aesthetic feature (this will influence the product design) or internally at a safe location that would not undergo extensive wear and tear.

The algorithm developed for secured tag encoding and validation showed promising results. A high membership difference was observed between two unlike tags. However, considering the new developments in the image processing and pattern recognition tools, fine-tuning of the algorithm could be an area of research to improve the processing time, error handling capacity, and robustness of the tag. On the other hand, for the durability analysis and experimental validation, two widely used textile substrates (100% cotton and 100% polyester) with a relatively stable woven structure were selected. Different fiber blends and textile structures (including knits and nonwovens) were selected for experimental validation. Although not very common in the clothing product, the secured

tag can also be tested for dry cleaning and other chemical cleaning processes. Future studies can also focus on lifecycle analysis of Binder 1 and Binder 2 to explore the more sustainable alternative. An in-depth analysis of various commercially available textile binders can be done in future research to restrict particle movement over the textile surface. This can be followed by piloting of the developed tag in the actual T&C supply chain to find and address the implementation challenges.

In the context of information traceability, Paper V discusses a blockchain-based framework to implement traceability, which can be used in future studies as a reference model to modify it according to actual needs. The example is an initial step for customized blockchain development and can be made more complicated by adding more interaction and network rules.

In summary, the work presented in this thesis has an emergent scope and opens multiple research directions for future studies.

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Appendix A – List of publications by the author

(* directly related to thesis topic)

Journal publications and Book chapter

- ***Agrawal, T.K.** and Pal, R. (2019), Traceability in Textile and Clothing Supply Chains: classifying implementation factors and information sets via Delphi study, *Sustainability* Vol 11 No. 6, 1698
- ***Agrawal, T.K.**, Campagne, C. and Koehl, L. (2018), “Development and characterisation of secured traceability tag for textile products by printing process”, *The International Journal of Advanced Manufacturing Technology*, Vol. 101 No. 9, pp. 2907–2922
- ***Agrawal, T.K.**, Koehl, L. and Campagne, C. (2018), “A secured tag for implementation of traceability in textile and clothing supply chain”, *The International Journal of Advanced Manufacturing Technology*, Vol. 99 No. 9, pp. 2563–2577.
- ***Agrawal, T.K.**, Sharma, A. and Kumar, V. (2018), “Blockchain-Based Secured Traceability System for Textile and Clothing Supply Chain”, in Thomassey, S. and Zeng, X. (Eds.), *Artificial Intelligence for Fashion Industry in the Big Data Era*, Springer Singapore, pp. 197–208 (Book Chapter)
- Liu, K., Zeng, X., Wang, J., Tao, X., Xu, J., Jiang, X., Ren, J., Kamalha, E., **Agrawal, T.K.** and Bruniaux, P. (2018), “Parametric design of garment flat based on body dimension”, *International Journal of Industrial Ergonomics*, Vol. 65, pp. 46–59.
- Agrawal, T.K.**, Thomassey, S., Cochrane, C., Lemort, G. and Koncar, V. (2017), “Low-Cost Intelligent Carpet System for Footstep Detection”, *IEEE Sensors Journal*, Vol. 17 No. 13, pp. 4239–4247.
- * **Kumar, V., ****Agrawal, T.K.**, Wang, L. and Chen, Y. (2017), “Contribution of traceability towards attaining sustainability in the textile sector”, *Textiles and Clothing Sustainability*, Vol. 3 No. 1, p. 5. (**Authors with equal contribution)
- Liu, K., Kamalha, E., Wang, J. and **Agrawal, T.K.** (2016), “Optimization design of cycling clothes’ patterns based on digital clothing pressures”, *Fibers and Polymers*, Vol. 17 No. 9, pp. 1522–1529.

Conference publications

- ***Agrawal, T.K.** and Pal, R. (2018), "Exploring secured traceability systems for implementation in textile and clothing supply chain", *The 91st Textile Institute World Conference (TIWC)*, Textile Institute, Leeds, UK.
- ***Agrawal, T.K.** and Pal, R. (2018), "Classification of traceability information in textile and clothing supply chain: A Delphi-based approach", *25th International EurOMA Conference*, Budapest, Hungary.
- ***Agrawal, T.K.** and Pal, R. (2017), "Towards a secured traceability system for closed-loop textile supply chains", *22nd International Symposium on Logistics (ISL 2017)*, Ljubljana Slovenia, pp. 359–367.
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- ***Agrawal, T.K.**, Koehl, L. and Campagne, C. (2016), "Pattern coded based tagging system for traceability and brand authentication in sustainable Textiles supply chain" *Young researchers' day GEPROC – UgePE (Union of Process Engineering and Energy, North of France)*, Université catholique de Louvain, Belgium. (Poster and Short presentation)
- ***Agrawal, T.K.**, Koehl, L. and Campagne, C. (2016), "Cryptographic tracking tags for traceability in textiles and clothing supply chain", *Uncertainty Modelling in Knowledge Engineering and Decision Making (FLINS conference 2016)*, Volume 10, World Scientific, pp. 800–805.
- Agrawal, T.K.**, Thomassey, S., Cochrane, C., Lemort, G. and Koncar, V. (2016), "Footstep-Based Human Tracking Using Sensor-Integrated Nonwoven Carpet", presented at the *EDANA- International Nonwovens Symposium 2016*, Warsaw, Poland.
- Agrawal, T.K.**, Thomassey, S., Cochrane, C., Lemort, G. and Koncar, V. (2015), "Intelligent Nonwoven Carpet for Human Footstep Tracking", *EDANA- Nonwoven Innovation Academy (NIA)*, Leeds, UK (Poster).
- Agrawal, T.K.**, Thomassey, S., Cochrane, C. and Koncar, V. (2015), "Data Analysis and Statistical Interpolation of Signals for Human Footstep Tracking Using Intelligent Carpet", *15th World Textile Conference AUTEX 2015*, Bucharest, Romania available at: *Journal of Fashion Technology & Textile Engineering*, Vol. 2016, <https://doi.org/10.4172/2329-9568.S2-007>.

Appended Papers

Paper I

Kumar, V., Ekwall, D., and **Agrawal, T.K.** (20xx) Traceability in Textile and Clothing Supply Chain: Synthesizing the Potentials and Setting the Future Agenda. *Production Planning and control* (In 3rd Revision)

Traceability in Textile and Clothing Supply Chain: Synthesizing the Potentials and Setting the Future Agenda

Abstract

Traceability is one the growing concerns in the present industrial scenario. Its significance in Textile and Clothing (T&C) industry has grown due to complex distribution channels resulted from the migration of a large segment of the industry to developing countries. Further, consumer awareness towards social and environmental aspects of textile products has pushed the industry to talk more about the product history and other intangible aspects of the products. In this context, this paper critically analyses the importance of traceability and challenges in its implementation in T&C industry. This article synthesizes the relevance of traceability from scientific and non-scientific literature from different perspectives, including organizations, consumers, and third-party certification/surveillance, and reports insinuations on T&C industry. Further, a discussion has been made aiming the challenges that industry facing in implementing traceability and future research agenda is proposed.

Keywords: Traceability, textile, clothing, supply chain

1. Introduction

Traceability – the ability to track the history of a product – is a not only basic requirement expected by ISO 9000 standards for high-quality management but also a requirement for modern firms improving efficiency and internal functionality (Rizzi and Zamboni 1999; Kvarnström and Bergquist 2012). According to Kumar et al. (2009) it is commonly understood that a company needs to be able to trace its products throughout the supply chain, all to handle issues like product recalls, stock levels, and inventory locations. Pharmaceutical and food companies have due regulations and the general danger with expired drugs, and thus widely use supply chain traceability (S. Kumar, Dieveney, and Dieveney 2009; Thakur and Hurburgh 2009). Traceability was defined internationally as *the ability to retrieve history, use*

or location of an entity by means of recorded identifications in 1987 in the context of food safety (Ene 2013).

Over the decades, traceability has been emerged as a requirement in almost all sectors including T&C sector, and widely used in different contexts (Abad et al. 2009; Informal Product Traceability Expert Group - Final Report 2013; Goswami 2014; Guercini and Runfola 2009; Solanki 2015; Zhang and Kraisintu 2011)

The Textile and Clothing (T&C) industry is inherently characterized by a broad range of products with short life-cycles, high seasonality, high volatility, high-impulse purchasing and complicated distribution and logistics operations (Christopher, Lowson, and Peck 2004; Moon and Ngai 2008; Caniato et al. 2015). Firms often require multiple suppliers, and a continuous and systematic development of new products and services to remain competitive in the market (Kwok and Wu 2009; Legnani et al. 2011; Caniato et al. 2015). Recently, the migration of T&C industry has been observed towards developing nations to gain the advantage of low-labour-cost and relaxed-environmental-policies (Keenan, Saritas, and Kroener 2004; Gereffi and Frederick 2010). This increased manufacturers–buyer geographical distance brings more dependency on supply chains (Kwok and Wu 2009). The emerging fast fashion has created volatility and forecast complexity in demand. The offshore manufacturers are required to respond to the market demands as quick as possible and retailers need to collect real-time sales statistics to balance the supply-demand (Bhardwaj and Fairhurst 2010; Perry, Sohal, and Rumpf 1999). Therefore, it is imperative to link various actors in the textile production, distribution, and retail sectors. Considering the abovementioned characteristics of industry, traceability has been seen as an element integrating various supply chain actors for synchronous functioning. It provides a possibility to trace back the components used in bill of material, accurate and specific product information, and the position of material/products inside the production and supply chains to have a maximum control on the production and/or distribution channels. Moreover, the real-time sales statistics can be collected by integration of various point-of-sales using traceability system, which helps in evaluating actual market trends and forecast (Kwok and Wu 2009). In addition traceability applications include anti-counterfeiting, brand protection, consumer safety, product development, production and quality optimization, efficient resourcing, transparency in production and distribution channels, and so on (Alves et al. 2014; Cheng et al. 2013; Corbellini, Ferraris, and Parvis 2006; Guercini and Runfola 2009; Jansen-Vullers, van Dorp, and Beulens 2003; Sun et al. 2014; Terzi et al. 2007; Töyrylä 1999; S. H. Choi et al. 2013; Gobbi and Massa 2015). Despite numerous applications of traceability, T&C

industry does not have a long history to work with traceability; however, recently it has become the growing concern to the industry (Johansson and Månsson 2013). According to European Commission (EC) report (Informal Product Traceability Expert Group - Final Report 2013), a main issue with the implementation of traceability is “the lack of awareness and understanding among all stakeholders of why traceability is important for themselves and for others”. Moreover, as traceability is a collaborative effort of all supply chain actors, therefore their participation is a primary criterion for implementing traceability. In this context, the purpose of this paper is to explore the potential of the traceability system in the T&C industry from different perspectives including industrial, consumers and monitoring agencies. It attempts to understand holistically the relevance of traceability by reviewing the existing literature, therefore identifies the practical significance for each supply chain stakeholder. Further, the article discusses the complexities associated with its implementation in the present industrial scenario and sets up the agenda for future research.

The following sections are arranged as follows: Section 2 briefly describes followed research methodology, Section 3 describes various definitions of traceability; Section 4 covers the need for traceability in T&C sector from three perspectives, namely industry, consumers, and monitoring/surveillance agencies. Section 5 discusses the challenges in implementing traceability in present T&C sector. Further, Section 6 sets the agenda for future research. Finally, Section 7 concludes the paper.

2. Methodology

Literature reviews provide an ability to understand the existing literature related to a topic. According to Pautasso (2013), the necessity of doing literature review can be related with four purposes based upon the previously published research and reviews. Broadly speaking, when there is few published research, depending on the amount of published literature reviews, the literature reviews are required for the identification of research questions or pointing out the need of more research. On the other hand, if there are many published research, the literature review can focus on summarizing the existing literature or reviewing of the published review literature in case there are sufficient number of published reviews. To identify the breadth of published literature related to traceability in T&C sector, we have used two citation databases including Web of Science and SCOPUS with the restrictions of time frame 1900 – 2017. The following queries were used,

Web of Science citation database: TS = (traceab* AND (textil* OR cloth* OR garment*))

Scopus citation database : TITLE-ABS-KEY (traceab* AND (textile* OR cloth* OR garment*))

Here * denotes the wildcard which finds words that contain zero or more characters in place of the asterisk-character. For example, traceability may appear in the form of traceable or traceability in the published literature. Therefore, wildcard i.e. asterisk (*) with term 'traceab' implies that all words which start with 'traceab' would be looked for in the database. Furthermore, 'AND' and 'OR' represent the Boolean operators to merge the search keywords. It should be noted that the SCOPUS database more widespread than WOS, includes a vast range of publications. In this preliminary analysis we focused only on English language literature originating from academic journals, conferences and books.

The initial search revealed total 43 results in WoS and 72 results in Scopus. However, the abstract analysis of the papers revealed that there were only 27 unique publications (13 journal articles, 13 conference articles and one book chapter) relevant to traceability in T&C supply chain directly or indirectly. A limited indexed published research and reviews certainly reinforce the need for conducting the literature review which identify the future research questions (Pautasso 2013). In this context, it is important to gain a broad understanding of the topic and make learning from other sectors where traceability is comparatively better established. Therefore, we broadened our search and other non-indexed publically available publications in form of relevant journals papers, conference articles, white papers, government/organization reports, etc. were also included. Further, to broaden the learnings, some relevant traceability literature from other fields, including agri-food, were analysed where traceability is considered an important issue and has been prioritized. The work compiles extensively researched literature to organise the distributed school of thoughts in the particular area and provides a 'launch pad' for future conceptual developments and research. To best of our knowledge, the study is first of its kind to explore and compile various literature sources to define, enlist the needs and challenges related to T&C supply chain traceability.

3. Definition of traceability

GS1 Global Traceability System (Ryu and Taillard 2012) defines traceability as

“The ability to track forward the movement through specified stage(s) of the extended

supply chain and trace backward the history, application or location of that which is under consideration.”

ISO 8402:1994 defines traceability as

“[...]the ability to trace the history, application or location of an entity by means of recorded identifications.”

A detailed definition given by Moe (1998) as

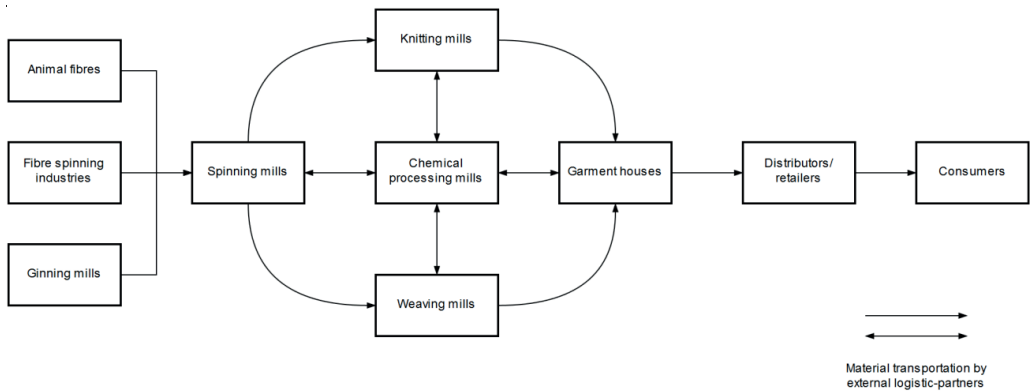
“Traceability is the ability to track a product batch and its history through the whole, or part, of a production chain from harvest through transport, storage, processing, distribution and sales (hereafter called chain traceability) or internally in one of the steps in the chain for example the production step (hereafter called internal traceability).”

In addition to above-mentioned definitions, many authors came with more added points. Jansen-Vullers et al. (2003) define traceability based upon application as active and passive. Passive traceability is one that tracks and records the product history. An active traceability not only tracks and traces the product history but also uses this information to optimize and control processes in and between different links of the supply chain and production. This active traceability leads to reduced failure cost, increased productivity, and/or better quality in the long term. Dupuy et al. (2005) present traceability by two ways *i.e.*, tracing and tracking, and argue tracing as ability to recall origin and characteristics of a product at any point in supply chain whereas tracking as ability to find localization of production in supply chain. Regattieri et al. (2007) define traceability as product history in terms of product direct properties, associated value added processes accomplished during production and environmental condition of processes carried out on the product. Guercini and Runfola (2009) describe traceability as the “generalization of information on product and product processes, examining the way information is shared” thus identify the use of traceability as a tool for inter-organizational control and a tool for market power. Despite the different application, the core notion of the traceability can be stated as “keeping track of a given set or type of information to a given degree, or the ability to chronologically interrelate uniquely identifiable entities in a way that is verifiable” (Djatna and Ginantaka 2014).

4. Structure of T&C supply chain network and need of traceability

4.1. Structure of T&C supply chain network

As aforementioned, T&C sector consists of a relatively long network which involves a number of actors located worldwide and dealing with diverse raw materials and processes (Bruce, Daly, and Towers 2004; Jones 2000; Bruce and Daly 2011; Gereffi and Frederick 2010; Gereffi and Memedovic 2003; Gobbi and Massa 2015). Fig. 1 shows a typical T&C supply chain network consisting multiple actors involved in the conversion of fibre into intermediate products (such as yarn, graige fabric and finished fabric) into final garments and distribution to the end users. In addition, there are external logistics-partners involved in the movement of materials among various actors. These actors differs in their operations and specialization and mostly handled by independent organizations (Nordås 2004). Distributor/retailer acts as a “supply chain driver”, who places the order to the upstream actors (Thomassey 2010; Gereffi and Memedovic 2003).

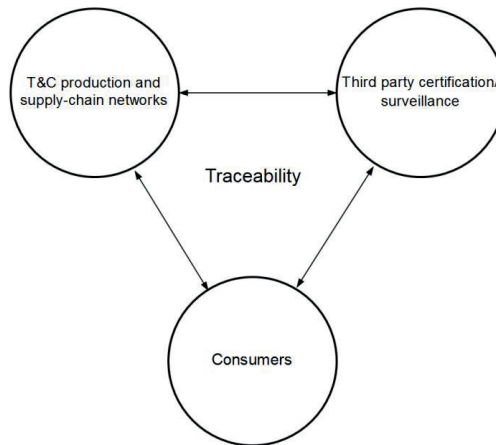


[Figure 1: Typical T&C supply chain network, adapted from Thomassey (2010)]

From the demand perspective, the T&C sector is customer demand-driven where the customers' requirements shape the retailers' inclination in terms of their policies and services. As a result, companies need to be quickly responsive to market demands to maintain their worth and survive in the competition. The manufacturing process shown in Fig. 1 takes months-long lead-time (Thomassey 2010). Consequently, the brand owners need to forecast the demand and trend well in advance, and various actors need to have synchronous functioning with each other for the on-time delivery of the products (Bruce, Daly, and Towers

2004; Romano and Vinelli 2001). Any quality issue or production delay is potentially damaging to the distributors, which deals with the end consumer.

In addition to industrial actors and end users (i.e. consumers), monitoring agencies, such as their party certifiers, accreditation and government agencies (including customs and surveillance), act as an integral part. Certifications from third parties are particularly well known, which certify the use of standard raw material, processes, and fair practices followed during production and distribution. The customs and surveillance authorities check if the products are legitimate and follow the safety standards. Therefore, based upon the above discussion, the T&C sector can be divided into three components i.e. industrial (T&C production and supply-chain networks), customers and third party certification/surveillance as shown in Figure 2. The following section discusses the need for traceability from above-mentioned components' perspective.



[Figure 2: Differentiated components of T&C sector]

4.2. *Need of traceability in T&C industry's perspective*

4.2.1. Visibility in offshore production and distribution channels

Supply chain visibility is often considered as a tool for a company to make informed decisions about products and practices (Chapman 1995). T&C supply chain has a geographical spread. Most of the labour-intensive production activities are carried in recent industrialized countries (Egels-Zandén and Hansson 2016; Gobbi and Massa 2015). This

global shift has resulted in an increased producer–consumer geographical separation, complexity in supply chains, and diminished the transparency (Guercini and Runfola 2009; Bruce, Daly, and Towers 2004; Gobbi and Massa 2015). The manufacturing processes, which take a long lead-time needs synchronous functioning of involved actors (Thomassey 2010). In this context, traceability-based geographically dispersed inter-actor visibility can help actors to organize their production activities. Traceability also helps in reducing handling cost and allows efficient use of various resources by providing a real-time pinpoint location and identification of products in the supply chain (Cheng et al. 2013; Guercini and Runfola 2009; Töyrylä 1999). Traceability allows the brand-owners to share the critical information regarding the product; hence, provides more safety and conveys the proper use of information to the end users (Goswami 2014). Furthermore, the information helps various supply chain stakeholders in different decision-making for achieving various supply chain or organizational objectives (Singh and Garg 2015). Further, studies in the past have shown that the increased length and complexity of supply chain creates more risk and gives space for offshore suppliers to opt their policies, which are not visible to the buyers. Sometimes, it is even difficult for the lead firms to name their suppliers (Egels-Zandén and Hansson 2016). The possibility of questionable practices in these opaque supply chains has been challenged by the anti-sweatshop campaigns (Bartley 2007). Since a buyer cannot directly observe the offshore manufacturer, traceability provides an alternate opportunity for the buyer to monitor the production activities at a distant manufacturer, which brings some level of transparency. In fact, traceability has been used by some companies as a tool to respond anti-sweatshop campaigns. For example, Nike, Adidas, and H&M have disclosed the names of their first-tier suppliers (Egels-Zandén and Hansson 2016). All American Clothing Co. uses traceability number with each pair of jeans which allows consumers to trace the history of the jeans back to the cotton field (Goswami 2014). Hence, traceability is a promising tool, which records the information, allows easy tracing of product origin, materials, production and distribution history, thus enhance the safety, security, and transparency in the supply chain.

4.2.2. Quality control

T&C industry involves multiple suppliers and manufacturers for the conversion of fiber into finished products. In various operations, it is important to follow the materials so that the quality of the final product can be assured (Cropper and Wang 1995; Gobbi and Massa 2015). Furthermore, the quality of the final product depends upon the suppliers' materials quality

(Cheng et al. 2013). In the case of quality or production issue, traceability can help the manufacturers to identify the source of error and thus optimize the product quality (Cheng et al. 2013; V. Kumar, Ekwall, and Wang 2016; V. Kumar 2016). Alternately, if any one of the involved actors uses banned materials or chemicals, this may result in financial penalties to the firms/actors involved in the production. Such instances bring liability on multiple actors for the wrongdoing of a single or some of the actors. Since the traceability system stores the information about the processes, materials used and various involved actors in production and distribution. Therefore, it reduces the information asymmetries among different actors and brings more transparency (Egels-Zandén and Hansson 2016). Consequently, traceability system can not only identify the source of the defect, but can also protect the actors, which have no role in that particular defect.

Nowadays, the end consumers are more concerned beyond product's quality and cost, and strenuous toward intangible sustainability characteristics including social, environment and other ethical aspects. Organic cotton based clothing, clothing's environmental impact, Fairtrade, and chemical used in production are some intangible characteristics which have gained more attention recently (Chen and Burns 2006; Hae Jin Gam 2011). In reality, all of the above-mentioned information cannot be provided by retailer or distributor – who sells the product in the market – without known history of product. For example, organic cotton cannot be verified by laboratory experiments, rather a proper documentation about cotton farming practice is required for the claim (Bureau Veritas 2010; Cotton Inc. 2016). Similarly, the life cycle or environmental impact of a textile product cannot be calculated without knowing the production processes, parameters and other related information (Muthu et al. 2012; Slater 2003). Hence, to calculate or claim such quality characteristics a proper documentation of raw materials, production processes, production location, etc. is required, which essentially requires some degree of traceability (Muthu et al. 2012; Muthu 2015; Resta et al. 2016; V. Kumar, Agrawal, et al. 2017). Moreover, such traceable information provides additional assurance which helps in building customers confidence and positively affects purchase intentions (Guercini and Runfola 2009). Conversely, traceability maintains the trails of information related to various product components procured from different suppliers (V. Kumar, Hallqvist, and Ekwall 2017). Therefore, it helps organizations in verifying their sustainability claims and make sustainability progress accountable through verifiable traceability information (UN Global compact team and BSR team 2014).

4.2.3. Forecasting and production management

Forecasting is one of the commonly discussed issues as far as textile business is concerned due to short fashion life cycle (Thomassey 2010). A good forecasting can reduce the possibility of understocking or overstocking and helps in inventory management and production planning, pricing and achieving high customer service (Liu et al. 2013; Thomassey 2010). The modern fashion industry has changed in many aspects. In the '80s, a typical life-cycle of fashion apparel was characterized by four stages, namely introduction, growth, maturation and decline (Bhardwaj and Fairhurst 2010), the market was mostly industry-dominated, and change in fashion was seasonal. The consumers were less sensitive towards fashion and retailers used to place big orders. However, now the characteristics have changed. For instance, now apparels have a shorter lifecycle, more number of fashion seasons, small orders and more competition (Thomassey 2010). Moreover, the demand has changed from industry-driven to consumer-driven. These changed characteristics contribute towards complexities in forecasting (Bhardwaj and Fairhurst 2010). The success of a design or company itself is reported to be highly correlated with the precise forecasting and demand-supply synchronization (Link 1987). In such changing dynamics, it is important to have live or up-to-date statistics of inventory, sales, purchase orders and location of transit logistics in the supply chain, which need a good traceability system. It is also argued that proper tracking of products helps in improved forecasting (Guercini and Runfola 2009; Kwok and Wu 2009; Bindi, Bandinelli, and Rinaldi 2016). Therefore, in highly complex textile manufacturing and distribution systems, the integration of product to customer interaction node, *i.e.* a retailer with the supplier is the new requirement for monitoring the real-time demand around the world. Here, traceability system opens possible ways by monitoring the flow of goods from retailers to consumers in a real-time. The feedbacks from customers can also help in continuous improvement of the existing products and future strategies. Hence, the information flow between the organization and consumer has its own place in the traceability system (Guercini and Runfola 2009; Kwok and Wu 2009).

Furthermore, the decreasing order size, quick-changing fashion and external competition have pushed the manufacturers to process and produce multiple orders of different designs and/or materials simultaneously to reduce the possible lead-time (Bhardwaj and Fairhurst 2010; David Tyler, Jo Heeley, and Tracy Bhamra 2006; Guercini and Runfola 2009). Hence, it is important to track and trace various materials for proper production channel within the

same industry for a better inventory management, improving the effectiveness of resources and reduce the handling cost (Bindi, Bandinelli, and Rinaldi 2016). Studies in the past also showed that the traceability helps in lean manufacturing and reducing the bullwhip effect (Anders Ringsberg and Mirzabeiki 2013; Saikouk and Spalanzani 2012). Considering the above-mentioned complexities, traceability has a great potential in managing and facilitating appropriate production planning in quickly changing market demands.

4.2.4. Marketing tool

As mentioned before, customers' demands are no more limited to product's quality and cost. Consumers are now concerned with social and environmental impacts of the product, especially after knowing the various unethical practices (such as the use of harmful chemicals, child labor, poor labor conditions, etc.) in the production phase. Therefore, consumers are more likely to ask about the production history such as producer, chemical used, etc. (Goswami 2014). Creating social and environmental transparency to the consumer brings extra work and responsibilities to the firms. Nevertheless, it provides a competitive edge to attract customers. In apparel buying, consumers' preference is considered polarized to certain brands. These polarizing factors are style, marketing strategies, brand value, country of origin/made in, etc. Consumers feel confident if the traceability information is available, which positively influences their purchase decision (Du Plessis and Gerrie 2012). In this context, traceability information assures the safety and quality of the product which results into building consumer trust and confidence (Clemens 2003). Production history by means of traceability opens opportunities for enterprises to take advantage of 'made in' aspect of the product (Guercini and Runfola 2009). The conventional made-in labels used in the apparels signify the country of manufacture, whereas they hide the source of various raw materials used in production. By traceability, the sources of each raw materials can be conveyed to the consumers. Thus the traceability information on 'made-in' becomes more useful than that of conventional labels (Goswami 2014). Yang and Fryxell (2009) report a positive correlation between brand positioning and traceability. It is also reported that consumers prefer to pay more if they can trace the product history (Dimitri Soverini 2014). A few companies have started to exploit traceability as a marketing tool. For instance, All American Clothing Co. provides traceability information about the source of fiber used in production (Egels-Zandén, Hulthén, and Wulff 2015). Similarly, Levi Corporation conveys the company's initiatives in environmental activities to its customers using traceability (Goswami 2014). Ubilava and Foster

(2009) argue that some consumers even consider traceability equivalent to quality certification. Thus, the traceability has potential applications as a marketing tool to attract customers by enriching them with more information, building trust and brand value, which bring a positive contribution in the long terms.

4.3. Need for traceability from consumer and post-consumer perspective

4.3.1. Consumer access to reliable product and supply chain information

Consumers' confidence in the textile brands have declined due to opaque supply chains, which has resulted into anti-sweatshop campaigns to bring transparency (Egels-Zandén and Hansson 2016). Consumers generally have limited access and trace about the fibers' origin, where the apparel is made and actors involved in production in the complex and opaque T&C supply networks. In this regard, traceability is an essential tool to integrate different players and collect product information in T&C production supply chain, which works on uniquely mapping the individual product or batch of products with the information relating to materials, process, handling actors etc. Hence, traceability acts as a reliable source of information for product and product's safety aspect. Consumer buying preferences have recently changed in many dimensions. Attributes such as cost and quality seem inadequate to align consumers' preferences toward a product due to their other expectations such as products' direct or indirect impact on the user, society, producing organization, labor associated with production, environment and trend (Brunk 2010; Marcketti and Shelley 2009). Demands related to environmental aspect information with consumer awareness towards increasing carbon house gas emission, deforestation, and waste accumulation. The social aspect of T&C manufacturing has sporadically gained a media and public attention.

Further, different governments have also introduced laws and regulations for providing one or more above-mentioned information to consumers in different forms to bring transparency in production or distribution system (Egels-Zandén, Hulthén, and Wulff 2015). Traceability provides a unique opportunity for the consumers to access more information about the product. Traceability information also assures the safety and quality of the product, consequently, building consumer trust and confidence (Clemens 2003).

4.3.2. Consumer protection

Textiles are one of the most forged/counterfeit product categories. Counterfeit goods

represent 5-7% of total world trade (Beltrametti 2009). European Union (EU) customs statistics suggest that clothing contributed > 9% of all counterfeit products in the year 2014 (European Commission 2014). In general, counterfeiting refers as any unauthorized production of goods; that appear identical to the legitimate product in appearance, trademark, and labeling (Ha and Lennon 2006). Counterfeit involves minimum investment to gain maximum profit, therefore likely to use inferior quality materials, which may pose a direct threat to the consumers (Ekwall 2009). Moreover, the counterfeit is an illegal activity. Therefore, the related products bypass regulatory testing for safety, which further amplify the security concerns. Counterfeit products create financial and reputation loss to the brand owner and the inferior quality obviously harms the consumers, which could range from few dollars to serious health concerns (Kelesidis et al. 2007). In such scenario, traceability provides an opportunity not only to the companies to monitor their products and protecting their brands by uniquely identifying, but also the consumers for the brand authentication (S. H. Choi et al. 2013). For example, Italian brand 'Safilo' uses traceability as anti-counterfeiting and consumer uses it for brand authentication (Guercini and Runfola 2009). Similarly, traceability marking such DNA marking and Microtaggant are commonly used solution for brand authentication (Tarun Kumar Agrawal, Koehl, and Campagne 2016; Corbellini, Ferraris, and Parvis 2006).

The other aspect of the consumer protection includes safety from harmful products. Monitoring agencies like RAPEX in EU, regularly report and recall harmful products present in the market (V. Kumar and Ekwall 2016). In the EU, firstly, textile is one of the most recalled product categories in non-food items and secondly, most of the textile recalls possess serious threats to the user, especially to the children, hence it is important for the consumers to be alerted about such products (European Commission 2015). In this context, traceability plays an important role, because firstly, it helps to identify the locations of recalls products and secondly consumers can trace back if their products are recalled. For food and medicine sectors, government regulations mandate the use of traceability to handle and control the recall crisis. For non-food items, Research support for an informal expert group on product traceability (2013) describes traceability as an effective solution for controlling the recalls.

4.3.3. Post-consumer applications

Textiles are engineered with certain functional characteristics, which require proper handling especially during the washing and drying. Nowadays, smart washing machines offer the

functionality to automatic adjust washing/drying parameters based on the information provided to them (Kim et al. 2007; Legnani et al. 2011). Here, traceability offers direct application by recalling fiber history and other washing cares required for processing for a particular garment.

Another important traceability application concerns the end-life of textiles. Shrinking cultivable land has inclined the industry towards the use of synthetic fibers which creates serious concerns such as exploitation of non-renewable resources and non-biodegradable wastes generated on disposal (Hawley 2006). Governments and companies have taken the initiative to reduce solid waste by recycling or reuse of textiles. However, there are certain issues, which obstruct the successful implementation of recycling/reuse process and traceability can potentially assist. For example, every fiber or group of fibers has certain recycling process or process parameters. Therefore, before recycling, discarded textiles need to be sorted (Hawley 2006), which essentially relies on information about the constituent fibers. Here, traceability has a potential to recall the textile product's history including the material composition, therefore, could be helpful in sorting and other recycling applications (Wyld 2010). Further, there are standards for the companies using recycled materials. One of the essential requirements set by Global Recycle Standard includes the use of traceability to prevent the substitution or contamination of the contents, and the material must be verified by declaring the source (Global Recycle Standard 2011). Consequently, traceability plays a major role in the post-consumer phase of textiles and clothing.

4.4. Traceability requirement for monitoring and certification agencies

4.4.1. Market Surveillance Authorities and Customs

Market surveillance authorities, which check and control the consumer goods within the market, and customs, which check and monitor the cross-border goods, have direct application of an effective traceability system. According to RAPEX statistics, textile and fashion goods contributed ~23% to total recall notifications issued under dangerous non-food items within 31 European Countries in 2013. However, only 6% of the total notifications for the textiles and clothing were successfully followed up (European Commission 2015). The main reason for such a small proportion of successful follow-ups is the inadequate or incomplete information about the economic operators (suppliers, distributors, manufacturers, importers, exporter, and origin/destination country) of the recalled items. Hence, with the

increasing recall incidents and above-mentioned complexities, traceability is suggested to be one of the recommended solutions for handling recalls, which provides an easy access to the correct and reliable information about the product identification, useful contacts of actors involved in production/distribution and legal documentations (Informal Product Traceability Expert Group - Final Report 2013). Even though a product is identified as harmful, it is sometimes difficult to find the history and origin of these products. Easy recall of the unsafe and counterfeit product will be possible with ease of tracing back the responsible actors, which is only possible by the implementation of traceability.

4.4.2. Certification and audit agencies

Certification is an important aspect of the textile products and supply chains. Certifications such as Fairtrade USA (Fairtrade USA 2017) assure fair labor treatment in the production and distribution. Similarly, organic cotton certifications (for example, Organic Textile Standard - ICEA (Italy), Standards for Organic Textiles - ETKO (Turkey), Organic Fibre Standards - Oregon Tilth (USA)) with textile products provide the assurance that the product contains certified organic cotton. There are numerous other certifications used to certify numerous standardizations and description of social and environmental aspects. Traceability is one of the prime requirements for many of these certifications to function properly. For example, organic cotton certification requires proper information of cotton fiber and the practices used for its production; traceability is an integral part of such certification. Moreover, for government/private audit agencies, traceability serves as a valuable tool that maintains the inventory, product, material and related information (Cheng et al. 2013).

3.4.3 Regulatory Agencies

Regulatory agencies are public / government authorities or sometimes professional bodies established on legal authorization and deal with administrative laws and regulations for public protection. Presently, there exist various government agencies regulating traceability in different product segments, especially food and agriculture supply chain (UN Global compact team and BSR team 2014). Implementing the same in globalized T&C supply chain needs crossing many regulatory borders and multiple challenges like geographical gaps, information, and knowledge gap, communication gaps, compliance or implementation gaps, power gaps and credibility or legitimacy gap (Boström et al. 2015). Despite this, these regulatory requirements are more likely to be asked after events like Rana Plaza catastrophe

in Bangladesh (Marshall 2014), controversial cotton cultivation in Turkmenistan and Uzbekistan (Michelle Russell 2016), Syrian child refugees working in Turkey textile industries (Frederik Johannisson, Mersin, and Adana 2016), raw cotton procurement from ISIS captured region (Sara Malm 2015) to name a few. All these incidents have attracted public attention internationally towards social and ethical practices. In this context, various reports on traceability developed by government agencies and researchers suggested the implementation of traceability regulations in T&C supply chain, but presently it is still a voluntary norm (Marshall 2014). Concerning T&C firms' initiatives to account customer development and brand marketing, there have been some NGOs regulating, grading and monitoring the supply chain for better transparency (Nimbalker, Mawson, and Cremen 2015).

5. Challenges in implementation of traceability in T&C sector

The textile industry is one of the oldest industries. The traceability requirement always existed, but not prioritized as it is projected presently due to changing dynamics of the industry. Earlier, simple approaches were adopted to fulfill the demand of traceability such as document-based traceability, inherent traceability, and eliminations of the factors underlying the need for traceability (Töyrylä 1999).

Presently document-based traceability is the common form of traceability, uses a documentation process to provide the required information about the product. However, a large part of the manual documentation is replaced with automatic processes, such as data collection and maintenance has been carried out using machine-readable barcodes/RFID, which increases the efficiency and minimizes the human interference (McFarlane and Sheffi 2003; Töyrylä 1999). The documentation covers various elements regarding the product. In this context, Steele (1995) identified four elements to define the document-based lot traceability system, stated as, physical lot integrity, data collection, lot-process linking and reporting. Physical lot integrity means the preciseness to the identification of sources of error maintained in case a faulty lot is identified in the later stage of distribution. Data collection means the documentation of process data, which includes process information and parameters, and lot-tracing data, which involves the information regarding the movement of a lot. Lot-process linking – as the name specifies – is the mapping of information obtained using the data collection element to the physical product lot such as by lot number, etc. Further, the last element, i.e. reporting, means the design of data storage and retrieval system for information exchange regarding traceability. As previously mentioned, traceability is a

concept of keeping the track of information related to a product covering its various aspects. Within this context, the system that realizes the traceability (i.e. traceability system) works on an arrangement of product identification, product related information management and exchange of the relevant information between various supply chain stakeholders (Informal Product Traceability Expert Group - Final Report 2013). In this direction, the product identification is generally carried-out by using traceability marking which acts as a unique identifier to each intended traceability resource unit (or traceable product). Consequently, each product can be identified uniquely. Here, the product (hereafter called *Traceable Resource Unit* or *TRU*) could be an intermediate or a finished single product or a group of products which carries a traceability marking. Presently, traceability markings have been developed in various shapes, sizes, and work on different principles, such as barcodes and RFIDs. Based on the identification of each TRU using traceability marking, traceability system records and/or recalls TRU's history. Here traceability system referred is not a singular entity; rather it is a collection of interconnected systems and managed by various supply chain actors, each contributing in collection and exchange of traceability information. Consequently, the implementation of traceability consists of two parts, i.e. first, traceability information identification, management and exchange, and second, mapping information with the traceability marking. Nowadays, the mapped information is stored on a cloud database server to share with different actors using the internet, therefore information technology plays an important role in communication of traceability information. The following sub-sections explain in details about the challenges in contexts namely, traceability information collection and exchange, and traceability markers.

5.1. Information collection and sharing

Information collection is the primary requirement for a traceability system. The first and foremost step in traceability implementation is to identify the relevant traceability information. There are a large number of processes involved in production, which generate huge information. Consequently, it is challenging for various actors to identify the all traceability information which is required recorded from the product and manufacturing process (Radley Corporation 2009). Moe (1998) described the use of traceability information in four contexts given as, product which includes raw material information, product and processing history; data related to the quality of the product; calibration with regards to government or standardization organization quality standards; and data management of all the

collected data. While data management is an important aspect for proper utilization of traceability information, calibration is necessary to comply with government norms and standardization claims such as organic cotton, chemical free, etc. Furthermore, in a garment manufacturing, the number of partners sometimes grows up to 20 and no single collaborating industry can provide all the product related data (Artschwager et al. 2009). Therefore, the implementation of traceability becomes a collective effort of supply chain actors. Within this context, one of the foremost challenges in implementing traceability is aligning various supply chain actors to agree on maintaining required data management systems and transacting the traceability information with others (Lam and Postle 2006; Egels-Zandén, Hulthén, and Wulff 2015; V. Kumar, Hallqvist, and Ekwall 2017). It essentially includes technological challenges such as adopting appropriate technology and engaging appropriate skilled workforce, and organizational challenges such as financial investment on technology and workforce, and collaborating with other supply chain actors to exchange traceability data (Probst, Frideres, and Pedersen 2015). Further, a T&C supply chain consists of agents as mediators between buyers and suppliers, who may not prefer to disclose the suppliers' details to buyers to maintain their place in supply chain (Egels-Zandén, Hulthén, and Wulff 2015) which poses a significant challenge in traceability implementation.

As mentioned earlier, a T&C supply chain consists of multiple independent actors. In this context, one important question, while implementing traceability, is who should take the responsibility to maintain the traceability information exchange and physical storage of the traceability data. Nonetheless, for such a supply chain, one-step-up and one-step-down traceability configuration is the preferred traceability system where every actor is responsible for maintaining own traceability information and linking it to one-preceding and one-following actors (Informal Product Traceability Expert Group - Final Report 2013). This configuration distributes the responsibility in multiple actors; however, for the realization of supply chain-wide traceability every actor should be in operative so that it can connect preceding and following actors, which is somewhat complex in practical scenario (V. Kumar, Hallqvist, and Ekwall 2017). For example in the European context, T&C industry is dominated by Small and Medium Enterprises (SMEs) (Legnani et al. 2011), which face financial constraints and probability to go bankrupt or out-of-business. In such a scenario, the vacuum created by the dysfunctioning of an actor in the supply chain may create a break in traceability (Informal Product Traceability Expert Group - Final Report 2013). Furthermore, in case each actor manages own data, it creates technological complexities during sharing because each one may have a different format, language, reliability, etc. (Ruiz-Garcia,

Steinberger, and Rothmund 2010). Hence, the semantics need to be unified for proper information exchange between various actors involved in the supply chain (Donnelly et al. 2011). The inter-actor flow of information is hindered by factors such as the global spread of different actors, unwillingness to share data, the company's data sharing policy, etc. The flow of material in various processes leads to the addition of product history, and every process stacks certain information, which may be useful for further processes or to the consumer. For example, in order to calculate the carbon footprint of a shirt, one needs to know the energy consumed in its manufacturing start from fibre to finished garment beside raw materials and other consumable items used in its production. Now, here information-gathering model of a traceability system is required to be done in a stacked manner where every industry or process adds information for next counterpart. Therefore, the size of data cumulatively grows as material flows in production and supply chain as discussed by Jover et al. (2013). Hence, it is important to design systems to handle such a large data about various aspects of the product.

Further, Töyrylä (1999) defines certain characteristics for the traceability information for its maximum utilization, such as accuracy of the tracing information for its practical realization, comprehensiveness – which implies a complete information availability, starting not only from receiving a material lot but also lower-tier vendors/operators, timeliness of the information to monitor supply chain and processes more accurately, easy availability of data for a better control over processes, security of inter-organizational data transfer to offer security, protection and confidence to various users. Some of these mentioned characteristics work on the actor's credibility. For instance, an actor, who provides the information for the traceability system depends on upon his willingness, and he can easily manipulate the information. In fact it has been reported that suppliers in T&C supply chain fabricate their records for compliance with regulatory or code standards (Khurana and Ricchetti 2016). Since the actors in the T&C supply-chain are often distantly located, therefore verifying all traceability data may not be practically feasible. Moreover, traceability information may also contain some confidential information meant for only partner actors or certain section of the supply chain. Hence, the security of data transfer and storage is another important aspect, which depends on upon the data handling and network security used by an actor. Therefore, it is important to have confidence and credibility among various actors for a good traceability system.

In addition to challenges mentioned above, the financial aspect of traceability information is one of the deterring factors, especially when T&C production supply chain involves SMEs,

which have financial constraints. Although, traceability is economically beneficial in the long term, the one-time investment might act as deterring factor for the opting traceability by SMEs.

5.2. Traceability marker

The use of appropriate traceability marker is another important criterion for the success of a traceability system. A traceability marker integrates the information to the product and is the only link between product data server and the TRU (or an authentic product at the consumer level) (Informal Product Traceability Expert Group - Final Report 2013). Bandinelli, Pampaloni, and Rinaldi (2013) define an authentic product based upon three criteria namely product authenticity, traceability, and integrity. The product authenticity means the product manufactured by or belongs to the parent company. Integrity refers to product specifications conformation, no alteration, damage or tamper, and traceability means the recall of the product history. For example, if a TRU replaced with a duplicate TRU having same/appealing same traceability marker in a distribution system can create problem in traceability implantation. This is because when a supply chain actor receives the product and try to recall its history using traceability marker, the product data server will respond with the data of the replaced product (Juels 2005). This situation may not be complicated during the intra/inter-industry material movements because the received material is cross-verified using lab-based tests. However, at the consumer level, the consumer tests a garment by his/her visual and tactile interpretation, the situation may complicate. In fact, counterfeits take this advantage to introduce their product in the market. Therefore, anti-cloning is an important criterion for the selection of the traceability markers (Garfinkel, Juels, and Pappu 2005; Juels 2005; Legnani et al. 2011; Nayak et al. 2015; V. Kumar, Koehl, and Zeng 2016; Tarun Kumar Agrawal, Koehl, and Campagne 2016; T. K. Agrawal, Koehl, and Campagne 2017). RFIDs and printed barcodes are the most commonly used traceability markers in T&C sector (Blankenburg, Horn, and Krüger 2013; Corbellini, Ferraris, and Parvis 2006). While, the abovementioned traceability tags lack in anti-clone protection (i.e. they can be easily replicated to use with counterfeit products (Blankenburg, Horn, and Krüger 2013)), use of RFID-based traceability tags are limited to point-of-sale as products with RFIDs attached or integrated can be potentially used for tracking the end-user (Clarke III and Flaherty 2008; Lu et al. 2011). In fact, because of the privacy concerns, clothing brand Benetton has planned to withdraw the use of RFIDs in their products (Nayak et al. 2015).

Moreover, the use of RFID or any other electronic chip integrated into the textile creates significant problems in disposal and recycling. For example, it is imperative to remove the non-textile components (such as electronic chips) before processing a garment in the recycling processes, which include shredding of the garment into smaller pieces. However, if the electronic components are integrated into the garments, it requires extra care and sometimes removing them manually as automatic processes inevitably increase the cost (Köhler, Hilty, and Bakker 2011). Inability to remove electronic components during the recycling process results into recycled fibers contaminated with a scrap of these components. Therefore, using RFIDs integrated into the textiles are not preferred from recycling perspective (Köhler, Hilty, and Bakker 2011). In this context, selection of an appropriate traceability marker is an important criterion for a successful traceability system (Informal Product Traceability Expert Group - Final Report 2013; V. Kumar, Koehl, and Zeng 2016).

6. Agenda for the future research

Traceability is a vital need in the manufacturing sector, and the T&C sector has seen an unprecedented demand due to the cross-border sourcing, rapidly changing market demands, and consumer concerns to name few. Based upon challenges discussed in the implantation traceability, some issues are discussed further from the future research perspective. As the T&C sector has a global spread with various actors dealing with different raw materials and processes, the previously discussed issues need an understanding from common as well as specific aspects. The common aspects would require examination for the common challenges that the whole sector generally faces in implementing traceability. On the other hand, specific aspects would include the issues that are not common, rather limited to one or more supply chain actors or a segment of the supply chain. Furthermore, as the most supply chains are globally spread, probably initial efforts would be required to take different segments of the supply chain (which are located in different countries) to bring them on the same plane for example in terms of technology, information architecture, business alignment, etc. To realize this, the involvement of different governments or global organizations would be particularly required. The following subsections describe the key areas, which can be explored in the future research for implementation of traceability in the T&C sector.

6.1. Global regulation for traceability in T&C sector

Regulations play an important role in the implementation of traceability. For example,

traceability is a legal requirement in the food sector in the EU, which mandates that every firm must be able to trace their products in all manufacturing stages (Alfaro, Sebrek, and others 2015). Subsequently each supply chain actor responsibly maintains the desired traceability level by law. As a result, traceability implementation in food sector is considered one of the most efficient (Probst, Frideres, and Pedersen 2015). On the other hand, some countries have guidelines for traceability in the T&C sector. A typical T&C supply chain consists of multiple actors and supplies often flow cross-border. As a result, different suppliers are often located in the various international locations, which results in various level of traceability (if any) based upon the local jurisdiction. From the implementation perspective, all actors need to align regarding the desired level of traceability and technology for exchanging information (Bechini et al. 2008). However, due to a different degree of traceability requirements set by local regulations, it is difficult to attain the same level of traceability or standards throughout the supply chain. Due to unavailability of standardized guidelines, organizations often end with following multiple standards and semantics for information exchange, which makes the process more complicated (Lam and Postle 2006). As traceability is analogous to information chain, where each actor acts like a linkage; any inadequacy in managing a required level of traceability or technology for information exchange at any stage of the supply chain acts as a weak link or bottleneck in traceability chain (V. Kumar, Hallqvist, and Ekwall 2017). In this context, it is important to enforce global regulation for traceability, at least for the minimum level, so that every actor maintains a minimum level of traceability and exchanges required traceability information with other actors in the supply chain. This would not only help the industrial actors to self-identify their responsibility in attaining a necessary level of traceability but also helps the surveillance or regulatory authorities regarding product control in the market, product recalls, and security. Hence, the interference of different governments or policymakers at the global level would be required to moderate the implementation of traceability in T&C sector and discussion and research at a global scale is needed from the policymakers.

6.2. Framework for traceability information identification and management

According to Djatna and Ginantaka (2014), traceability can be stated as “keeping track of a given set or type of information to a given degree, or the ability to chronologically interrelate uniquely identifiable entities in a way that is verifiable.” Therefore, the foundation of any traceability relies on how efficiently the information is captured, management and

communicated throughout the supply chain. As mentioned before, T&C supply chain consists of multiple actors dealing with a diverse range of raw materials and processes. Therefore, to realize a supply chain wide traceability, each actor needs to identify and record the traceability data, which is expected from the business partners and required for achieving the goals expected from traceability implementation. The goals can vary from simply maintaining of the suppliers detailed for record-keeping purposes to more complex applications such as monitoring the whole supply chains and keeping details of different processes. As many of these traceability objectives are based upon the collective efforts of the supply chain actors; for example, to calculate the environmental impact of a garment in manufacturing phase, detailed information about various processes that were performed by various actors in the supply chain would be required (Yasin et al. 2016). Every supply chain actor performs a series of operations, which can potentially result in a huge traceability data or information, whereas only a part of the traceability data may be required to pursue the expected goal. Therefore, practically, it is neither reasonable nor useful to collection every bit of information. On the other hand, it would also be problematic if some necessary data were not captured by the supply chain actors. Therefore, in order to handle the above scenario, it is imperative that each supply chain actor either, informed for the required traceability data to capture, or follows a mechanism to self-identify the traceability data based upon required objectives. Furthermore, the information management is required for the appropriate and proper utilization of the stored traceability data. These progressions are required to be done in a systematic and cohesive way, which is acceptable to all the supply chain actors. According to Bechini et al. (2008), this can be accomplished “by developing a generic supply chain technical disciplinary, which defines a set of rules with regards to material and document flow, production process management and execution, business process collaboration through partners agreement, and responsibility placements”. Therefore, a standardized framework would be required develop which can be followed for aligning the traceability goals with the traceability information component to captures and standardized methodology for the data management at each level of the supply chain.

6.3. Global unified semantics for information exchange

As stated, business operations in a supply chain are expected to ensure that traceability data is exchanged with partners and the requests for additional data are handled and responded properly (S. H. Choi et al. 2013). Unavailability of common method and format for

exchanging information often results in the companies to follow multiple information systems suitable or in line with their buyers and suppliers, which inevitable increases the complexity and cost (Lam and Postle 2006). Furthermore, it affects the surveillance authorities during product recall or inspection which often need traceability information during their operations (Informal Product Traceability Expert Group - Final Report 2013). Therefore, a necessary requirement for a meaningful information exchange is the use of common method or technique that different the supply chain actors. Electronic Data Interchange (EDI) and eXtensible Markup Language (XML) are the commonly used methods that have been used in business organizations exchange information electronically and various sectors utilize them for information exchange (Thakur and Hurburgh 2009). In this direction, EC has funded the project TraceFood for implementing traceability in the food sector, which has developed TraceCore eXtensible Markup Language (TCX) as a standardized information exchanging method which covers the information characteristics which are common to all food supply chain actors (TraceCore XML 2017). In fact, there are many sector-based projects have been carried out for standardized of information exchange (such as agXML for grain- and oilseed-related business processes (AgXML 2017), agroXML for farm management information, and landXML for data exchange during civil engineering (landXML 2017)). eBIZ is one of such initiatives, dedicated for fashion sector, aiming towards developing a common language for communication in the fashion industry supply chain (De Sabbata et al. 2008; Bindi, Bandinelli, and Rinaldi 2016). In a similar way, to align the actors in T&C sector semantically, future research can be focused on formulate suitable standardized semantics considering the role of different actors of T&C supply chain. Learning for the best practices from other industrial sectors, which are forerunner in traceability implementation, can help in the selection of suitable techniques and avoiding previously faced issues.

6.4. Product identification markers

As mentioned earlier, the core notion of traceability is to make an information web so that it can track and trace the product and process information in a supply chain. In this context, the physical products are labelled with unique numbers so that they can be traced in the supply chain. RFIDs and printed barcodes are the common tags or labels which are widely used with the physical products, and the product information is stored and exchanged with reference to the unique numbers on labels (V. Kumar, Koehl, and Zeng 2016; V. Kumar, Koehl, et al. 2017; V. Kumar, Hallqvist, and Ekwall 2017). As a result, the tag acts as a link between the

physical product and information. While the abovementioned labels are widely used, the primary limitation mentioned in Section 4 includes easy replication and reproducibility, and their limited lifetime or scope in the supply chain. On the other, the application of traceability spans from initial raw material to the final disposal of the product. Therefore the traceability tag should accompany the product for the possible recalling of traceability information. In order to address above issues, researchers in the past have carried out their studies in multiple directions which can be broadly divided into two categories – first, securing the existing traceability tags (i.e. RFIDs and printed barcodes) with features which are difficult to replicate, and second, incorporating the tags into the product itself. One example of a former category is the use of 2D holograms, which are difficult to replicate by unlawful means. Although the holograms are difficult to replicate accurately, it needs an authentication mechanism to identify a real. Unavailability of such authentication provides an easy opportunity to disguise customers with a visually similar appealing hologram. Similarly, securing RFIDs from unauthorized replication have been addressed by using several protective measures; however, it results in increased tag cost, which hinders its application (Tuyls and Batina 2006). Therefore, a potential area for future research includes devising or introducing the features, materials, or methods, which can be used for tag security and authentication while keeping the cost in low.

On the other hand, incorporating a tag into the product ensures that it cannot be removed from the product while providing extended traceability; it can be used for securing the product from issues including tempering of the product and replacing with a counterfeit product during the shipping. However, incorporation of traceability tag not only be potentially used for tracking the user (as resulted from the use of RFIDs discussed in Section 4) but can also create concern on the product disposal. Therefore, the selection of appropriate materials is an important criterion. In this direction, previous studies (such as Xin et al. 2011; V. Kumar, Koehl, and Zeng 2016; V. Kumar, Koehl, et al. 2017) have provided a direction on how fabric and yarn visual features can be used for integrated traceability tags. Alternate approaches such as incorporating customized DNA in the fibers (Applied dna science 2016) and coating material with surface to embed traceability information (Bernardin et al. 2006) have been explored to implement traceability in textile products. DNA-based tagging has recently gained more attention for anti-counterfeiting applications due to high level of security that it provides to the product. Nevertheless, further research would be required to explore from the perspective of different materials and assimilation with current production

systems and practices.

6.5. *Systems and security*

From the application perspectives, traceability is an information web generated from the components of information originated from different actors in the supply chain. Therefore implementing traceability is also assessed as a technology-driven model where sophisticated IT capabilities play a significant role and supported by the skilled workforce to maintain the systems (Probst, Frideres, and Pedersen 2015). Furthermore, the shared or exchanged data often consists of critical information, which is shared with selective members of the supply chain. Therefore, while traceability contributes in towards transparency and attaining other business objectives by creating a channel for traceability information exchange, any unauthorized access to the information channel or traceability data – specifically related to the confidential data – can potentially provide undue advantages to other supply chain actors or opponents. Generally, a T&C supply chain consists of agents or mediators between the suppliers and buyers (Bruce and Daly 2011; Egels-Zandén, Hulthén, and Wulff 2015). The key competitive advantage of these agents are the names of their suppliers and buyers (Egels-Zandén, Hulthén, and Wulff 2015). Therefore, agents consider revealing the suppliers' information to the buyers as a factor which can potentially allow the buyers or suppliers to bypass the agents in future contracts or transaction (Egels-Zandén, Hulthén, and Wulff 2015). Moreover, implementing traceability without supplier–buyer communication is also not a plausible option. Therefore, the two potential areas for the future research originate from developing secure systems – first, which can be implemented and maintained in a sector, which is dominated by semi-skilled or limited skilled workforce and second, how the information can be exchanged between supplier and buyer where confrontation among them is not possible or limited by previously discussed factors. In this direction, the role third party agencies can be explored in implementing traceability, which can be positioned as a bridge between the supplier and buyer thus avoiding supplier–buyer confrontation while ensuring that each of them complies with required traceability standards. Learning can be made from previously proposed designs and developed traceability systems (Alves et al. 2014; Alves et al. 2013; S. H. Choi et al. 2013; V. Kumar, Hallqvist, and Ekwall 2017).

7. **Conclusions**

The aim of this paper was to review the application of traceability and challenges in its implementation in the T&C sector to identify the future research directions. We have found that the traceability has numerous applications spanning from the origin of raw materials to the end-of-life of the final product (including recycling), covering a vast range of scenarios. In the past, studies have acknowledged that an efficient implementation of traceability besides benefitting the business organizations, serves as a tool for to customers and surveillance/regulatory authorities to access authentic information. In fact, consumer demand for traceability information (such as to know the sustainability aspects of the products) is identified as one of the major factors that have pushed the organizations to implement traceability in their business processes. In this direction, various organizations have come forward with different practices to share varying degrees of traceability information with the customers.

In a simple term, one can describe traceability as keeping track of information of a product. Depending upon the expected objectives, information in a traceability system include the raw materials data, supplier info, records of the processes and sustainability practices, compliance details and so on and is often supplied and managed by different supply chain actors. As a T&C supply chain consists of multiple independent actors – which are located in different geographical locations worldwide, the successful implementation of traceability relies on actors’ organizational and technological alignments with each other for traceability information collection, management, and sharing. In this direction, this paper has highlighted multiple aspects such as standardization of technology, semantics, and systems, therefore suggesting the further research directions. Further, the role of policymakers and government regulation is pronounced, which play a vital role in introducing or bridging different regulations at global as well as local levels for traceability implementation. The future research directions discussed in this paper are literature-based and suggestive at this stage, whereas putting forward a definitive list would further require evaluation from the experts of respective areas. Nonetheless, the directions have been highlighted for various stakeholders, which can play a major role in the successful realization of traceability in T&C sector.

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Paper II

Agrawal, T.K. and Pal, R. (2019), Traceability in Textile and Clothing Supply Chain classifying implementation factors and information sets via Delphi study, *Sustainability*, Vol. 11 No. 6, 1698

Article

Traceability in Textile and Clothing Supply Chains: Classifying Implementation Factors and Information Sets via Delphi Study

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Received: 23 February 2019; Accepted: 17 March 2019; Published: 21 March 2019



Abstract: The purpose of this study is twofold. First, to explore and classify factors influencing traceability implementation, and second, to cluster essential traceability-related information that demands recording and sharing with businesses and customers, in the context of the textile and clothing supply chain. A Delphi study is conducted with 23 experts (including research practitioners and industry experts) to explore, validate, and classify traceability factors and related information using distribution analyses and hierarchical clustering. As a result, 14 factors and 19 information sets are identified and classified with a moderately high agreement among the experts. Among these, risk management, product authentication, and visibility are the highest ranked and the most important factors influencing traceability implementation in the textile and clothing supply chain. While origin, composition, and sustainability-related information are crucial for sharing with customers, the information vital to businesses includes manufacturer/supplier details, product specifications, and composition. It is noteworthy that this research is among the few that classifies traceability factors and information through expert perspectives, and it creates decisive knowledge of traceability for the textile and clothing supply chain. It further provides insights on the extent to which this information can be shared among supply chain actors. Outcomes of this study can be helpful for the development of an information traceability framework. Policymakers can use the results to draft traceability guidelines/regulations, whilst top management can develop traceability-related strategies.

Keywords: traceability; Delphi study; supply chain; textile and clothing

1. Introduction

Information asymmetry and lack of transparency have made the textile and clothing (TC) supply chain almost untraceable [1–3]. Although connected through a complex network, supply chain partners find it difficult to identify and access information related to all involved suppliers [4]. Ignorance and lack of proper information sharing systems have resulted in unfortunate events in the past and have raised serious concern among governments and consumers [3,5]. These incidences have exposed the unethical and unsafe practices widely followed in the TC supply chain, and have questioned the accountability and auditing methods [6].

Besides, such untraceable or opaque supply chains facilitate easy intrusion of counterfeits, which has always been an important concern for the TC industry. Because of these products, the TC supply chain suffers huge losses every year [7]. As per the European Union Intellectual Property Office Observatory report, due to counterfeit products, on an average (from the year 2007–2012) the TC

industry has lost around 9.7% of sales, EUR 26.3 billion of revenue per year in the sector (EUR 8.1 billion of revenue by the government), and 36,300 direct jobs [8].

To address these challenges, the Organization for Economic Co-operation and Development [9] suggests (in their guidelines) traceability system as one of the mechanisms that can be adopted to achieve information symmetry, security, and accountability in the TC supply chain. Traceability, as defined by ISO (9001:2015), is “the ability to identify and trace the history, distribution, location, and application of products, parts, materials, and services. A traceability system records and follows the trail as products, parts, materials, and services come from suppliers and are processed and ultimately distributed as final products and services”. In general, a traceability system can be used to access information related to all involved actors, activities, and products including raw material components, processing conditions, logistics movements, carbon footprints, etc. As explained by [10], traceability systems facilitate information flow in a way similar to freights carried by railway. In this analogy, the carriages contain traceability information instead of freights, whereas systems related to product identification and transformation can be related to the railway track that ensures the safety and integrity of these carriages (containing traceability information). Thus, the outputs or the benefits of a traceability system are in the forms of transparency, visibility, quality control, etc., depending on the type and extent of information one records and shares in the system (or load on the carriages). Besides, the application and features of traceability systems are largely influenced by the type of supply chain. As a result, researchers and practitioners are working towards the development of a customized traceability system that can cater to the specific needs and requirements of the related supply chains [11]. For instance, traceability is a significantly researched and adopted system in food and pharmaceutical supply chains [12–15].

Regardless of its numerous benefits, traceability is still an emerging and less implemented concept in TC supply chains. Some of the primary reasons, as highlighted in [6,16], are: lack of dedicated and inexpensive technologies that can be developed taking into account the complexities of TC supply chain structure and product features, lack of awareness and consensus among stakeholders regarding the potential benefits of a single traceability system, and absence of traceability rules and regulations. Thus, traceability is still a voluntary measure in the TC supply chain, and it is partially adopted by brands to share information related to their sustainability aspects in the form of green certifications, eco-cotton labels, carbon footprint data, or supplier details [3,17]. Steps are required to promote traceability and develop consensus among the TC supply chain partners for the implementation of a single and complete traceability system that can record and share information related to each supply chain stage in a standardized format [6,16].

One of the steps in this direction could be exploring and prioritizing important factors influencing traceability in the TC supply chain. These factors can induce the perception of the practitioners and motivate traceability implementation. Further, based on these key factors, traceability information can be ranked and classified to determine the extent to which it can be shared among the businesses and with end customers. This requires sector-specific study [11], which is currently missing for the TC supply chain.

In this direction, the study formulates and empirically explores two specific research questions (RQs):

RQ 1: What are the key factors influencing traceability implementation in the TC supply chain?

RQ 2: What essential traceability information needs to be recorded and shared among various TC supply chain stakeholders?

The two RQs are correlated, and to answer them, this paper follows a Delphi methodology with TC supply chain experts. Various key factors influencing traceability implementation in the TC supply chain and related traceability information are explored, prioritized, and classified by reaching consensus through a multi-round survey analysis. To support the findings, the study examines the results in light of arguments from literature and commentary inputs from the experts.

The following sections describe the Delphi-based survey methodology followed in this study, which was conducted in six steps (shown in Figure 1) until a consensus was reached.

Methodology (Delphi based approach)	
Step 1	Exploring key factors and essential traceability information from literature
Step 2	Subject selection based on Delphi guidelines
Step 3	Design of semi-structured questionnaire based on results from step 1
Step 4	Survey round 1 with the selected subjects (Researchers and Industry experts)
Step 5	Evaluation (survey round 1) to find degree of consensus and response with low-agreement, followed by survey round 2 (opportunity to reconsider the responses)
Step 6	Final evaluation (survey round 2) using 'Distribution analysis', 'Hierarchical clustering' and 'Optimal leaf ordering' methods.

Figure 1. Steps of Delphi-based methodology followed in the study.

2. Methodology

Developed at Rand Corporation, Delphi is a well-acknowledged methodology to attain consensus on a complex and multidisciplinary problem. It is a systematic group communication process, allowing anonymous interaction among dispersed panel experts, in multiple rounds. (See detailed explanation in [18]). Delphi has been adapted in numerous research studies designed for needs assessments, policy determinations, and forecasting and program planning [19–21]. In the area of supply chain management, studies highlighting applications of the Delphi technique for investigating factors influencing decision making can be found in [22–25].

2.1. Exploring Key Factors and Essential Traceability Information from the Literature (Step 1)

Traditionally, a Delphi study starts with an open-ended questionnaire; however, as a common and well-accepted modification in format, a structured or semi-structured questionnaire can be designed based on literature analysis (mentioned in [18]; practiced in [25]). Therefore, different factors influencing traceability implementation and related information sets were identified through a narrative review of literature. The explored articles were further segregated into those specific to TC vs. other supply chains. To eliminate potential bias related to narrative review methods, during the first round of survey the experts were asked to validate and add missing factors and information that can be considered for the study.

2.1.1. Traceability—Factors

It is evident from previous studies that traceability implementation in supply chains has numerous advantages, as it leads to better visibility, authentication, quality assurance, and product data management [26–28]. For instance, in [27] the author took the example of the horsemeat scandal in European markets and highlighted the importance of complete traceability in the form of product authentication and quality assurance. As an initial step towards traceability system development, the study summed up all the key factors (in Table 1) influencing its implementation in the TC supply chain from extant literature. It can be noted that the detailed discussion on how these benefits are achieved through traceability is not congruent with the purpose of the paper, and it has been opted-out from the review. It is evident that traceability in TC supply chains, even though a pressing issue for practitioners, has gained limited attention in the literature.

Table 1. Factors that influence traceability implementation in TC supply chain.

Influencing Factors	Supporting Authors		How It Influences
	Textile	Others	
Transparency	[2,29–31]	[32–34]	Transparency is the extent to which information is shared among the supply chain partners, and visibility implies the extent to which a buyer can trace back the details about the suppliers and sub-suppliers. Both are high in demand and crucial elements for a sustainable TC supply chain. To achieve these, an effective traceability mechanism is required that can connect and integrate all the involved supply chain partners.
Visibility			
Product Maintenance	[30,35]	[36]	Textile product maintenance in its use-phase, especially during washing and drying, is one of the key concerns influencing the durability and recyclability of the textile product. Traceability mechanisms are essential to share product maintenance aspects with end users, and at the same time an active traceability mechanism can be programmed to record product use-phase data (e.g., number of washes) that is crucial in recycling stages
Market surveillance	[30,37]	[38–40]	Market surveillance by public authorities that closely observes products in the market and ensures that the products conform to the applicable law, require crucial information about the history, origin, and composition of product/raw material and intermediate product. Examples of such authorities are the Administrative Cooperation Group (AdCos), Rapid Alert System (RAPEX), etc. Traceability mechanisms connect the supply chain partners and enables tracking and tracing of product at each stage of the supply chain.
Reverse logistics	[41,42]	[26,43–45]	Reverse logistics management, involves collection, sorting and segregating of the used product during recycling and inventory management during re-manufacturing, and return. An automated reverse logistic system using traceability mechanisms and information can save cost, time, and enable effective recycling, reuse, and renting of products.
Renting, sharing and reuse			
Quality Monitoring	[16,42,46]	[47,48]	Recording and sharing quality-related information enables effect control, monitoring of product quality, and recall management to identify the origin of defects. In the case of recalls, traceability mechanisms can trace the origin of the defect and locate the responsible partner.
Recall Mechanism	[41,49]	[26,43,50]	Real-time tracking and tracing of product and product data management enables effective and more precise sales forecasts, production planning, and control. This can be ensured by a traceability mechanism that integrates the supply chain and records real-time product data.
Sales forecasting	[7,30]	[38,43,51]	Product and information security are one of the key concerns of the TC supply chain that requires secure technologies and systems for counterfeit detection and data protection. In this direction, a traceability system with secured mechanisms can ensure product authentication and prevent data leakages.
Product authentication			
Intellectual Property Rights (IPR) Protection	[30,52]	[43,53]	In this era of fast fashion consumers, more information is needed about the product to make an ethical buying decision. Enabling the customer to trace the history of textile products through a traceability mechanism can create a positive brand image and boost sales.
Marketing			

Note: Factors with overlapping literature are discussed together.

2.1.2. Traceability—Information Sets

Supply chain traceability requires recording various types of information at different stages of the product transformation, starting from raw material production to reverse logistics. For instance, traceability implementation has long been reported to restore consumer confidence in product quality and safety by providing more information related to product origin, composition, quality, etc. [28]. In [11], the authors highlighted that traceability information, especially concerning product traceability, can be broadly classified as product-, process-, and quality-related. Product information includes name, origin, composition, specifications, and details related to all the raw materials, intermediates, and final product that is delivered to the end consumer [30,50]. Process information includes all the details related to all the processes involved in the manufacturing of the product [16,31]. Finally, quality information is mainly concerned with product quality and the details associated with it [11,16]. A fourth type of information, concerning the social and environmental impact of a product throughout its transformation stages, forms a separate category, especially to convey ethical and ecological concerns. Furthermore, in [11] the authors suggested that not all traceability information is essential to record and share with other actors, including customers. This may act contrary to the functioning of a traceability system. Actually, little is known or explored in past studies about views and opinions associated with traceability, nor consumers' or businesses' preferences for traceability information provisions, especially in the case of the TC supply chain [54]. In this context, there should be segregation of essential and non-essential traceability information for optimum information sharing and efficient functioning of a traceability system [30]. In light of this, as an important step for initiating the investigation in this study, Table 2 presents a comprehensive list of all the information related to traceability that should be recorded and shared, as obtained from the literature. It can be noted that this traceability information is not limited to the final product, but also contains details of intermediate production and reverse supply chain stages.

Table 2. Essential traceability information sets.

Information Sets	Supporting Authors	Sub-Category	Description
Product Information	[11,16,31,49,50,55]	Origin	Origin of the final product, component, sub-component, and raw materials utilized in the production of the final product.
		Composition	Composition of the final product, component, sub-component, and raw materials utilized in the production of the final product.
		Manufacturer/supplier details	Information about all the manufacturers, suppliers and sub-suppliers involved throughout the lifecycle of the product.
		Inbound material specifications	A detailed description of design and product/material specifications that are procured from the supplier/upstream actor.
		Outbound product specifications	A detailed description of design and product/material specifications of finished product that is transferred to the next downstream actor
		Costing data	Information related to the cost of the final product, raw material, and the entire intermediate product.
		Lot numbers	Unique series of the number provided to a bundle or lot of product to facilitate batch traceability
Quality Information	[11,16,31]	Sales data	Real-time data related to product sales in different retail channels.
		Audit reports	Various audit-quality audit reports done throughout the lifecycle of the product
		Test procedures and reports	Various audit-quality test procedures and test reports done throughout the lifecycle of the product
		Quality Certification Data	Various quality certifications related to raw material, intermediate product, and final product throughout the lifecycle of the product
Process Information	[11,16,31]	Tracking data of surplus or damaged material/product	Tracking data of each product, the damaged or discarded product/intermediate, and raw material in the supply chain.
		Process names/details	Information and details about all the involved manufacturing processes throughout the lifecycle of the product.
		Machines Ids	Machine Ids of the machines involved in product processing throughout its lifecycle.
Social-Environmental Information	[16,17,31,56]	Timestamps	Time stamps of all the important events and processes throughout the lifecycle of a product.
		Social audit-report/certification	Various social audit reports and certifications associated directly or indirectly with the product
		Environmental audit-report/certification	Various environmental audit reports and certifications associated directly or indirectly with the product
		Carbon footprint data of products	Complete carbon footprint data of the final product throughout its lifecycle

Figure 2 presents the deductive model of factors and information sets. Factor 14 ‘Risk Management’ in Level 1 and ‘Recycling data’ in Level 2 were added through commentary inputs from experts after survey Round 1 (in Step 5).

2.2. Subject Selection (Step 2)

Being limited in number, Delphi subjects (experts) must have appropriate knowledge and experience related to the particular issue being discussed so as to represent an assortment of perspectives [25]. For this reason, companies initially affiliated with the Sustainable Apparel Coalition (SAC) [57] were approached to nominate traceability and supply chain-related experts from their respective enterprises for the study. SAC was deemed appropriate to initiate the expert search because of its global outreach to textile and clothing industry players, including advocacy groups and academicians, with the objective to create a sustainable industry. The nominated individuals further recommended around 50 potential panelists. Finally, an invitation letter explaining the topic, aim, and duration of the study was sent to these nominated experts. These experts, associated with various multi-national TC companies all over the globe, held major positions, as CEO, COO, or Global Heads, responsible for sustainable development with extensive experience in the TC supply chain. Additionally, fifteen well-known academics, senior consultants, and investigation journalists researching TC supply chain traceability and related topics were conjointly invited. To determine the suitable size of the panel, a method prescribed by [21,24] was followed.

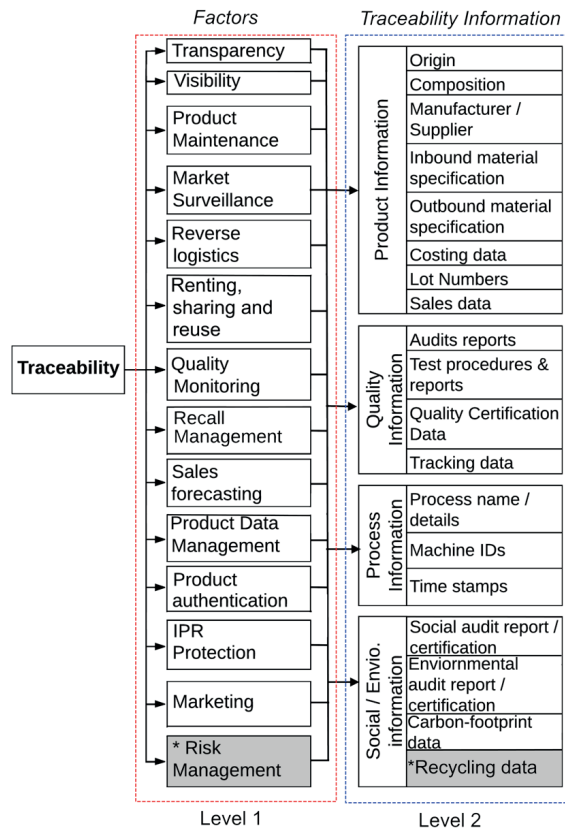


Figure 2. Summary of different traceability factors and information. Marked with (*) are the factors and information type added through commentary inputs.

2.3. Design of the Semi-Structured Questionnaire (Step 3)

Based on outputs from Step 1, factors and information were compiled in a semi-structured questionnaire. For questions related to traceability factors (Level 1), the experts were asked to rate each factor based on their importance for traceability implementation along a five-point Likert scale, where 5 was ‘most important’ and 1 was ‘least important’.

To identify traceability information related to each factor (Level 2), matrix questions were created with the rows containing the sets and subsets of information (Table 2) and the columns containing the traceability factors. The experts selected the information corresponding to each factor that must be recorded and shared at the business-to-business (B2B) level and with the end customer, i.e., at the business-to-customer (B2C) level. Additionally, open-ended questions were included to receive feedback and comments (if any).

A pilot run of the survey was conducted with four supply chain experts to: (a) test the relevance and clarity of the formulated questions and avoid ambiguity, (b) evaluate the usability of the survey tool, and (c) validate the content and enhance the quality of the survey structure. However, no significant changes were prescribed. The survey form can be obtained from authors on request.

2.4. Survey Round 1 (Step 4)

The survey was distributed to the selected panel of experts through the Survey Monkey e-platform. All the terminologies, factors, and information types were explained and defined in the survey. The experts were contacted individually in case further clarification was required or if they encountered any technical difficulties. A time limit of three weeks was decided to collect the responses.

2.5. Evaluation (Round 1) and Survey Round 2 (Step 5)

Level 1 questions were assessed using pairwise comparison and a distribution analysis to select responses with relatively higher standard deviations (meaning lower agreement among experts). Therefore, in the survey Round 2, experts re-evaluated these factors only. The Level 2 questions were evaluated through a weighted mean formula as shown in Equation (1).

$$\bar{m} = \frac{\sum_{i=1}^n (m_i * w_i)}{\sum_{i=1}^n (m_i)}, \quad (1)$$

where, n is the number of experts in the panel, w_i is the Likert scale value provided by expert ‘ i ’ to the w th factor (from Level 1), and x is ‘Yes, record and share’ ($m = 1$) or ‘No response’ ($m = 0$) for the traceability information corresponding to the factors. Information with response rates $\leq 75\%$ or $\geq 25\%$ was re-considered in Round 2.

2.6. Final Evaluation (Step 6)

To test consensus, a Pearson correlation coefficient (ρ) was calculated between the survey responses from different rounds and between the different group of respondents within the same round, using Equations (2)–(4):

$$\bar{X}_a = \sum_{i=1}^n (X_{a,i}) / n, \quad (2)$$

$$\bar{Y}_b = \sum_{j=1}^n (X_{b,j}) / n, \quad (3)$$

$$\rho(a, b) = \frac{\sum_{i=1}^n (X_{a,i} - \bar{X}_a)(Y_{b,i} - \bar{Y}_b)}{\sqrt{\left\{ \sum_{i=1}^n (X_{a,i} - \bar{X}_a)^2 \sum_{j=1}^n (Y_{b,i} - \bar{Y}_b)^2 \right\}}}, \quad (4)$$

where n is column length or a number of questions, X_a is the responses by group ‘a’ and X_b by group ‘b’, and $\bar{X}_a$ and $\bar{Y}_b$ are the means of responses. The value of ρ ranges from -1 to 1 , where -1 , 1 , and 0 indicates a perfect negative, a perfect positive, and no correlation, respectively.

Level 1 questions were analyzed using a distribution analysis. The final data matrix (Z) of weighted mean responses of Level 2 questions was clustered, classified, and logically arranged using hierarchical clustering with optimal leaf ordering. For this, the pairwise Euclidean distance (d) was first calculated between two data points (e.g., 's' and 't') in the form of different row vectors (each with dimension 'n' equal to the number of factors) using Equation (5):

$$d_{st}^2 = \sum_{i=1}^n (z_{si} - z_{ti})^2. \quad (5)$$

A similarity matrix of the obtained distances was computed (d) using Ward's linkage algorithm. This method creates a dendrogram with a multilevel hierarchy. Additionally, to generate an optimal relationship among the clusters, the optimal leaf ordering algorithm was followed. This arranges all the elements in a logical order, typically with the most weighted element towards the origin and the least weighted element towards the end of the dendrogram. For further details related to the algorithm, refer to [58].

3. Results

Out of 27 experts who agreed to participate in the study, 23 finally attended the survey in both the rounds (85% response rate). Out of these, 12 were research practitioners, and the rest were industry experts. After Round 2 of the Delphi study, a moderately high consensus was observed firstly between research practitioners and industry experts, and secondly, between aggregate responses from Round 1 and Round 2.

3.1. Traceability Implementation Factors in Textile and Clothing (TC) Supply Chains

The means and standard deviations (SD), obtained through the Likert scale corresponding to each factor in both survey rounds, are shown in Table 3. Three factors with low agreement (high SD value), obtained through pairwise comparison and distribution analysis, were further validated in the next round. After Round 2, a general consensus among the experts' responses was observed with a low SD (value corresponding to each factor) and a Pearson correlation coefficient ρ (rho) = 0.66 (p -value < 0.01). Figure 3 is the graphical representation of aggregate results (mean value on a Likert scale) corresponding to each factor obtained after Round 2, arranged in descending order (ranking).

Table 3. Results (Likert scale) after each round.

Implementation Factors		Mean (SD) -					
		Round 1 (R1)			Round 2 (R2)		
		Rec (N = 12)	Ind. (N = 11)	Aggregate	Rec (N = 12)	Ind. (N = 11)	Aggregate
1	Transparency	4.17(0.69)	4.27(0.61)	4.22(0.66)	-	-	-
2	Visibility	4.33(0.47)	4.54(0.50)	4.43(0.49)	-	-	-
3	Quality Monitoring and control	4.58(0.64)	4.27(0.45)	4.43(0.58)	-	-	-
4	Recall mechanism	4.42(0.76)	3.82(0.57)	4.13(0.74)	-	-	-
5	Marketing Tool	4.16(0.69)	4.45(0.66)	4.30(0.68)	-	-	-
6	Market Surveillance	4.58(0.49)	4.10(0.70)	4.36(0.64)	-	-	-
7	Product authentication	4.58(0.64)	4.50(0.67)	4.54(0.65)	-	-	-
8	IPR protection	4.33(0.74)	4.40(0.66)	4.36(0.71)	-	-	-
9	Product Data Management	4.33(0.74)	3.70(0.85)	4.04(0.79)	-	-	-
10	Sales Forecasting	3.92(0.95)	3.50(0.81)	3.72(0.91)	3.75(0.60)	3.55(0.78)	3.65(0.70)
11	Product use/maintenance	3.66(1.10)	3.30(1.00)	3.50(1.08)	3.41(0.75)	3.27(0.75)	3.35(0.75)
12	Reverse logistics activities	4.25(0.82)	3.70(1.01)	4.00(0.95)	4.08(0.85)	3.90(0.67)	4.00(0.77)
13	Renting, sharing and reuse	3.67(0.62)	4.10(0.85)	3.86(0.76)	-	-	-
14	* Risk Management	-	-	-	4.75(0.43)	4.45(0.65)	4.60(0.57)

Note: Total N = 23; Rec = research practitioner; Ind. = industry experts; * = added after R1. Marked in bold are the final mean (SD) values corresponding to each factor after survey R2.

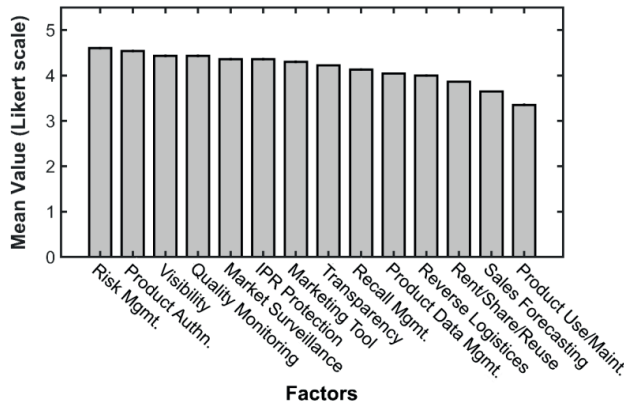


Figure 3. Bar plot of aggregate results corresponding to traceability factors after R2, in descending order of importance.

3.2. Traceability Information in TC Supply Chains

The study prioritized and classified two sets of traceability information. The first set consisted of information that can be shared with customers/end-users, i.e., at the business-to-customer (B2C) level, while the second set consisted of the information that supply chain actors could consider sharing among themselves, i.e., at the business-to-business (B2B) level. After the two rounds of Delphi, a moderately high degree of agreement and stability in responses—related to the B2C set of information—was observed between the group of research practitioners and industry experts, with $\rho = 0.77$ and 0.74 for Rounds 1 and 2, respectively. In addition, a substantial degree of correlation ($\rho = 0.92$) was observed in the mean responses from the two rounds.

Similarly, for responses related to the B2B set of information, the agreement between the two groups was moderate ($\rho = 0.6$ for both the rounds), hence, showing stability in the responses. Furthermore, the consensus between the rounds was also high ($\rho = 0.84$), indicating a strong correlation.

After ensuring a consensus and stability in the responses, mean values from Round 2 were clustered through hierarchical clustering, and the obtained dendrogram was optimized through an optimal leaf ordering algorithm. The obtained dendrogram, as shown in Figure 4; Figure 5, represents clustering of traceability information at the B2C and B2B levels such that the elements in cluster one have the highest rank (C-1: most important information), followed by cluster two (C-2: important information) and cluster three (C-3: less important information).

At the B2C level, information related to the origin, composition, manufacturer/supplier details, and product sustainability were in C-1, and they were the most important. While at the B2B level, manufacturer/supplier details, product specifications, and quality certification data along with composition and origin-related information were in C-1 and were among the crucial elements. Moreover, the overall ranking, composition, origin, and manufacturer/supplier information were among the most crucial elements for both B2B and B2C levels, while process-related information, such as machine ID, time stamps, and sales and costing data, were among the least important elements for both B2B and B2C levels.

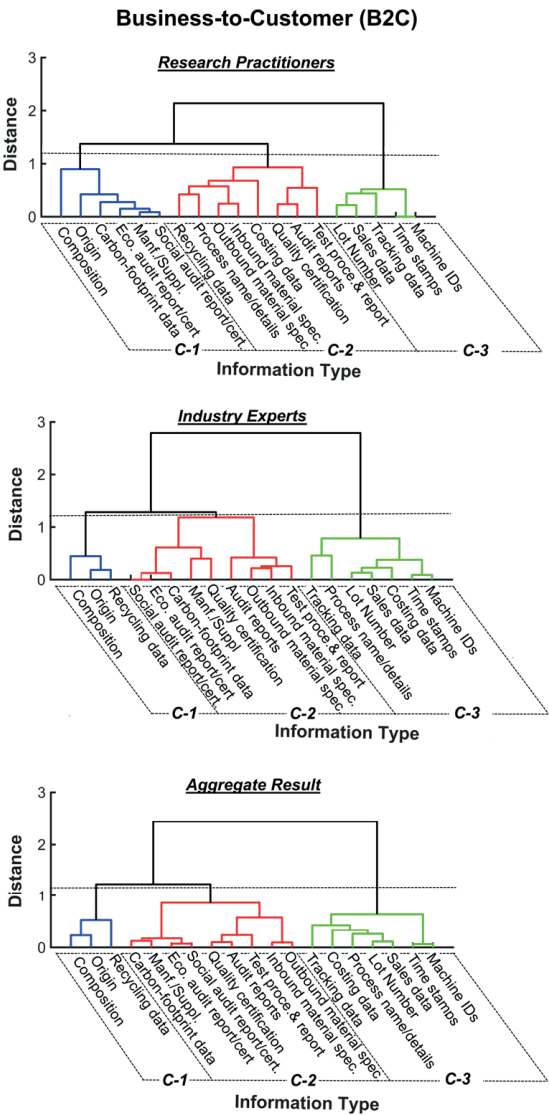


Figure 4. Information that can be recorded and shared at the business-to-consumer (B2C) level.

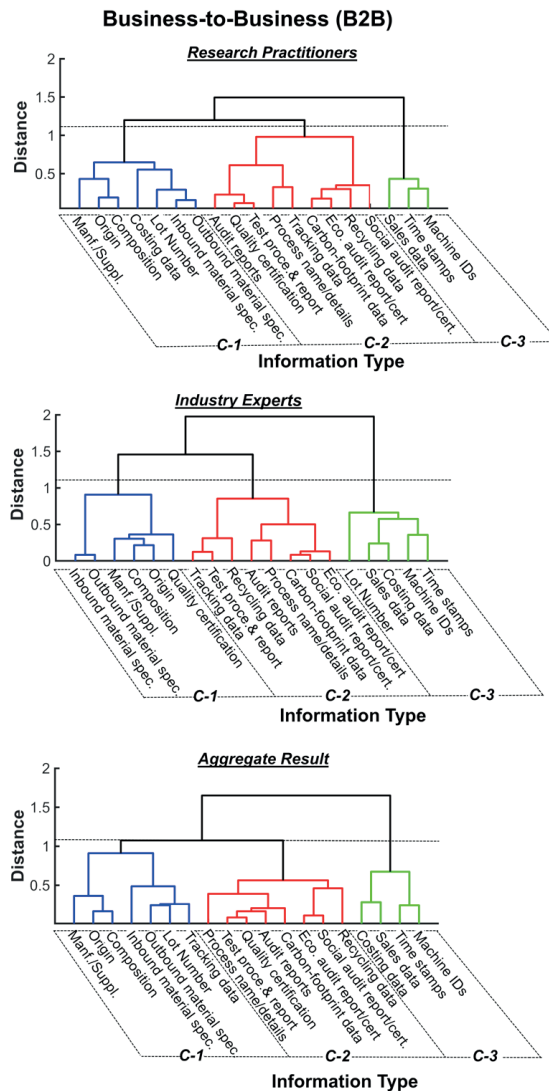


Figure 5. Information that can be recorded and shared at the business-to-business (B2B) level.

4. Analytical Discussion

This section presents an analysis of the obtained results using commentary inputs from the experts, along with inputs from literature, as sources of validation.

4.1. Traceability Implementation Factors

Risk management emerged as the most significant factor influencing traceability implementation in the TC supply chain. In general, traceability can contribute extensively to risk management in a multi-tier supply chain (e.g., TC) that deals with various risks causing delays and disruptions (also supported by [59] for the food supply chain). According to one of the experts, the “[...] main need for traceability is about—risk assessment and enabling brands to assess whether they will get the product on time with expected quality”. It is also supported in study by [60], wherein the authors analyzed

different supply chain risks (including TC) and mentioned the importance of traceability to identify and eliminate potential sustainability-related risks. Following this, product authentication emerged as the second most influential factor, owing to the issue of counterfeit products. It was mentioned that because of the lack of dedicated traceability technology in the TC supply chain, brands suffer huge economic losses from counterfeit products. One of the experts further added, “[...] most of the [traceability] solutions until now are hard to realize in the production systems [...]. Example [...] RFID, which is very hard to produce in a large quantity [...]. The cost of a durable, washable tag is very high, and the programming is complicated. The label printers that effectively can produce RFID or Barcode tags cannot print and program the durable tags because of their size and thickness. The barcodes and 2D codes that are easy to reproduce are also very easy to counterfeit or copy”. In this regard, various studies in the past [7,30] have worked towards the development of product traceability and authentication systems for the TC supply chain.

Closely associated is the supply chain visibility that emerged as the third most influencing factor, and as per an expert, “Traceability implementation can increase visibility also of in-shored/re-shored production. It provides an opportunity to better monitor supply chain actors and their activity”. Traceability can also assure the claims of the quality certifications (like green labels and organic cotton certification schemes) and can enable effective quality monitoring. It verifies certification reliability by tracking and recording each step of the product lifecycle and “ensures that certification schemes are independent and applied in an equal manner globally.” This is also highlighted by [3,46].

Fifth in rank was market surveillance and, as mentioned by the experts, “due to lack of traceability mechanism, border surveillance authorities and customs find it challenging to verify origin and ingenuity of products when they cross borders”. Additionally, in the case of product recalls, since there is no traceability system, market surveillance authorities such as RAPEX (Rapid Alert System) find it difficult to trace the origin of defects or the accountable stakeholder [3].

Following this, the sixth influencing factor was concerns related to IPR Protection. Security and IPR concerns are also essential for the TC industry as per the IBM security report [61]. To highlight its importance, one of the research practitioners working on blockchain technology stated, “[...] traceability ensures that information is controlled at various levels of the supply chain with restricted access to authorized actors only. All information [in the survey] plus even more should be available and accessible. [...] I am a strong believer of the future [...] of blockchain technology-based traceability systems. The [...] spot where traceability and transparency come to a collision”.

After risk, accountability, and quality-related factors, the seventh, eighth and ninth positions were factors related to marketing, transparency, and product recall. Sharing traceability information with customers can act as a marketing tool and “can showcase sustainability concern of a brand, create a positive image and act as a competitive advantage,” as mentioned by one of the experts. Further, transparency can help “to gather information on the origin of materials, in order to measure social/animal welfare/environmental impact [...],” as mentioned by an expert and supported in the literature by [2,29,30]. Moreover, traceability information can help in tracing the recalls, identifying its early warning signs, following products, and monitoring customer reactions.

Product data management and sales forecasting got the tenth and thirteenth positions, respectively. As per one of the experts, “traceability can help in effective management of product and production data by real-time tracking and tracing of material in stock exchange—trading the total quantity sales for each product/color, location or the factory address and name, and traceability code for the manufacturing mapping”.

Interestingly, factors related to supply chain circularity and share economy, i.e., reverse logistics, rent/share/reuse and product use/maintenance, were ranked at the eleventh, twelfth, and fourteenth positions. Unlike what was expected from the literature, these factors got lower ranks because of the lack of a complete traceability mechanism in the TC supply chain. Supporting experts mentioned, “[Traceability] information are not relevant during the use and maintenance of the product, but during the purchasing decision making. Traceability is more necessary at the post-sales level, for the collection

of relevant data and information on consumers' behavior [...] set of elements that could give customers the traceability/transparency of their footprint while using/not using, maintaining/not maintaining, re-cycling, up-cycling/discharging their textile products. In order to apply to the sharing business, the tag [traceability mechanism] should have its recording system that harvests the number of washes, mistreatment, etc., while the garment is being shared. Aftersales traceability information of the kind [...] is crucial for recyclability reasons".

4.2. Traceability Information in TC Supply Chains

It was observed that information related to 'origin' and 'composition' was always in the first cluster and among the most important elements. As a mandatory government regulation (e.g., EU TC legislation), this information is already shared with end customers and surveillance authorities. Albeit, it lacks correspondence to all tiers of the supply chain. Following this is the information related to manufacturer/supplier details and social-environmental sustainability (like 'recycling data', 'social audit report/certifications', 'environmental audit report/certifications', and 'carbon footprint data'). As is evident from Figure 4, research practitioners consider this information very important and among those that should be shared with customers along with origin and composition details. One of them even stated that "[...] traceability relevant information is not only about sourcing locations, but also on the environmental and social footprint of raw material sourcing, an, i.e., agricultural method of production, soil regenerative performances of the plantation. (E.g., best fibers used in agricultural rotation cycles, water consumption in case of organic cotton, pesticides, and fertilizers used in conventional agricultural systems) as well footprint of virgin oil extraction referred to synthetic materials." They believe that these sustainability aspects are often ignored and not communicated properly to the customer. Further, one researcher added, "raw material and production footprints, as well as social and economic footprints of the tiers' "deeper depth" (for example the tier with chemical manufacturers), are too often the blind spots of any social and environmental assessment today. Customers [...] should not only be informed about carbon-emission but on all the relevant factors that represent the negative and/or positive environmental and social footprint. Carbon-emissions during transportation [...] starting from raw material to the consumers purchasing location, all should be part of traceability information shared at B2C level".

On the other hand, as per industry experts, recycling-related information is more important than any other sustainability information. They added, "[...] recycling data related to recyclability and where to send the product at the end of the usage' [...] would be key for both B2C and B2B. [...] closing the loop of the material is the most important objective of being transparent. Moreover, disposal information can be a component of traceability information which can help the consumers at the end of the product's life." Despite differences in opinion, information in the two clusters (C1 and the first half of C2) are close to each other in the aggregate results and among the most important elements.

In the latter half of C2 is information related to product quality and specifications, such as 'quality certification', 'audit reports', 'test procedure/reports', and 'inbound and outbound product specifications', and are among the important information elements. Based on the level of traceability and information storage capacity of the traceability system or tag, brands or retailers can choose to share this information with customers and end users.

Finally, in the last cluster, and among the less important traceability information for customers, are those related to 'costing' and 'tracking', and process-related elements like 'machine ID', 'timestamp', 'sales', and process details. As per one of the experts, "[...] customers do not require timing, tracking and sales data. It can be important for B2B sharing purposes."

It is understandable from Figure 5 that at the B2B level, 'inbound and outbound material specification', 'quality certification/audit', 'lot number', and 'tracking data' are considered very important to be recorded and shared, along with traceability information related to 'manufacturer and supplier details', 'origin', and 'composition' (that were also among the most important ones for B2C). Previous studies have also advocated the importance of this information in order to have better

visibility, accountability, and control over the supply chain activities [2,30,34]. Traceability information related to all the suppliers across tiers (i.e., tier 2, and even 3) should be recorded and shared with all supply chain partners. Moreover, as stated by one of the experts, “incomplete or improper specification leads to quality issues and problems in production”.

Product quality and social-environment sustainability were clustered in C2. As mentioned before, based on the traceability level, supply chain actors can choose to share this information with all supply chain actors. It was observed that information related to social and environmental sustainability fall in the second important cluster, rather than the most important one as in B2C level.

Finally, in the last cluster the least important set of information for businesses is almost the same as that for the B2C level. This consists of information related to ‘product costing,’ ‘sales data’ and process related to ‘machine ID,’ ‘timestamp,’ ‘sales,’ and process details. Usually, businesses find it unsafe to share such sensitive data, primarily related to cost and sales, in order to maintain their competitive advantage [32].

5. Conclusions

This research is one of the few that empirically investigates key factors and their level of influence in implementing traceability in TC supply chains. It is also unique in classifying essential information in a traceability system that is needed to record and share among various stakeholders in the TC supply chain. In line with the RQs posed, two specific contributions emanate from this study. First, a list of a wide range of factors and essential traceability information were explored from the literature, which was then validated via a Delphi-based survey with leading experts in the field to attain consensus. Secondly, with the data obtained, the factors were further ranked, and traceability information was classified using hierarchical clustering. It can be observed that factors related to supply chain security (risk management and product authentication) followed by visibility, quality (quality monitoring, market surveillance, and recall management), and marketing have the highest impact and major influence in traceability implementation in the TC supply chain. Among the information, ‘product information’ (related to composition, origin, manufacturer details), and ‘social/environmental information’ (related carbon footprint, environmental/social certification, and recycling data) are the elements that must be shared with customers. Product information (related to composition, origin, and manufacturer details), quality information (related to audit reports and test reports), and process information (related to process details, tracking, and specifications) are the elements that must be shared among businesses in the supply chain.

5.1. Research Implications

The study contributes to traceability research by exploring and ranking the factors influencing its implementation and the traceability information essential in TC supply chains. It works towards solving some of the major concerns (as stated in [6,62]) related to traceability systems in the TC supply chain for stakeholders and policy makers. The outcome of the study can be useful for a number of reasons. (i) The supply chain actors can determine the information that is needed to be linked with different traceability systems and that can be shared with customers, also indicated in [16]. (ii) The supply chain leaders or fashion brands can refer to the study for traceability-related decision-making and in determining the extent of traceability in their supply chain. (iii) The study can aid the policy makers in setting traceability rules and regulations. Finally, (iv) it can influence the customer to make ethical buying decisions [63,64].

In terms of advancements made in scientific research, the work can support the development of a blockchain-based traceability framework for the TC supply chain, as proposed in [16,65]. The blockchain technology stores the entire database across different nodes of the blockchain system; therefore, storage of minimum essential information is advisable for an effective and energy-efficient system. Essential traceability factors can also be useful for the development of an innovative business model based on blockchain technology. Through interesting qualitative inputs from experts

belonging to top-level management, it can be perceived that implementing traceability and sharing sustainability-related information could lead to competitive advantages and can contribute to strategic management literature, e.g., to reduce information asymmetry in supply chains [16]. For instance, in literature related to the food supply chain, it is supported in [32].

5.2. Limitations and Future Research

Commonly in Delphi study, the choice of panelists from a specific industry, as in this paper, can challenge the generalizability of the results in the larger supply chain context. However, as mentioned earlier, such sector-specific research is of significant importance and required in order to answer the RQs [11]. Another limitation is potential biases in the Delphi panel selection. However, following guidelines by [24] and referring to [25], it is unlikely that another panel would reach entirely different agreements.

Additionally, it can be noted that “why” and “how” questions were not addressed. Detailed explanations of the ranking or clustering, and how a factor influences traceability or how recording and sharing of particular information would affect traceability, were not covered. In future research, the findings can be used to (a) do an in-depth qualitative work, e.g., via interviews to address the above-mentioned “why” and “how” questions; (b) look into traceability through various strategic theoretical lenses, e.g., information asymmetry; and (c) incorporate more developmental research related to understanding the design issues and performances of traceability systems [16] with the results of this study.

Author Contributions: T.K.A. collected the literature, conducted a Delphi study, analyzed the results, and wrote the manuscript. R.P. contributed to methodology development and refinement of the manuscript. All authors read and approved the manuscript.

Funding: This work has been comprehended in the framework of Erasmus Mundus Joint Doctorate Project—SMDTex (Sustainable Management and Design for Textiles), which is financed by the European Commission.

Conflicts of Interest: The authors declare no conflict of interest.

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Paper III

Agrawal, T.K., Koehl, L., and Campagne, C. (2018), “A secured tag for implementation of traceability in textile and clothing supply chain”, *The International Journal of Advanced Manufacturing Technology*, Vol. 99 No. 9, pp. 2563–2577.



A secured tag for implementation of traceability in textile and clothing supply chain

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Received: 25 March 2018 / Accepted: 22 August 2018
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Abstract

Textile and clothing industry is one of the oldest manufacturing industries and is a major contributor in the economic growth of developing countries. However, from past few decades, it has been criticised for its opaque, unsecured and untraceable nature of supply chain. Addressing these challenges, the paper proposes a system approach to introduce an item-centric secured traceability concept to monitor and control manufacturing processes and supply chain activities. In order to implement such secured traceability system, the paper describes the process for manufacturing, encoding and validating an innovative two-factor secured tag based on particle randomness that is printed on the surface of textile. Being micro-sized, the particles are easy to read and validate with pattern recognition. Further, as achieved through an uncontrolled manufacturing process, the randomness is unclonable to produce counterfeit tags. Furthermore, a sequence of experimental analyses has been conducted using various simulated scenarios to verify its applicability. A secured tag can be a low-cost and durable substitute for detachable, unsecured identifiers commercially available in the market.

Keywords Supply chain management · Manufacturing · Traceability · Textile and clothing · Secured tag

1 Introduction

Supply chain transparency and security have emerged as key concerns for various industries. With growing number of ethical issues and increasing counterfeits, it has become a necessity to make the supply chains more secure and transparent [1–3]. Textile and clothing (T&C) supply chain is one such example. Complex supply chain structure with large geographical distance among actors has made the T&C sector one of the most opaque and vulnerable networks [4]. Although all T&C supply chain partners are linked together as a network, yet, they do not have sufficient information

about their supply chain. Owing to this, suppliers and other involved actors use unethical means of production and distribution, which have resulted in several catastrophic events in the past. This has distressed the governments and drew their attention towards the sustainability issues in T&C industries [5].

Security and counterfeits are other major concerns of the T&C supply chain [6]. According to McMillen et al. [7], manufacturing industries including T&C have experienced a high level of security issues in past few years. In the European Union (EU), T&C sector has lost more than EUR 26 billion of revenue in the years 2010–2011, resulting in approximately 500,000 direct and indirect jobs and EUR 17 billion sales loss in the related sectors [8]. Unlike other sectors, the problem of counterfeits in T&C supply chain is not only limited to the final product. It is also a major concern in the intermediate products [6]. The fake products not only result in financial losses for the companies but also endanger the health and well-being of the end users [9].

Adoption of a secured traceability system has emerged as a possible solution to overcome the aforementioned problems [10, 11]. Traceability is a key concept related to all types of products and supply chains [12]. It is an item-centric approach for tracking and tracing a product [13]. It generally uses a unique identifier tag (such as RFIDs, QR

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codes and barcodes) assigned to each traceable unit. The tags track the products at various levels of the supply chain. However, they are often detached, removed or deactivated at the point of sale due to privacy concerns [14]. Moreover, most of the tags can easily be replicated and do not have any security mechanism for authentication. As a result, the T&C market is vulnerable to unsafe, counterfeit products, and often, the internal operational information cannot be recalled which may expose the end users to serious security concerns. For instance, clothing is one of the most recalled products [15], albeit only a small fraction of items are taken back from market due to lack of traceability. In this direction, barcodes (such as linear barcodes and QR-codes) are generally used to track products in the supply chain. On one hand, the barcodes are relatively cheap to manufacture and implement [16], they do not create privacy concerns (unlike RFID) on the other hand [17]. Moreover, linear barcodes and QR codes are eco-friendly and degradable [16]. With selection of appropriate printing mechanism and ink, they can be made waterproof and durable. These characteristics make them appropriate for application in T&C product.

In the context of implementing secured traceability, the present paper introduces a two-factor product authentication and tracking system for T&C supply chain. With the view of securing the existing QR code, a random particle-based secured tag as an additional security layer has been introduced. The unique and random feature of each secured tag is associated with the corresponding QR code. This combination acts as a key to unlock the traceability code, authenticates the product and traces its history. Unlike widely used detachable RFID and barcode tags, the proposed system is to be integrated onto the surface of the textile product. This makes the tag almost inseparable, preventing loss or replacement with counterfeits in the supply chain. Produced by conventional textile printing mechanism, the tags are anticipated to be of low-cost and easy to manufacture on a large scale. This can be one of the useful contributions to the T&C supply chain with low-cost product wherein a slightly higher investment in the traceability technology can increase the final product cost and reduce profit margin. Particle randomness generated during printing process with no control on the distribution acts as a unique feature for each product, which is hard to replicate. This randomness is read and encoded as a secured code to access the product database through the QR code and prevent it from cloning. To prove the uniqueness and evaluate its performance, a series of experiments have been conducted which simulate various mechanical agitations that a textile tag usually undergoes during its use phase. Although the proposed system is developed for T&C supply chain, the methodology can be used for other similar supply chains.

2 Literature review

According to (ISO 9000:2015), ‘Traceability is the ability to identify and trace the history, distribution, location, and application of products, parts, materials, and services. A traceability system records and follows the trail as products, parts, materials, and services come from suppliers and are processed and ultimately distributed as final products and services’. It has multiple benefits including transparency, enhanced quality perception, and better control of the material flow [18, 19]. Traceability is a useful tool to overcome challenges in an omnichannel retailing and to reduce the risks in supply chain by identifying the upstream source and downstream recipients in real time. It further helps in decision making, product recall, recycling and remanufacturing. Its applications can also be explored for shared economy business models where traceability can act as an authenticating mechanism and information related to the history, origin, date of purchase, etc. could be shared at customer-to-customer level.

A significant research has been carried out in the past to develop various technologies to prevent counterfeiting and/or tracking and tracing the product in a supply chain [20–22]. There are *authentication technologies* that aim to identify counterfeits without tracing the product footprint in the supply chain. On the other hand, there are *track and trace technologies* which are used for locating the products within the supply chain. It relies on tagging each product or group of products with a unique identifier such as RFIDs and barcodes, and then these identifiers are used as a tracing element. However, due to lack of security mechanism, these identifiers are cloned or replicated and then used with counterfeit products [23]. As a result, track and trace systems cannot rely solely on traceability tags and requires an additional security mechanism for authentication and prevention of unauthorised reproduction/cloning [10]. Such system is often known as a ‘secured traceability’ system [11] and can be found in food, pharmaceutical, cosmetics and luxury product supply chain [10, 11, 24]. Table 1 provides an overview of the various technologies and their pros and cons with respect to product authentication, tracking and security.

In general, the security mechanisms in a secured traceability system are applied at two levels; first, at a product level, where authentication and traceability are ensured by identification and tracking of each product using unique feature-based secured traceability tags; second, at a business level, where information flow is controlled and secured by using mechanisms such as ‘circle of trust’ and ‘block chain’ [10].

Given the peculiarities of the T&C supply chain, the traceability requirements are special and it cannot use off-the-shelf solutions in the market [40]. Durability, clonability and detachability of the traceability tags are some of the major issues in T&C products [4]. A secured traceability tag for textiles should have security

Table 1 A systematic overview of various technologies for traceability

1. Authentication technology Feature-based identification techniques are useful for differentiating the original product from counterfeits [21]. These are most widely used technologies for product authentication but do not support product tracking. Moreover, most of these technologies required sophisticated and expensive equipment or an expert with discerning eye for product validation	
1.1 Direct authentication Inherited physical, chemical or visual properties, e.g. diamonds, leather goods, gems etc. [25–26]	1.2 Security features based authentication Externally added features [25] that can be a) Overt: Visible to the naked eye and vulnerable to attack, e.g. holograms and micro-engraving; b) Covert: invisible to naked eyes, requires a special device for authentication, e.g. digital watermarking, ultraviolet (UV) sensitive inks and c) Forensic: Chemical or biological features, required sophisticated instruments for reading and analysis [27–29]
2. Track and trace technology Based on the principle of unique identifier in the form of tracking tags [30], track and trace technologies are extensively used for freight tracking in logistics operations. These are mature technologies with relatively low investment, high readability and with high level of standardisation. However, they are extremely prone to counterfeiting or illegal reproduction	
2.1 RFIDs Contactless, electronic tags consisting of an electronic microchip for data storage and antenna for communication [31]. Find wide application due to its long-range readability, small size, low-cost and high memory storage; however, they can easily be cloned, requires a special device for reading, and are usually removed or deactivated at the point of sale to prevent privacy issues	2.2 Barcodes/QR codes Machine-readable optical pattern used for data representation. Printed or attached in the form of labels or stickers, are a systematic arrangement of codes describing something about the associated product. High readability and low cost, find wide application in fast-moving commercial products. However, they can be easily copied and applied to counterfeit products and lack authentication method [17] 2.3 Miscellaneous Magnetic strip cards, magnetic ink character recognition (MICR) code or magnetic barcode are some examples of other miscellaneous technologies useful for product tracking. They are remotely sensed and decoded using magnetic sensing technologies. Find application in the packaging industries, banks and in transportation industries in metro or tram tickets [32]
3. Secured traceability technology Technologies that can track and trace product and capable of authenticating the brand or product identity without the threat of easy clonability. Presently, most of the secured technologies are relatively expensive and used in high-value product with more profit margins. They also find application in pharmaceutical or food products, contamination or counterfeiting of which can lead to serious health consequences	
3.1 Secured RFIDs a. Watermarking and RFID-based self-validation system (WARDS): two-factor authentication system. Uses scanned watermark information from labels along with product's identification code from RFIDs as a two-factor authentication system [21] b. Physical unclonable function (PUF) based RFIDs: RFID IC chip equipped with PUF to prevent product clonability [33] c. Fingerprinting RFID tags: prevent cloning by using physical attributes or features based on minimum power responses measured at multiple frequencies [34] d. Other examples can be found in [35, 36]	3.2 Secured barcodes/QR codes a. Cryptographic barcode [6] for traceability and brand authentication in the textile industry. Printed directly on the surface of textile and tested against deformation due to the unstable textile surface b. QR code and a digital signature [16] for fishery product. The system uses weight of individual fish as their digital signature c. Microtaggant [24]: lithographically fabricated to consider the QR code pattern for traceability on pharmaceutical industries 3.3 Miscellaneous a. Yarn-based traceability tags by [37] used yarn-based feature to secured traceability system b. Permanent sub-surface tattoo [38] developed for leather products for traceability and counterfeits reduction c. SigNature® T [39] protects the product using unique molecular-based tagging of each textile and clothing product.

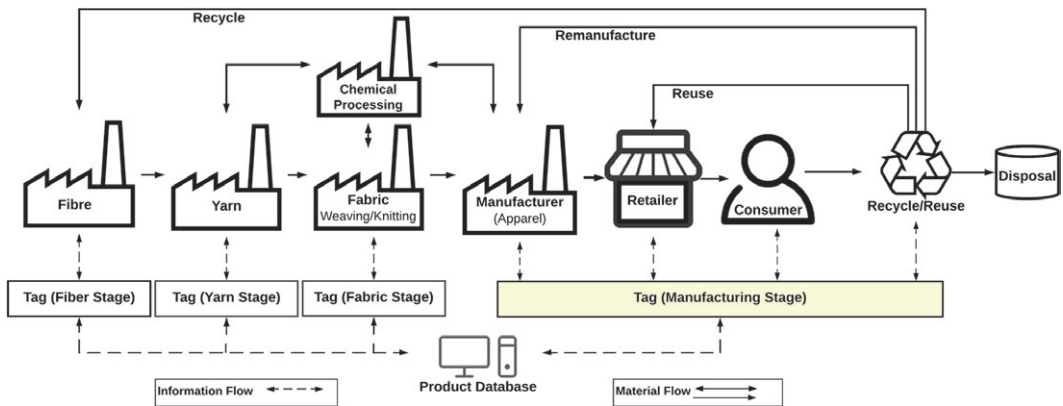


Fig. 1 An ideal secured traceability system for T&C supply chain

mechanism preventing the easy and unauthorised reproduction of tags. However, at the same time, it should be *durable* to withstand mechanical agitation during washing and abrasion. It should also be *integrated* onto the flexible textile product to prevent the disintegration of tracking tag. Finally, taking into account the usual low cost of textile product, the developed solution should be *inexpensive*, *eco-friendly* and *readable* by a readily available device to allow the customer to authenticate and trace the product.

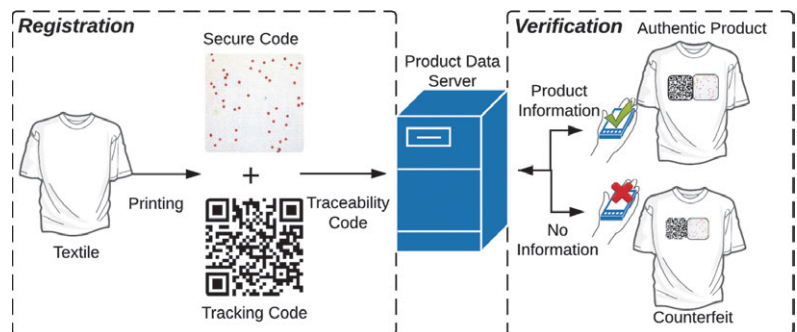
3 Ideal secured traceability system

As aforementioned, traceability is an item-centric approach tracking, tracing and connecting each physical product with their information. Within this context, traceability tag plays a crucial role in uniquely identifying the products and acts as an information-recalling agent. However, from a practical point of view, a tag also acts as the weakest point while implementing a secured traceability in the

supply chain [23]. The whole traceability system can be compromised if the tag is copied, washed away or detached. In an ideal secured traceability system, each product should be tagged with a secured tag. These tags should be hard to replicate, easy to integrate in the product or developed using inherent features and should remain with the product throughout its life cycle. For such a system in T&C supply chain, since the material lots are combined and transformed into new materials with changed physical or chemical characteristics; therefore, a single tag may not be sufficient to cover the complete supply chain.

As shown in Fig. 1, these secured tags should be integrated with the product/intermediate product at each supply chain stage before it passes to the next downstream level. Thus, each tag acts as a link to access the product data management system, responsible for stacking data in a time-based function, as the product passes through different life cycle stages. This database system must retain and should include the data related to current stage and that received from previous stages. Finally, the

Fig. 2 Tag registration (mapping of code with QR code) and verification process



tag integrated at the final manufacturing stage should incorporate the manufacturing data and data from all previous stages.

The current study focuses on the secured tags that must be integrated on each textile product during the manufacturing (apparel production) stage before it passes to the retailer and finally to the customer. Design and concept of such integrated secured tags are presented in the following section.

4 Concept and design

4.1 Concept

According to Oxford Dictionary [41], security can be defined as ‘procedures followed or measures taken to ensure the security of a state or organization’. One such measure to ensure the security of a physical entity consists of introducing features or markers that cannot be replicated or altered, and any attempt to tamper them leads to noticeable changes. These markers or features are usually introduced directly on the surface of the product through direct part marking (e.g. [42]) and act as a unique identifier to track and trace the product throughout the life cycle. Within this context, the study presents a novel methodology for the development of a secured tag or unique identifier for T&C supply chain. To develop these, micro-sized particles are mixed with printing paste and then screen-printed on the surface of the fabric. The natural positioning of the particles on the fabric surface forms a random and unique distribution on each product. These random distributions are characterised and converted into security features. It primarily has two advantages. Firstly, the use of conventional screen printing (which is a mature manufacturing process with low capital cost and find wide applications in surface functionalization; for example, see [43]) and commercially available printing materials, which are widely used. Selection of such printing mechanism and material does not significantly influence the production process. It generates value from the existing technology with possible low implementation cost. Secondly, the position of the particles cannot be controlled during the printing process; therefore, practically, it is extremely difficult—if not impossible—to control the position of each individual particle while printing on the fabric surface. This provides an extraordinary advantage as no one can replicate the positioning of the particles through a controlled process, thus acts as a strong security feature. In order to implement it, the positioning of particles has to be mapped with 2D QR code, i.e. QR code would retain the information related to the positioning of the particles and the tracking code. As shown in Fig. 2, for verification, the information of particle positioning and tracking code associated with QR code should match with that of particle position printed on the textile

surface and this correct mapping will only be possible for an authentic product.

It can be noted that the particle positioning can be either directly stored on the tag or indirectly on a server with reference to the QR code.

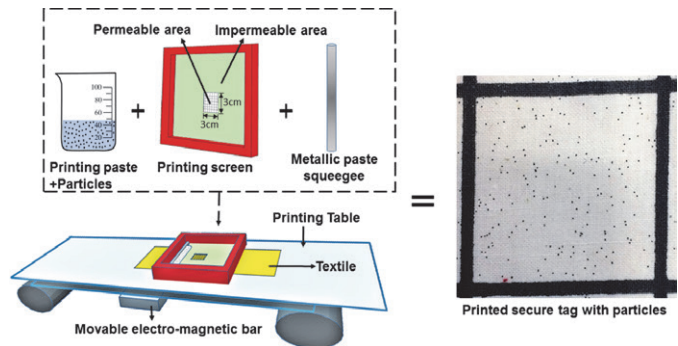
4.2 Design

The design of the secured tag is inspired from the coating Physical Unclonable Function (PUF) generated using explicitly introduced randomness. Widely used in the integrated circuit chip manufacturing industries to prevent counterfeits, these PUFs are easy to evaluate and read but hard to replicate [33]. The randomness acts as a fundamental building block of the cryptographic system and plays a crucial role in generating a strong secured communication key [44]. Therefore, randomness similar to PUFs is generated by scattering micro-particles in a confined area, on the surface of textile by an uncontrolled process. This type of security mechanism does not give control of code generation and security to a single trusted party or dependency on a single special product (e.g. special ink and microfiber); on the other hand, it would cast traceability onto the product (e.g. [45]). Therefore, the same tag cannot be reproduced even by the original manufacturer. Moreover, with an inconsistent concentration of the micro-size particle in relatively high tag area (in a few square centimetres), numerous tags can be printed with a very low probability of reproducing the same particle positioning again. The particle distribution on the secured tag is located using image-processing tools that are frequently used in surface classification and identification technologies (one such example can be found in [46]). Further, two distinct features (strong particle clusters and empty areas location, further explained in the ‘Methodology’ section) were extracted using particle locations and encoded to form the secure code. These innovative features take into account the flexible nature of textile surface, the durability concerns and also possible tampering of code through particle addition or erosion. Besides, use of image-based characterisation makes the secured tag readable by the smartphone-based camera, thereby giving customers the power to trace back the history of the product and making the supply chain more transparent and visible.

5 Methodology

The methodology followed in this study involves the printing of the secured particle-based tag (from hereafter referred as ‘secured tag’) on the textile surface, image of which is captured using smartphone, followed by processing of these images through image-processing algorithm to extract the tag features. Later, these features are registered, taking into account the flexible, unstable and non-uniform nature of textile surface, through a fuzzy membership function to get a code

Fig. 3 Magnetic table and screen printing setup adopted in the current study



and mapped with the QR code. The current study focuses on particle-based secured tag, whereas printing of QR code is already a mature technology.

5.1 Screen printing of secured tag

Secured tag is integrated on the textile surface through screen printing mechanism and textile printing paste. Screen printing is a stencil printing method in which

printing paste or ink is squeezed through a fine mesh (made up of synthetic or metallic fibre) onto the fabric surface, except the areas that are made impermeable by the blocking stencil. The printing paste is formulated by mixing micro-sized dark glitter particles (sourced from Geotech International B.V., Netherlands) with a commercial textile binder in a fixed weight-by-volume ratio. First, a square frame of inner area 3 cm × 3 cm was printed on the textile surface using black ink on a light-coloured fabric. (Relatively, a larger area of the tag will increase the possibility of numerous distributions and decrease the probability of generating same distribution). On the other hand, corner points of the black frame help in easy and fast detection of the quadrangles of the tag by referring to only a few pixels instead of the entire captured image [47]. It is also useful to determine the transformation caused by scaling, rotation and translation during the image-processing operations [48]. Printing paste (with micro particles) is then squeezed through the screen onto the fabric area inside the empty frame. The binder being almost transparent does not impart any colour to the light background; however, it strongly holds the particles onto the surface of the textile. This makes a good colour contrast that can easily be detected and captured in a digital image. For constant and uniform placement of the printing paste, an automatic squeezing mechanism was adopted using a magnetic table as shown in Fig. 3.

It should be noted, for commercial processes with large batch size, fully automated rotary screen printing can be adopted to reduce the process time.

5.2 Tag encoding and validation mechanism

As illustrated in Fig. 4, the tag encoding and validation mechanism followed mainly two steps. First set of steps were carried out to pre-process the image and extract the area of interest (particle area) followed by membership calculation (optical feature extraction and defining decision support system) and finally the validation step, where

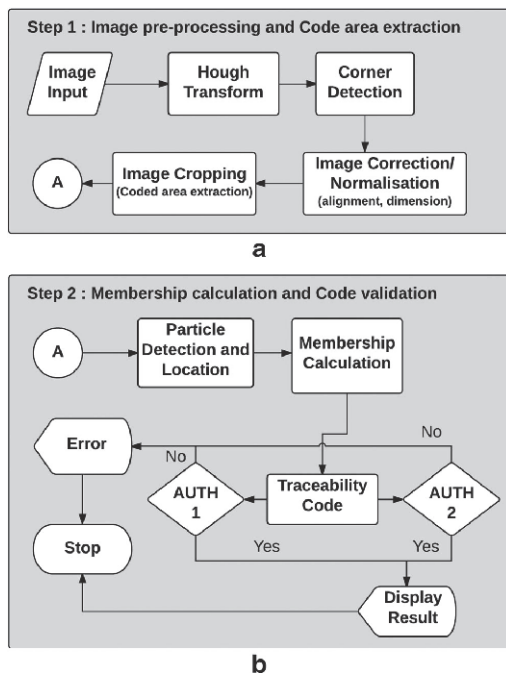
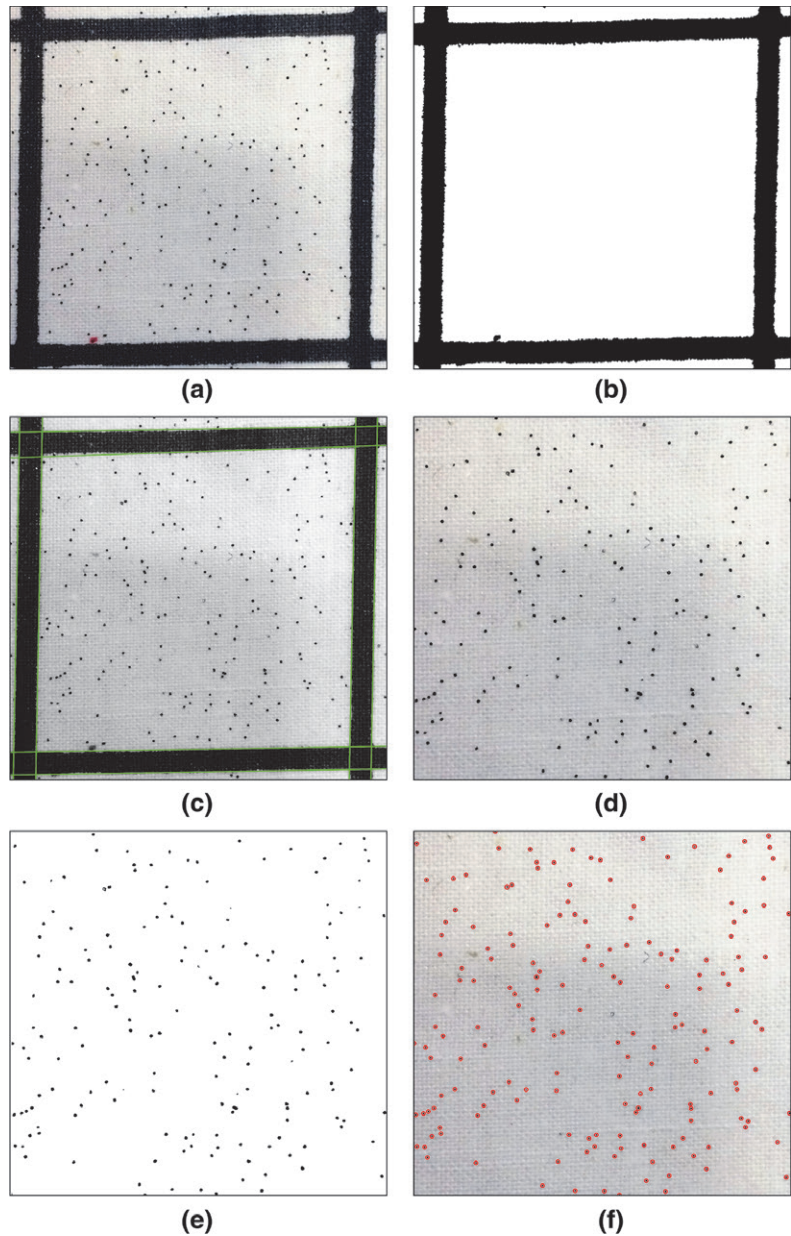


Fig. 4 Flow chart for tag encoding and validation mechanism. **a** Steps for image pre-process and code area extraction. **b** Steps for extracting the features, calculating the membership and validating the code

Fig. 5 Image obtained during different stages of encoding and validation process. **a** Original. **b** After correction, Otsu thresholding, and flood fill operations. **c** After Hough transformation. **d** Cropped image (area of interest). **e** Particle detection. **f** Particle location (after CHT)



the particle mapping (AUTH 1) is matched with QR code (AUTH 2) to authenticate and trace the product. It should be noted here that image pre-processing, code area extraction, particle detection and location steps would remain common for encoding and validation mechanism.

5.2.1 Image pre-processing and code area extraction

Image pre-processing is an important operation involving improvement of image data to suppress unwilling distortions and enhance image features that are important for further

processing [49]. Mainly two groups of operations are applied to the captured image during this step. The first set of operations involved morphological operators and linear contrast adjustment to correct the non-uniform illumination [49]. These are general methods applied by estimating the properties of degradation and evaluating image pixels during processing. The image was then converted to greyscale before further processing. The second group of operations was dedicated to detecting the quadrangle frame and its corner points followed by extraction of inner tag area printed with particle. For this, a copy of the processed greyscale image is converted to binary images using Otsu method (Otsu [50]). Otsu's method is a histogram threshold method that assumes the pixels of the image consist of classes, i.e. background and foreground, and calculate optimum threshold t separating the two classes. Thus, the greyscale 2D image in Cartesian plane with coordinates (x, y) and pixel intensity $I(x, y)$ is converted to binary image $B(x, y)$ with intensity 0 or 1 based on the derived threshold t where,

$$B(x, y) = \begin{cases} 0 & \text{if } I(x, y) < t \\ 1 & \text{otherwise} \end{cases} \quad (1)$$

This was followed by flood fill method [51] to remove all the unwanted background (including the particles) to extract only the frame. Flood fill algorithm checks each pixel in an image and analyses the connected area. It removes any unwanted noise by filling/changing the intensity of the pixel to be the same as the intensity of the majority of neighbour. As a result, image in Fig. 5b is obtained.

Further, *Hough transformation* [52] was applied to the obtained image to detect straight lines of the frame and thereafter the corner points, as shown in Fig. 5c. In Hough transformation, all the high-level pixels of a binary image are converted to polar coordinate (r, θ) form 2D Cartesian coordinate (m, n) following relationship:

$$r = m \cos \theta + n \sin \theta \quad (2)$$

Such that θ is confined between $[0, \pi)$ and results in forming a unique Hough's peak/points on the polar plane for all mutually linear points in the Cartesian plane. However, in practice, due to geometric distortions, the location of the corner might change from initial to subsequent readings. Therefore, 2D *projective transform* [53] was performed along the detected corner points of the tag on the initial greyscale image to normalise it by correcting the alignment and scaling it down to a fixed dimension. Finally, the normalised image was cropped along the corner points to extract the actual area of interest, i.e. particle area as shown in Fig. 5d.

5.2.2 Particle location detection

After pre-processing operations, histogram-based *intermode thresholding* [54] was applied on the cropped

image to extract the particle by subtracting the background (consisting of light colour textile), as illustrated in Fig. 5e. The input in this process was a greyscale image for which a histogram of the pixel intensity values (ranging from 0 to 255) was plotted and iteratively smoothed until only two peaks remained. The threshold value lies in the midpoint of the two peaks or the minimum point between the peaks corresponding to low-intensity white background pixels and high-intensity pixels with particles [55]. After identification of particles, in order to locate the center coordinates of particle, *Circular Hough Transformation (CHT)* [52] was applied on the obtained binary image. The resultant image is shown in Fig. 5f. CHT is similar to the standard Hough transform; however, the later tries and searches for circles in the given image between a predefined range of radius. Due to this predefined radius range (derived from calculating the average particle size and standard deviation), it is easy for the algorithm to differentiate two or more close or connected particles.

5.2.3 Membership calculation

After determining the location of each particle, two key features were extracted. The first key feature was the location of the strong clusters of the particles. In other words, areas in the tag where particles are very close to each other having a strong degree of belongingness in the cluster. The second feature was the locations of empty areas in the tag, especially the largest empty areas. It should be noted that these two features are inter-dependent. Any attempt to copy the features is made by increasing or decreasing the concentration of particles in the tag, one of the two features will vary significantly. There should be a balance between the two features that has a high probability to be present only in the original/authentic tag.

1. Locating strong clusters of particle

Initially, all the particle locations (observations) were divided into k predefined optimum clusters based on their location (Euclidean distance) using k -means clustering algorithm described below.

$$\arg \min_s \sum_{j=1}^k \sum_{x \in S_j} \|x - c_j\|^2 = \arg \min_s \sum_{j=1}^k |S_j| \text{Var } S_j \quad (3)$$

$$\arg \min_s \sum_{j=1}^k \frac{1}{2|S_j|} = \sum_{x, y \in S_j} \|x - y\|^2 \quad (4)$$

$$\sum_{x \in S_j} \|x - c_j\|^2 = \sum_{x \neq y \in S_j} (x - c_j)(c_j - y) \quad (5)$$

where x = observation (particle coordinates), c_j = centroid for the cluster j and S_j = set of particle location in j cluster.

The value of k is obtained through *Elbow method*. During clustering, given set data is divided into groups of similar elements; however, there are set of data that have high fuzziness or uncertainty of belongingness to allotted cluster/group. Similarly, in case of k -means clustering, the data points on the edge of the clusters will have a high probability of lying in the neighbourhood cluster. Hence, it becomes an important criterion to locate and store the strong clusters removing out all the outliers. Therefore, to eliminate all the outliers or points with high uncertainty of belongingness, the following steps were taken:

- Data from each obtained clusters were segregated and treated separately.
- Euclidean distance between each data point and cluster centroid was calculated.
- Area of the largest circle with the centre as the centroid of the cluster and radius equal to the distance of most distant particle in the same cluster was calculated.
- Graph of percentage increases in the area of the circle (from 0 to 100%, i.e. the area of the largest circle, at an interval of 10) against a cumulative number of particles within given area was plotted.
- The bending (elbow) point of the curve was calculated and the percentage area against it became the threshold area for the new cluster. Value of radius corresponding to the threshold area became the new largest radius.
- The centroid of the previous cluster later shifted to the centroid of the new cluster with reduced points.
- The radius and centres of all the k cluster were selected as part of the code.

Abovementioned steps were applied on the particle locations obtained from the image in Fig. 5f. These locations were divided into five clusters (marked with different symbols in Fig. 6), and later five strong clusters were extracted (encircled in Fig. 6).

The main reason for considering the location of strong particle cluster as an encoding feature is to avoid dependency on the location of a single particle. Therefore, even if some are eroded or added (noise), the average membership of the particles in the respective cluster should not vary significantly.

2. Locating empty areas

A more logical and systematic approach of locating and encoding empty area is to find the largest circle which can fit in that empty area without any particle inside. For this, Voronoi diagram and Delaunay triangulation methods were opted [56]. Delaunay triangulation, which is a popular computational geometry method of subdividing a given 2D Euclidean plane with a finite number of points in it into triangles such that none of the points on the given Euclidean plane, lies inside the circumcircle of any triangle. Voronoi diagram of a set of points is dual to its Delaunay triangulation.

For K different points in the 2D space, R^2 the Voronoi cell $V_k(i)$ of k_i is denoted by:

$$V_k(i) = \left\{ q \in R^2 \mid \|q - k_i\| \leq \|q - k\| \text{ for all } k \in K \right\} \quad (6)$$

After applying Delaunay triangulation, radiuses and centres of all the distinct circumcircles with no overlapping areas

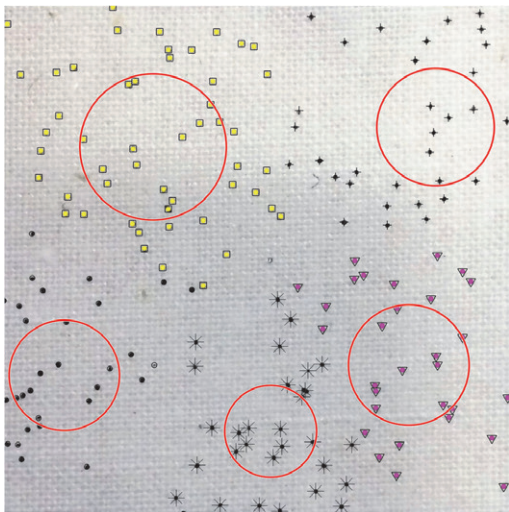


Fig. 6 Particles in different clusters marked with different symbols with circle enclosing the newly formed cluster

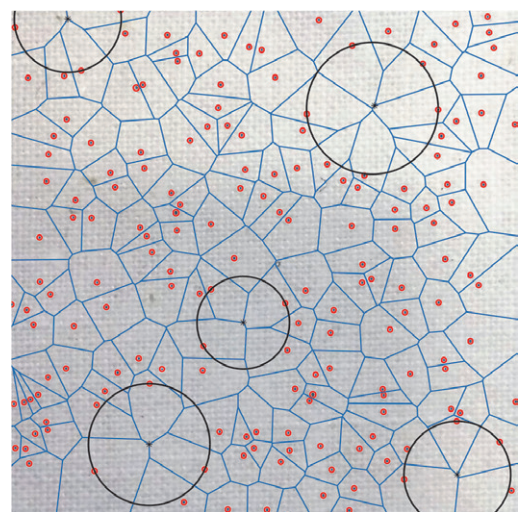


Fig. 7 Partition of the image plane into Voronoi cells and five largest circles, encircling the five biggest empty spots in the image

were recorded and top k largest circles (same as the optimum number of clusters obtained through Elbow method) were selected from them as a part of the optical feature. Figure 7, illustrates the application of Voronoi diagram on the particle locations obtained from the image in Fig. 5f and location of five biggest empty areas encircled in Fig. 7.

5.2.4 Decision support system for tag feature encoding

For an effective and fast decision support system (DSS) algorithm, it is not necessary to match exactly the true pattern with subsequent reading; rather, it should compute the difference between distributions of correlated like pattern with that of unlike pattern. Moreover, taking into account the flexible, non-uniform and uneven textile surface, while defining a membership function, it is necessary to incorporate some tolerance. In this direction, fuzzy set principle introduced by Zadeh [57] using the concept of similarity of inputs instead of crisp values were used to define and assign a fuzzy membership function to these features. Membership function $f(x)$ is a function that assigns, to every number x , the degree $f(x)$ $[0;1]$ to what this number satisfies the corresponding property. For example, in the proposed secured tag, the degree to which the obtained feature will belong to the original code while decoding. For the current study, one of the most frequently used trapezoidal membership function was selected. As described in the previous section, the location particles of the strong cluster and the empty areas are encircled and referred by the centre (c) and radius (r) of the circle. Therefore, the trapezoid membership $f(x)$ is defined as:

$$f(x) = \begin{cases} 0 & \text{if } x > r \\ 1 & \text{if } x < \frac{r}{2} \\ -\frac{2x}{r} + 2 & \text{otherwise} \end{cases} \quad (7)$$

where x is calculated as the Euclidean distance of the particle from the centroid of the cluster, i.e.

$$x = \sqrt{(a_0 - a)^2 + (b_0 - b)^2} \quad (8)$$

such that (a_0, b_0) are the coordinates of the cluster centroid and (a, b) are the position of a particle. Since there are more than one particle in each cluster, the average membership of the cluster (μ) is calculated as:

$$\mu = \frac{\sum_{i=1}^n f(x_i)}{n} \quad (9)$$

where n is the total number of particles and $f(x_i)$ is the membership to the i^{th} particle in the cluster. Moreover, since each tag consists of multiple clusters, the membership of all clusters can be represented as μ_i , $i \in \{1, k\}$ where k is the total number

of clusters. In order to increase the robustness of DSS and avoid ambiguity and uncertainty, individual membership of two optical features extracted in the previous section was aggregated. For the first feature, membership of each particle as per their location in the respective cluster was calculated and average membership values of each cluster were added to get the final membership of the first feature (strong clusters). For the second feature (empty area), the initial membership value will remain zero, as there will be no particle inside while encoding. However, while decoding, the membership value may vary due to deformation.

5.2.5 Membership difference for code validation

The membership difference is calculated as:

$$d = \sum_{i=1}^k |\mu_i^o - \mu_i^T| \quad (10)$$

Such that μ_i^o represents the membership of the i^{th} cluster for the original tag and μ_i^T represents the membership of the i^{th} cluster of the tested tag. It should be noted that the coordinate points of the clusters and their average membership value of the original tag should be stored in order to make a comparison as shown in Fig. 8.

6 Experimental

As mentioned before, in practice, unavoidable variations can occur in the initial and subsequent reading of the tag due to variations in camera, image resolution, light intensity, light temperature, etc. The most common variations that can occur in such textile-based tags are particle erosion due to washing or abrasion during textile use phase, pattern deformation due to elastic nature of textiles, noise (in form of migrated particle or foreign particle/lint) and alignment variation due to inappropriate handling of the camera while decoding. Therefore, to test the developed system for these variations, 50 different tags were printed. Images of these tags were captured with

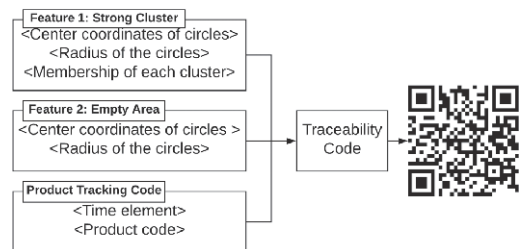
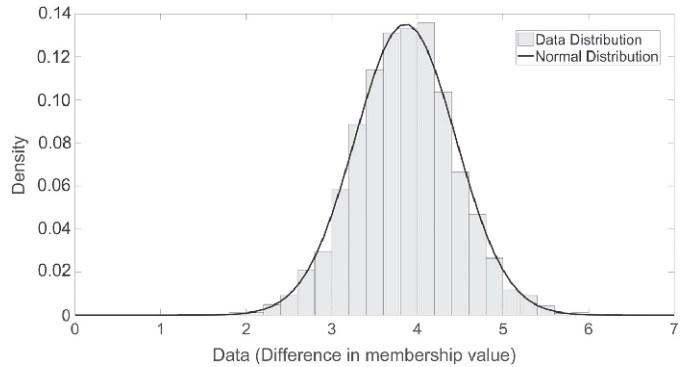


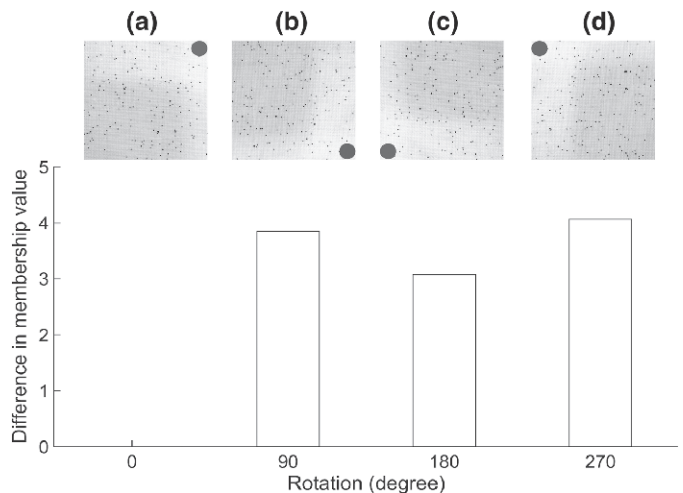
Fig. 8 Different parts of the traceability code that would be encoded and printed as QR code on the textile surface

Fig. 9 Variation of membership difference for inter-tag analysis

digital camera and processed using MATLAB 2015b as per the methodology explained in the 'Ideal secured traceability system' section. Variations were introduced synthetically followed by image decoding operation to verify the tag identity. Results obtained after decoding each tag were compared with the actual authentic code and with other 49 codes of different tags to validate the code and test the randomness.

6.1 Inter-tag analysis

An initial experiment was conducted to prove the uniqueness of each tag and estimate an average membership difference between two unlike tags. Membership code of each tag was applied on itself and on the other 49 tags. Frequency distribution of membership difference of 2500 possible combination thus obtained was plotted, to estimate the average and standard deviation value.

Fig. 10 Difference in membership value of the original tag and membership obtained when it is rotated by **a** 0°, **b** 90°, **c** 180°, and **d** 270°

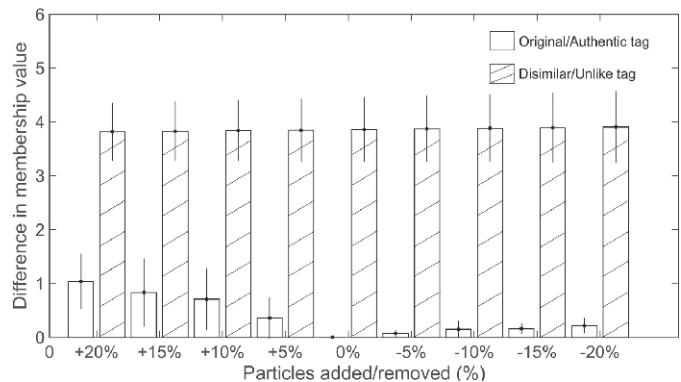
6.2 Alignment analysis

The tags are unidirectional and encoded in one fixed alignment. During verification, the algorithm would check the image by aligning and decoding it in all four directions, i.e. 0, 90, 180 and 270 (alternately, a positioning marker can be added like the QR code). The code should only validate with the original authentic code in one alignment and there should be variation in membership value in all other direction. Code of the authentic tag was compared with decoded images of 50 tags by rotating them in all directions. The experiment was repeated for all the 50 codes, and 50 images. The differences thus obtained were recorded.

6.3 Particle addition/erosion analysis

The proposed textile tag should be durable to withstand mechanical agitation. Washing and abrasion during the regular

Fig. 11 Difference in membership value when particles are added or removed



use of the T&C product can erode some particles or add some unwanted noise in the tag. To simulate the same, up to 20% of the particle locations were randomly added and removed in the obtained particle locations in original image and results were analysed in the subsequent section.

6.4 Pattern distortion analysis

Due to flexible nature of textiles, the original tag might stretch in due course of usage. In order to simulate such conditions, the original tag images were stretched to 20% in vertical, horizontal and diagonal direction and realigned about the corners using projective transform.

6.5 Particle shift

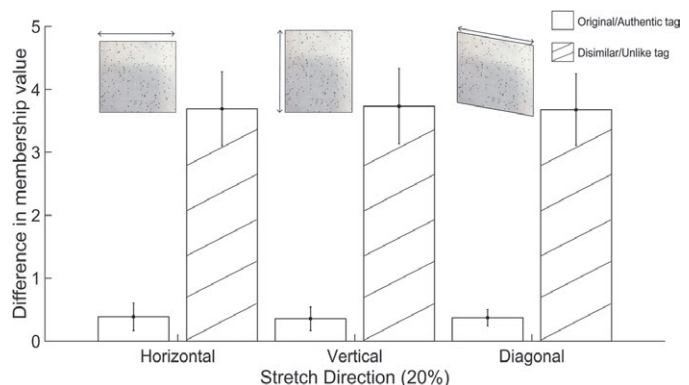
Due to improper image capturing method or shift in corner points, the particle location might shift to a certain extent. To simulate the same, all the obtained particle locations from the original tags were rotated up to 10° , leading to a rotational and

linear shift. The obtained locations were then validated to check the difference.

7 Results

For a robust, secured traceability system, the tags should be durable to last until the recycling stage. Pertaining to this, the experiments analysed the tag performance under common variations that might affect the subsequent tag reading due to its textile nature. The results are presented in terms of membership difference of 50 tags. To ensure low probability of false detection, the average value of membership difference between like patterns of the authentic tags before and after variation should be zero or very low, whereas the average difference between two unlike pattern should be high enough to result in significant and complete separation to facilitate selection of a threshold value. All the difference value below the threshold will have a high probability that the read pattern

Fig. 12 Difference in membership value when the tags are stretched to 20% in **a** horizontal, **b** vertical, and **c** diagonal directions



corresponds to the original tag even after variation, whereas the difference value above threshold corresponds to unlike or unauthentic code.

7.1 Results for inter-tag analysis

The frequency distribution of the membership difference for all the comparisons was plotted. It was observed that it followed a normal distribution, as shown in Fig. 9.

The average membership difference among two unlike tag was 3.89 with 0.59 standard deviation. It should be noted that membership difference for the tag, when compared with itself for all the 50 cases, came out to be zero and all those values were neglected for the distribution evaluation.

7.2 Results for alignment analysis

Figure 10 shows the average difference in membership value obtained by subtracting the original or authentic tag membership value with the correctly aligned original tag, followed by average difference between the membership value of authentic tag and membership obtained after rotating the same with 90° subsequent rotation. A complete and vast separation can be observed between the correctly aligned and misaligned tag, proving that the pattern is random and will authenticate only with correct alignment and correct pattern.

7.3 Results for particle addition/erosion analysis

Figure 11 shows the results of the average difference in membership values obtained after one-to-one comparison between first the distorted pattern with the authentic tag patterns and then with pattern of the 50 unlike tags. These distorted patterns are obtained after randomly removing or adding particle location values up to $\pm 20\%$. It can be observed that the

membership difference for the like or authentic tags with distorted pattern increases with increasing the level of erosion or addition. However, the difference between the unlike tags membership value is still high that proves the probability of false detection is still low even after removing or adding up to 20% of particles.

7.4 Results for pattern distortion analysis

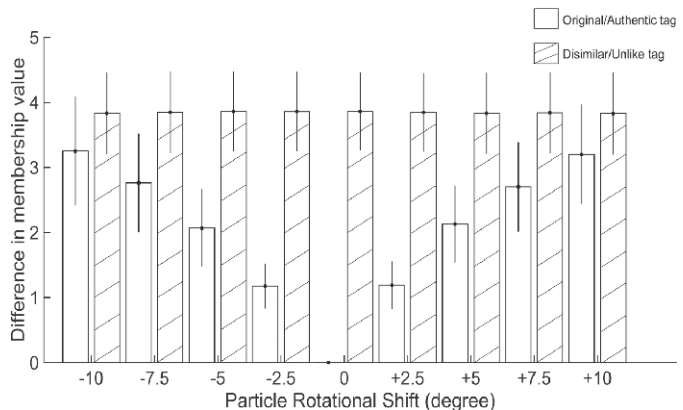
All the 50 patterns were stretched to 20% horizontally (x -direction), vertically (y -direction) and diagonally (in 45° direction) and realigned using proposed methodology.

Figure 12 shows the mean difference in membership values of original/authentic tags with undistorted patterns and that obtained after realigning the like pattern on one side. This is followed by mean difference in membership values of the realigned tag with other 50 tags on other. The results show a significant variation among the differences of like tags and differences of two unlike tags even after realignment and pattern distortion. This verifies that the algorithm proves effective even after stretching the tags and tolerates pattern distortion to a certain extent.

7.5 Results for particle shift

Figure 13 shows the mean difference in membership values of authentic/original tag with undistorted patterns and that obtained after shifting/rotating the locations of all the particle of the like pattern up to 10° on one side and the average difference in membership values of the shifted pattern tag with other 50 tags on the other. It can be observed that the difference up to 5° is not very high and the probability of false detection is comparatively low. However, a greater distortion more than 7.5° can affect the algorithm and increase the probability of false detection. This factor can be studied further and improved in the future study.

Fig. 13 Difference in membership value with particle rotational shift



8 Conclusions

This paper introduces and validates concept, design and methodology of an integrated and secured traceability tag for the T&C supply chain. The main novelty and contribution in this work are (1) in the form of a secured tag specially designed and developed for the T&C supply chain, taking into account the particularities of the T&C product, (2) in terms of value generation from the existing conventional printing technology and material with low capital investment and (3) selection and encoding of distinct features that complement each other and lead to high probability of true positive validation of the secured tag. It is anticipated that such tag would make the supply chain traceable and would be helpful in anti-counterfeiting. The developed tag showed good results when tested for use-phase treatment of the textile product. The tag only validates in one alignment, which proves that the distribution is random and unique. There was not a significant change in the membership difference value even after addition or removal of around 20% of particles. In addition, the membership difference did not increase (within the authentic tag) even after shape distortion due to stretching (up to 20%). This is an important criterion for the durability of the tag, as it should be validated (if authentic) even after some distortion due to washing or handling process.

However, it has certain limitations that need to be addressed in future research works. A physical wash and abrasion resistance analysis should be done to examine the impact of washing and abrasion of the tag under standard test conditions. It should also be noted the difference in membership value (for original tag) increased with the particle rotational shift. Therefore, the validation process can be affected by this distortion. An in-depth analysis of various commercially available textile binders can be done in future research work to restrict particle movement over the textile surface. This can be followed by piloting of the developed tag in the actual T&C supply chain to find and address the implementation challenges.

These secured tags presented in this study are helpful in securing the T&C supply chain at the product level and restrict unauthorised access to the product database. Nonetheless, future research can be undertaken to secure the traceability system at the business level to prevent the attack on the information sharing mechanism.

Acknowledgments This work has been comprehended in the framework of Erasmus Mundus Joint Doctorate Project—Sustainable Management and Design for Textiles (SMDTex), which is financed by the European Commission. The authors would also like to thank Mr. Christian Catel from ENSAIT/GEMTEX, France for his time and help.

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Paper IV

Agrawal, T.K., Campagne, C. and Koehl, L. (2018), "Development and characterisation of secured traceability tag for textile products by printing process," *The International Journal of Advanced Manufacturing Technology*, Vol. 101 No. 9-12, pp. 2907–2922



Development and characterisation of secured traceability tag for textile products by printing process

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Received: 2 August 2018 / Accepted: 22 November 2018

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Abstract

Product security is one of the major concerns in the textile industry. Every year, fashion brands suffer significant loss due to counterfeit products. Addressing this, the paper introduces a secured tag for traceability and security of textile products. The proposed tag is unclonable, which can be manufactured using conventional screen-printing process. Further, it can be read using a smartphone camera to authenticate the product and trace its history. Consequently, imparting additional functionality to the textile through surface modification. To validate its applicability, the study experimentally investigates the durability and readability of the developed secured tag using three different binders on polyester and cotton textiles substrates. A comparison is presented with an in-depth analysis of surfaces and binders interaction at different stages of the secured tag lifecycle, i.e. before print, after print, after wash and after abrasion cycles. The methodology and findings of the study can also be useful for other manufacturing domains dealing with the printing process.

Keywords Secured tag · Traceability · Screen printing · Adhesion

1 Introduction

Textile or clothing that is specifically engineered in order to deliver a predefined functionality or performance to the consumer, in addition to its normal functions is usually termed as ‘Functional textile’ or ‘Functional clothing’. Based on the additional functionality, these textile can be classified as protective-, medical-, sports-, vanity- and cross-functional [1]. Typically made by modifying the textile structure at different scales or adding auxiliary textile assemblies, these functional textiles are flexible and low-cost as compared to conventional non-textile

substitutes (e.g. [2, 3]). The additional functionality is usually incorporated at the raw material stage or during manufacturing process [4].

Surface mounting or modification through printing process is one of the most commonly used technique to fabricate supple and inexpensive functional textiles [5–7]. Printing usually transforms or modifies the surface properties for additional functionality and finds wide application in the electronics industries for developing printed sensors, flexible displays, RFIDs and wearable electronics [8–12]. A significant research has focused in past to develop interactive, smart and functional textiles through printing processes [13]. Screen-printing, inkjet printing and 3D printing are some of the well-known technologies used in past to impart various functionalities to textiles [8, 11, 14, 15]. Nonetheless, every technology has its pros and cons. For instance, screen-printing has low infrastructure investment and high deposition. However, it offers lower precision, limited variety and versatility. Inkjet printing, on the other hand, has higher precision, controlled deposition, high productivity and thin-layer deposition capability. Though, it is comparatively expensive, less resistant to bending and stretch and offers high surface roughness [16]. 3D printing, on the other hand, has even higher deposition (in three dimensions) but lower productivity due to its non-continuous process and requires higher infrastructure investment [17]. Overall, compared to

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other manufacturing technologies, these printed functional textiles usually face substantial challenges in the commercial market due to low-durability. Functional ink or paste used for printing are often eroded or washed-off due to low surface affinity. However, with technological advancement and in-depth analysis of the surface-to-surface interaction between printing paste/ink and textile substrates, it is possible to overcome these challenges and develop commercially viable products [18].

Printed traceability tag is one such example which is a widely recognised and accepted technology in the market [19–22]. These tags act as a unique identifier that links product with the central database and enables traceability in the complex supply chain. Printed RFIDs and barcodes are commonly used solutions for high-volume track and trace applications in pharmaceutical, food and logistics industries [23–26]. Though numerous studies in past have advocated the use of RFIDs in the T&C supply chain, consumers perceive them as a threat to privacy due to its hidden and remote readability feature [27]. In addition, RFIDs, QR code and barcode are easily clonable and often detachable, leading to product loss or replacement with counterfeits in the complex supply chain [28]. Nonetheless, when integrated directly on textile products along with an authentication mechanism, these traceability tags can remain integrated to the product, enabling brand authentication and traceability (communicating history of the product) throughout the lifecycle [22]. As a result, it imparts additional functionality to the textile through surface modification. Therefore, the printed tag—that can track and trace the product in the supply chain and secures it from counterfeit threat—are high in demand for the T&C supply chain. These tags are also expected to be durable, inexpensive and eco-friendly [28]. They should safeguard user privacy by restricting remote readability. Besides, these tags should be easily readable and authenticable by the customer in order to access traceability information. They can even be

used for sorting and segregation of textile material during recycling stage [29].

In this context, the current study presents a new secured tag for textile product authentication and traceability. The secured tag is unique for each product and extremely hard to replicate. It can be read and verified using a smartphone camera to authenticate the product and trace its history. The functionality in the secured tag is not solely due to printing material and mechanism, but it is a combination of the system developed during the study. It consists of a secured tag that is printed on the textile substrate plus the developed algorithms that read, encode and validate the secured tag using image processing and pattern recognition tool. In order to demonstrate the development process of the secured tag, a systematic approach has been followed. The study explains the concept and manufacturing process, followed by an in-depth analysis of various sourced materials and their interaction to determine the optimum combination that can result in a higher durable and readable secured tag. The parts of the paper are arranged in following order: Section 2 describes the security mechanism and its manufacturing process of the secured tag. Section 3 defines various raw material selected for secured tag manufacturing followed by overview of methods used for material characterisation and secured tag durability and readability analysis. Section 4 discusses the results from various characterisation and analysis and ranks different secured tag samples. Finally, Section 5 summarises the outcome of the study and lists the scope for future research.

2 Concept and manufacturing process

2.1 Concept

The secured tag is inspired by a physical unclonable function (PUF), which is a well-known security mechanism, acting as a

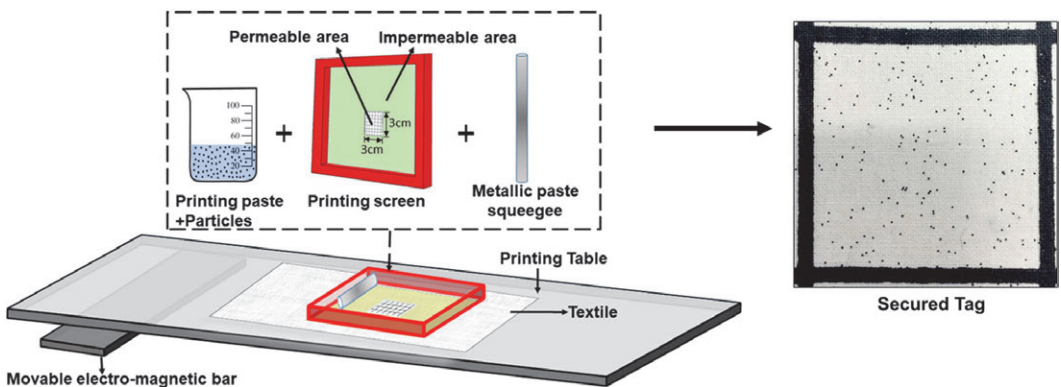


Fig. 1 Electromagnetic printing table with printing tools and image of the developed secured tag

Table 1 Properties of different binders

	Binder 1	Binder 2	Binder 3
Commercial name	Tubvinyl 235 MC® [32]	Silbione TCS 7541® A [33]	Helizarin ET Plus liq® [34]
Chemical nature [#]	Vinyl acrylic copolymer	Polydimethylsiloxane (silicones)	Styrene acrylic copolymer
Supplier	CHT Bezema (France)	Blue star silicones (France)	Archroma (France)
Catalyst/fixing agent [#]	Tubassist® Fix 102 W (3% w/w)	Silbione TCS® 7604 C (10% w/w)	Luprintol® Fixing Agent SE liq (1% w/w)
Glass transition temperature (T _g) (approx.) [#]	− 19 °C	− 120 °C	+ 5 °C
Solids content (approx.) [#]	59%	100%	38%
Viscosity – Brookfield (10 rpm) (approx.) [*]	150,000 mPa.s (needle no°7)	35,000 mPa.s (needle no°6)	140,000 mPa.s (needle no°7)
Curing temperature [*]	150 °C	150 °C	150 °C
Curing time [*]	5–6 min	2–3 min	5–6 min

Information source: [#] Supplier, ^{*}Experiment

digital fingerprint for each associated product. PUFs are easy to evaluate and encode but hard to replicate and breach. PUF mechanism taps and records certain innate, uncontrolled and random variation in each product developed during the fabrication process and makes them a unique identifier for that particular product [30]. The proposed tag is secured from reproduction or cloning (that can result in a counterfeit product) through the same concept of PUF and randomness. Each textile product is printed with a micro-level size of the particle through an uncontrolled process, in a confined tag area ($3 \times 3 \text{ cm}^2$) with varying particle concentration and distribution. This generates a unique particle randomness on each product with a very low probability of reconstruction. This unique randomness acts like a signature for each product that is extremely hard to replicate. These microparticles are detectable through camera images; therefore, the distribution can be extracted and encoded by the manufacturer (using image processing and pattern recognition methods). After the sale, the consumer can validate the product using smartphones to authenticate and trace its history thus promoting transparency and traceability in the T&C supply chain. A detail description of the algorithm and secured tag technology can also be found in our previous work [31]. Likewise, based on the design of garment or textile product, the secured tag can be placed externally and

make it an aesthetic feature or internally at a safe location that would not undergo extensive wear and tear. For instance, it can be printed internally, on the yoke or moon patch, just below the brand labels.

2.2 Manufacturing process of the secured tag

The secured tag is manufactured through the screen-printing method. The process uses a porous mesh, commonly known as a screen for the printing process. The printing area or motif acts like a stencil—developed by blocking all the pores of the non-printing area. While printing, the paste (consisting mainly of a binder mixed with a colourant) is squeezed through this stencilled screen onto the textile substrate, thus creating the motif on the textile surface. The print is then dried and cured to harden the paste by cross-link with the textile substrate.

In this study, the printing paste consists of microparticles mixed with a transparent binder, without any colourant. When the mesh screen is placed on the textile substrate and printing paste is squeezed, the microparticles pass through porous part of the mesh and are randomly placed on surface of the textile substrate. To maintain a uniform squeezing pressure, a semi-automatic magnetic print table can be used with a metallic squeeze, as shown in Fig. 1. In these printing tables, an

Fig. 2 SEM images of different textile substrates **a** 100% cotton and **b** 100% polyester

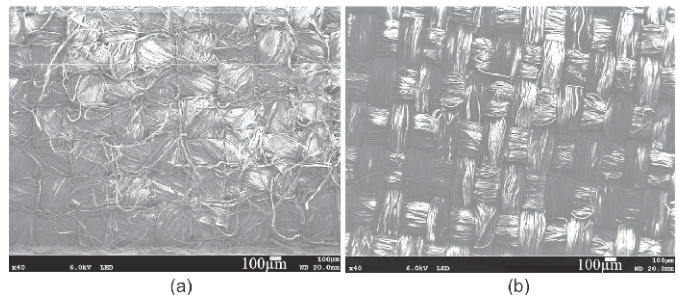
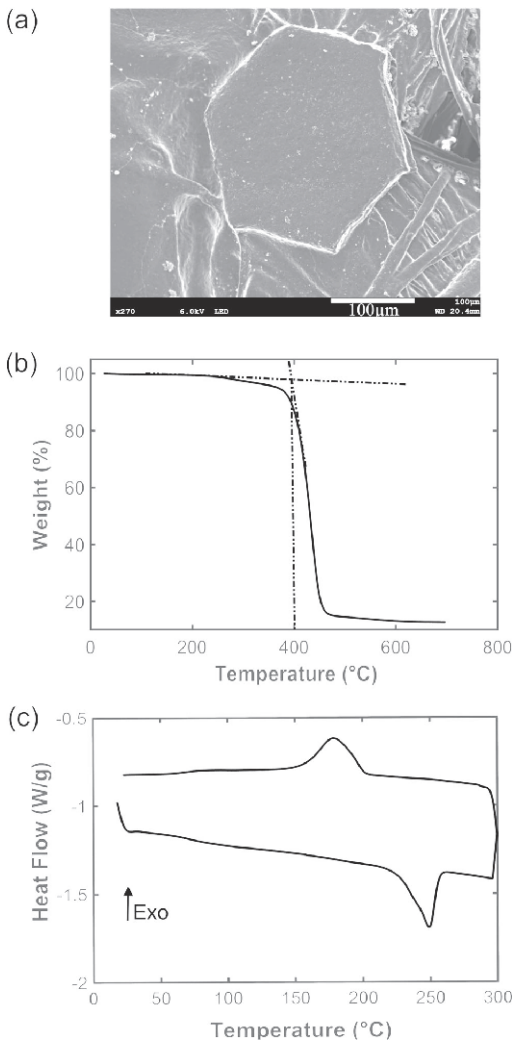


Table 2 Properties of different textile substrates

Textile substrates	Density (g/m ²)	Thickness (mm)	Air permeability (l/m ² /s at 20 cm ² test area)	No. of warp yarns per inch	No. of weft yarns per inch
100% cotton	118.7 ± 3.04	0.265 ± 0.010	24.68 ± 1.16	64 ± 0.63	58 ± 0.76
100% polyester	90.2 ± 2.24	0.169 ± 0.006	28.84 ± 1.42	82 ± 0.52	74 ± 0.61

Information source: experiments

**Fig. 3** **a** SEM image of micro particle (glitter) printed on the textile substrate, **b** Thermogravimetric analysis graph, **c** Differential scanning calorimetry analysis graph

electromagnetic bar that moves along the length controls the movement of the metallic squeeze and thus the squeezing pressure. Due to the transparent binder, the dark microparticles can be clearly seen on the surface of a light textile substrate after curing. While printing, these particles were enclosed within a black rectangular boundary to distinguish the printed portion and enable easy detection through a camera, as shown in Fig. 1. It can be further noted that unlike usual screen printing—that requires stencil design modification for each new motif—secured tag printing required a screen with a single square stencil of approximate size $3 \times 3 \text{ cm}^2$ (printing area), which can be reused multiple times.

3 Materials and methods

3.1 Materials

3.1.1 Binders

Three types of commercially available binders were used in this study and standard recipes were followed to develop the final printing paste. The detailed description of the binders and curing conditions can be found in Table 1.

3.1.2 Textile substrates

Two widely used textile compositions (100% cotton and 100% polyester) for clothing application were selected in plain woven structure as the textile substrates for secured tag

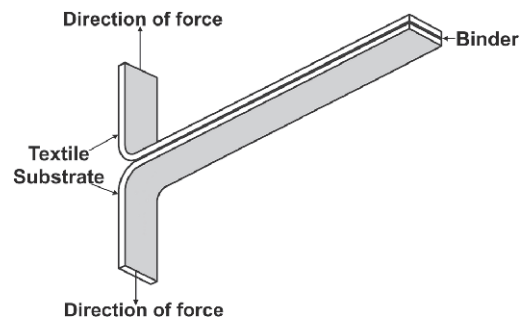
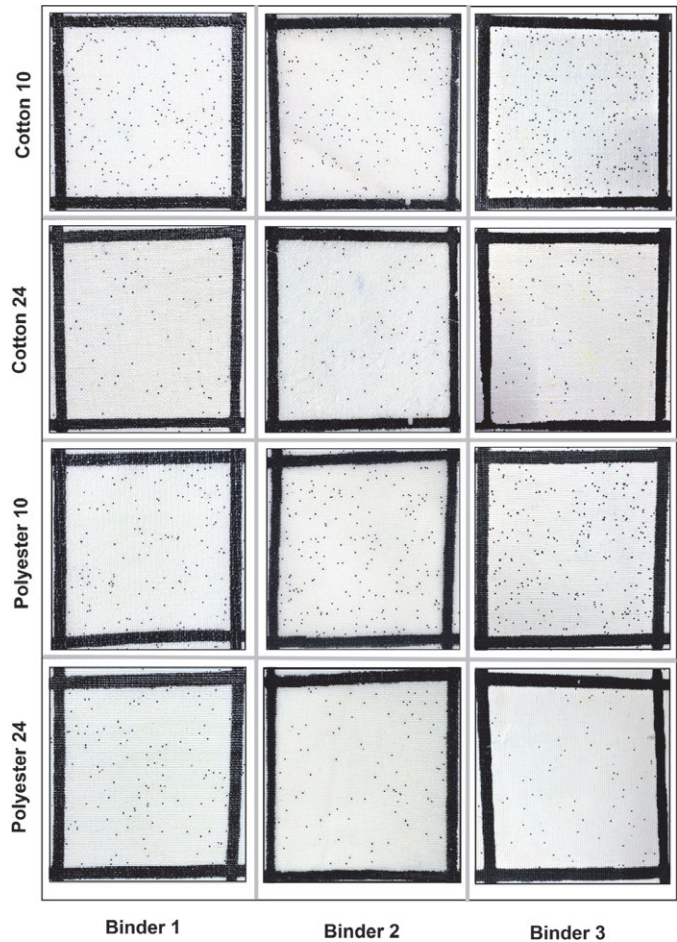
**Fig. 4** Peel test specimen

Table 3 Printing paste deposition on different substrates using different printing screens

Textile substrates	Printing paste deposition rate (g/m ²)		
	Binder 1	Binder 2	Binder 3
Cotton 10	99	205	24
Cotton 24	70	133	12
Polyester 10	86	176	21
Polyester 24	65	132	11

development. Cotton textile substrate—made up of yarns having stable fibers—had a rough and irregular surface whereas polyester textile substrate—made of continuous filament yarns—had a comparatively smoother and regular surface.

Fig. 5 Images of different printed tags

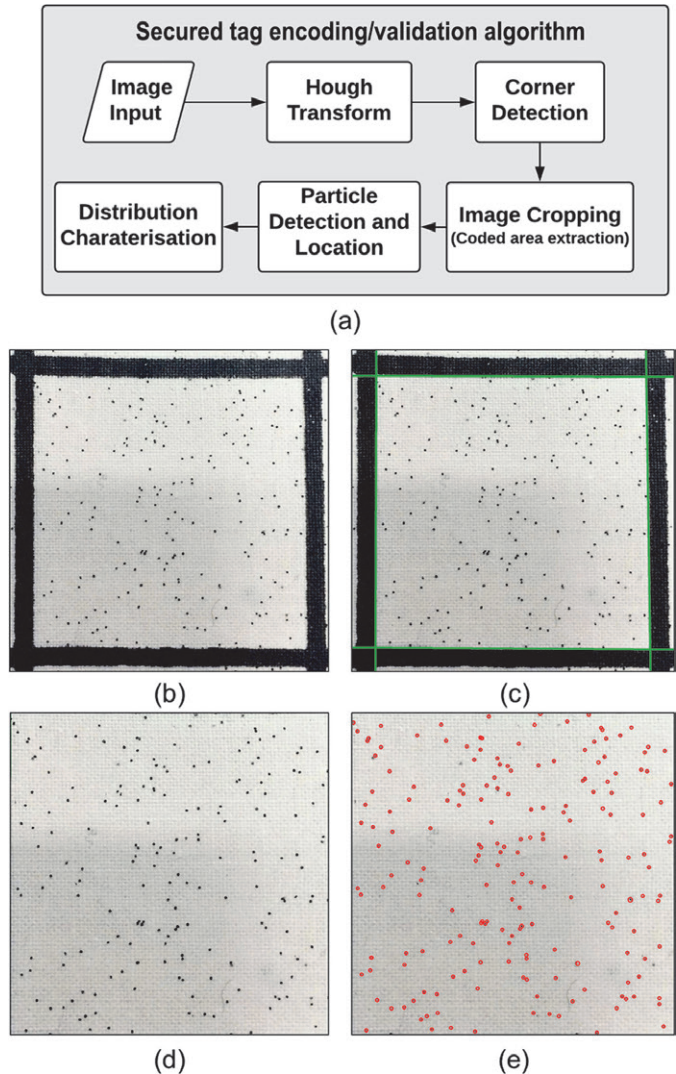


Scanning electron microscope (SEM) images of the two surfaces are shown in Fig. 2 and detailed characteristics can be found in Table 2.

3.1.3 Microparticles

The printing paste also includes microparticles that are mixed with the binder, along with fixing agents, in a predefined concentration. Commercially available black Geoshine® polyester glitter (supplied by Geotech International B. V, Haarlem, Netherlands [35]) were used as microparticle. As per information provided by the supplier, these glitter particles are suitable for textile coating/printing application with high brilliance, lightfast, solvent-resistant and non-toxicity. From a wide range of sizes offered by the company, hexagonal glitter particles with an average diameter of 200 µm (Fig. 3a) were

Fig. 6 **a** Secured tag encoding algorithm. **b–e** Different stages of particle detection. **b** Original tag image. **c** Line and corner detection. **d** Area of interest (actual tag area). **e** Particle detection



sourced for secured tag development. The size was appropriate, as it is not big and can easily be printed on the textile surface with screen printing, using screens of size 10 to 24 threads/cm. Bigger particles can block the screen mesh or would require a courser screen—resulting in high deposition and low print precision. On the other hand, smaller particles can be hard to detect by normal low-resolution cameras and would increase the processing time.

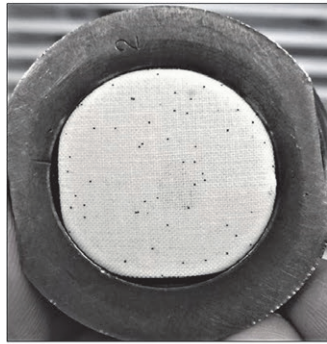
Further, the glitter particles were subjected to thermogravimetric (TG) and differential scanning calorimetry

(DSC) analysis. A TG analysis was carried out using thermal analysis (TA) universal instrument, under a constant stream of nitrogen. Four independent experiments were conducted on 10.0 ± 0.1 mg samples with a heating rate of $10^\circ\text{C}/\text{min}$ starting from 0 to 750°C . Figure 3b shows the graph of TG analysis wherein the particles were found to be thermally stable with a degradation temperature higher than 400°C . For DSC analysis, TA instrument type DSC 2920 was used. The analysis was done under a constant stream of nitrogen on 6.0 ± 0.1 mg samples at a

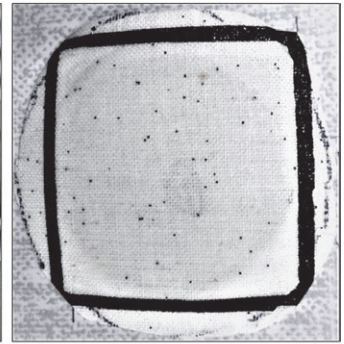
Fig. 7 **a** Martindale abrasion tester. **b** Tag mounted on the ring. **c** After abrasion cycle. **d, e** Tag area and particle detection to evaluate particle erosion



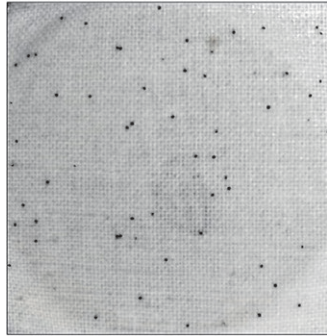
(a)



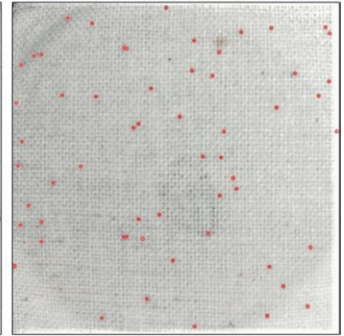
(b)



(c)



(d)



(e)

heating rate of 10 °C/min starting from 0 to 300 °C, then isotherm of 3 min followed by cooling at the same rate until 0 °C. The cycle was repeated again and the data from the second cycle was analysed and presented in Fig. 3c (DSC analysis graph), that characterises the

thermal transition of the particles. These analyses show that the particles are suitable for textile printing application as they can withstand high temperature without degrading during the curing process of the binders, i.e. usually between 130 and 170 °C (as shown in Table 1).

Table 4 Results from the capillary rise and sessile drop experiments

Material	Contact angle (°)		Surface tension (mN/m)	
	Water	Diiodomethane	Dispersive	Polar
Cotton textile substrate	68.9	54.1	52.6	4.8
Polyester textile substrate	66.2	49.6	55.7	5.2
Binder 1	66.4	48.6	55.7	5.1
Binder 2	100.6	83.4	16.1	2.3
Binder 3	86.8	48.6	22.3	5.2

3.2 Methods

3.2.1 Methods for material characterisation

After material selection and characterisation, it is important to test the surface interaction and adhesion characteristics of the binders and the textile substrates. To do so, work of adhesion and peel resistance were calculated—that are important parameters for predicting the durability of the binder at the surface.

Work of adhesion is one of the non-destructive tests to measure the contact strength or work required to separate two adjacent phase boundary. It is an important parameter particularly for processes including coating, printing and bonding in order to determine the surface-surface interaction and adhesion force. According to the thermodynamic mechanism of adhesion, the polymer system, in a neutral environment (like air) attempts to reduce the surface free energy by aligning the surface into non-polar regions of the polymer. The interfacial tension between polymer surface and polar substance (such as water) in contact minimises in case of a good adhesion system. Based on the concept, Young [36] formulated a relation for the strength of adhesion of a simple system that can be estimated through the work of adhesion (W_a). The formulated relation uses a liquid of known surface tension (γ_L) that is in contact with simple solid, smooth, isotropic and non-deformable surface and defines work of adhesion as

$$W_a = \gamma_S + \gamma_L - \gamma_{SL} \quad (1)$$

$$\gamma_L \cos \theta = \gamma_S - \gamma_{SL} \quad (2)$$

where γ_S = surface tension solid/air, γ_L = surface tension liquid/air, γ_{SL} = surface tension solid/liquid and θ = contact angle between solid and liquid surface.

However, in the above equations, even after knowing γ_L , there are other unknown variables. Therefore, to determine the work of adhesion between the binders and the textile substrates, we use the OWRK methods named after the originators Owens, Wendt, Rebel and Kaelble [37]. It is an extension of Fowkes' model [38] that considers the influence of both

polar (γ^p) (hydrogen bonding) and dispersive (γ^d) components (all the van der Waals forces) and takes their geometric mean to calculate the surface free energy as:

$$\gamma_{SL} = \gamma_S + \gamma_L - 2\sqrt{\gamma_S^d \gamma_L^d} - 2\sqrt{\gamma_S^p \gamma_L^p} \quad (3)$$

And by combining Eqs. (2) and (3)

$$\gamma_L(1 + \cos \theta) = 2\sqrt{\gamma_S^d \gamma_L^d} + 2\sqrt{\gamma_S^p \gamma_L^p} \quad (4)$$

And combining Eqs. (1) and (3)

$$W_a = 2\sqrt{\gamma_S^d \gamma_L^d} + 2\sqrt{\gamma_S^p \gamma_L^p} \quad (5)$$

In this study, using Eq. (4) and the method used by [39], the work of adhesion value has been calculated for different textile substrates and binders. Using two known liquids with different polarity (water and diiodomethane) whereas contact angle between the known liquids/binders (through sessile drop technique) and known liquids/textile substrates (through capillary rise method) has been measured in separate tests. These values served as input for Eq. 5 to calculate the work of adhesion.

Peel test is a destructive test method for direct adhesion measurement. It calculates the forces required to tear, break and delaminate adhered layers by peeling. In this study, we follow ISO 24345:2006 testing protocols to determine peel resistance. MTS tensile testing machine, capable to maintain test speed and provide appropriate load, has been used. Six bonded samples consisting of two types of textile substrates with three type of binders were developed for the test. Further, six test specimens—three each from the warp and weft directions of each samples with 150-mm long and 50-mm width—were cut at a regular distance at least 100 mm away from the edges. These samples were condensed at $23 \pm 2^\circ\text{C}$ temperature and $50 \pm 5\%$ relative humidity for 24 h before the test. Each specimen (as shown in Fig. 4) was placed in jaws of tensile tester (around 50 mm apart), and the jaws were separated by a speed of 100 ± 5 mm/min and separation force (peel resistance) is recorded.

3.2.2 Methods for secured tag analysis

As discussed earlier, the secured tag was printed using screen printing process. Therefore, to examine the variation in print durability and readability, two types of screens—with mesh size 10 threads/cm and 24 threads/cm were used for secured tag development. Screen with mesh size 10 threads/cm has coarser mesh or larger holes, which should allow more paste (along with particle) to squeeze through the screen as compared to 24 threads/cm. This results in higher paste deposition and more particle concentration in the printed area. The print deposition rates obtained through both screens on different textiles are shown in Table 3 and corresponding images of the tags are shown in Fig. 5. It should be noted that the 100% cotton textile substrate samples printed using a screen with 10 threads/cm mesh size are referred as ‘Cotton 10’ and likewise, ‘Cotton 24’, ‘Polyester 10’ and ‘Polyester 24’ denote the type of textile substrate and screen mesh size.

Tag encoding and validation mechanism In order to detect the printed particles, a digital image of each secured tag was captured and processed using image processing and pattern recognition algorithm on Matlab R2017b. The main steps of the algorithm to detect and extract the particle locations are shown in Fig. 6a, followed by a pictorial representation of the same using image of a unique secured tag in Fig. 6b–e. It should be noted that the same steps for particle detection would be followed during encoding as well as the validation stages. The image was first pre-processed to correct the contrast and light. Then, the Hough transform [40] was applied to detect the lines, tag corners and ultimately the secured tag area with random particle distribution. The resultant area was then cropped and particles were detected and located using Circular Hough transformation [40]. Using these particles, location features like the strong cluster of particles and empty areas in the secured tag were extracted and encoded in form of unique traceability code. Further, a fuzzy membership-based validation algorithm has been developed considering the flexible nature of the textile substrate and abrasion that it might undergo during the use phase. A detailed explanation of the algorithm can be found in our previous work [31]. As demonstrated in [31], the algorithm showed positive results with correct validation of authentic secured tag even after 20% particle erosions from the surface. In order to analyse the durability of the secured tag, images of the developed tag samples are taken at different stages, i.e. after print and after each wash/abrasion cycle. The obtained images are analysed using the image-processing algorithm to quantify particle erosion.

Washing test The samples were washed 10 times following ISO 6300:2015 washing test procedure. Each wash-cycle comprises of 30 min of washing at 60 °C temperature in a mixture of European Colourfastness Establishment (ECE) normalised detergent and water (0.5% w/w of detergent)

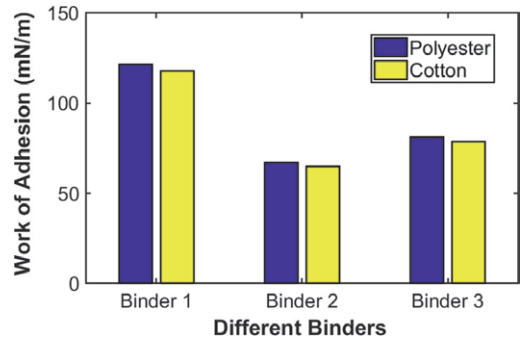


Fig. 8 Work of adhesion for different binders

followed by line drying. After each wash, images of the secured tag were captured and analysed using the image-processing algorithm, as explained in the previous section, to count the percentage of particle erosion.

Abrasion test In order to test the abrasion resistance, the developed samples were tested as per the ASTM D4966 test procedure using Martindale abrasion tester as shown in Fig. 7a.

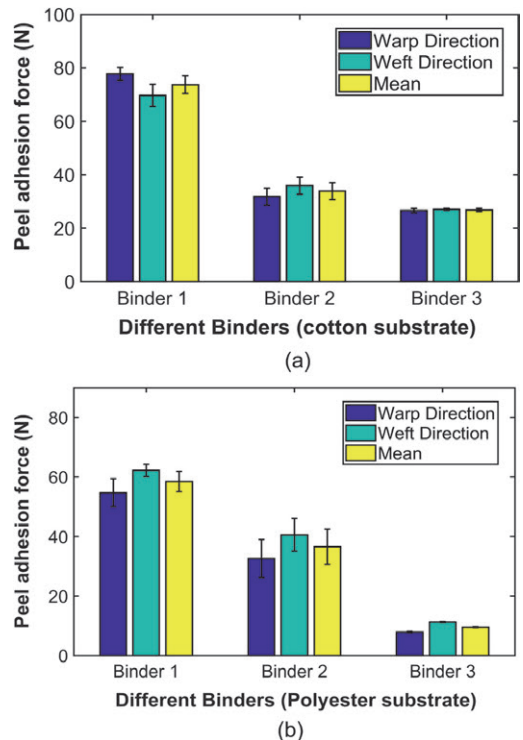


Fig. 9 Peel adhesion force (N) for the different binders with a cotton textile substrate and b polyester textile substrate

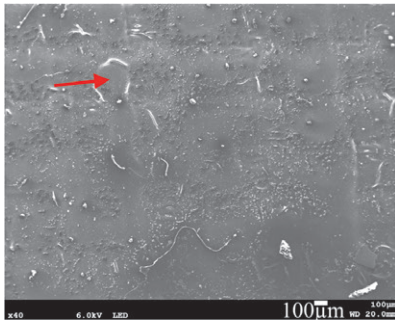


Fig. 10 SEM image of polyester 24 printed with Binder 1

During the test, circular specimen (38-mm diameter) of each sample tag, backed by a polyurethane foam is mounted on a ring. The ring performs a Lissajous motion against a standard wool abrasant textile with the face side of the tag in contact with the abrasant. In order to observe the particle erosion, images of the tag specimens were taken and analysed using the image processing as shown in Fig. 7b–e, at 0, 500, 750, 1000, 2500, 5000 and 7500 abrasion cycles.

SEM analysis Scanning electron microscopy is a widely used surface investigation technique that uses electron scattering to map the surface topography. In this method, an electron beam is rastered across the conductive surface (usually made conductive by coating with a conductive material) of the sample. An electron detector records secondary electron emitted signals generated during electron rastering that develops the image of the sample. SEM has a high depth of field compared to an optical

microscope and can generate images with few nanometres spatial resolutions. Topographical information provided by SEM analysis has been used to analyse the interaction between the substrates and printing paste before and after wash cycles.

Surface roughness analysis—profilometer In order to quantify surface roughness and surface profile of the prepared samples at different stages, the samples were subjected to a profilometer test. It consists of mainly two parts. Detector or stylus that moves and physically sense the surface of the specimen that is mounted over the sample stage that holds the specimen. The stylus in conjunction with a feedback loop physically moves over the specimen surface while maintaining a constant force to acquire surface height and roughness information along the scan line. Various ISO 25178 surface texture height parameters—the arithmetic mean height (S_a), root mean square height (S_q), maximum peak height (S_p) and maximum pit height (S_v) were evaluated for each sample using the equipment.

4 Results and discussion

4.1 Results of material characterisation

4.1.1 Work of adhesion value

Due to the hydrophilic nature of the two textile substrates (cotton and polyester), the contact angle and the surface tension has been calculated using the tensiometric method. Whereas, sessile drop technique was used for calculating the

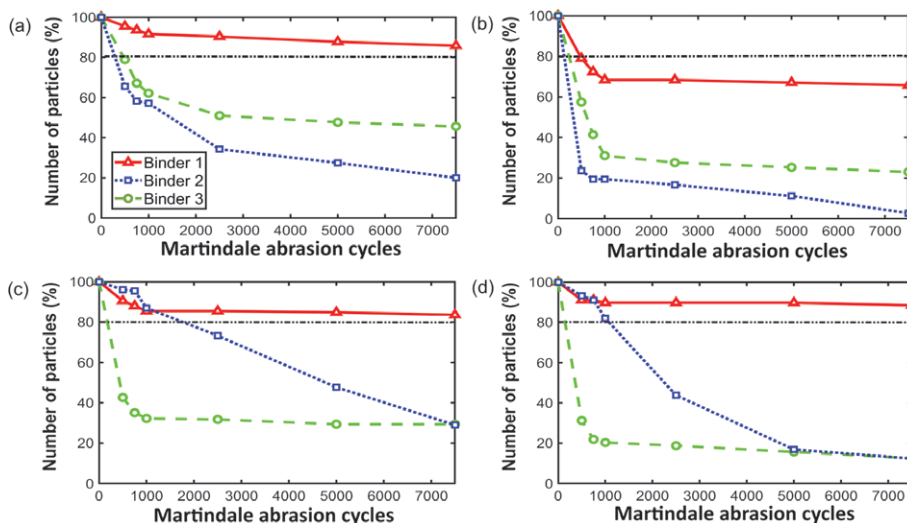


Fig. 11 Abrasion resistance test results. **a** Cotton 10. **b** Cotton 24. **c** Polyester 10. **d** Polyester 24

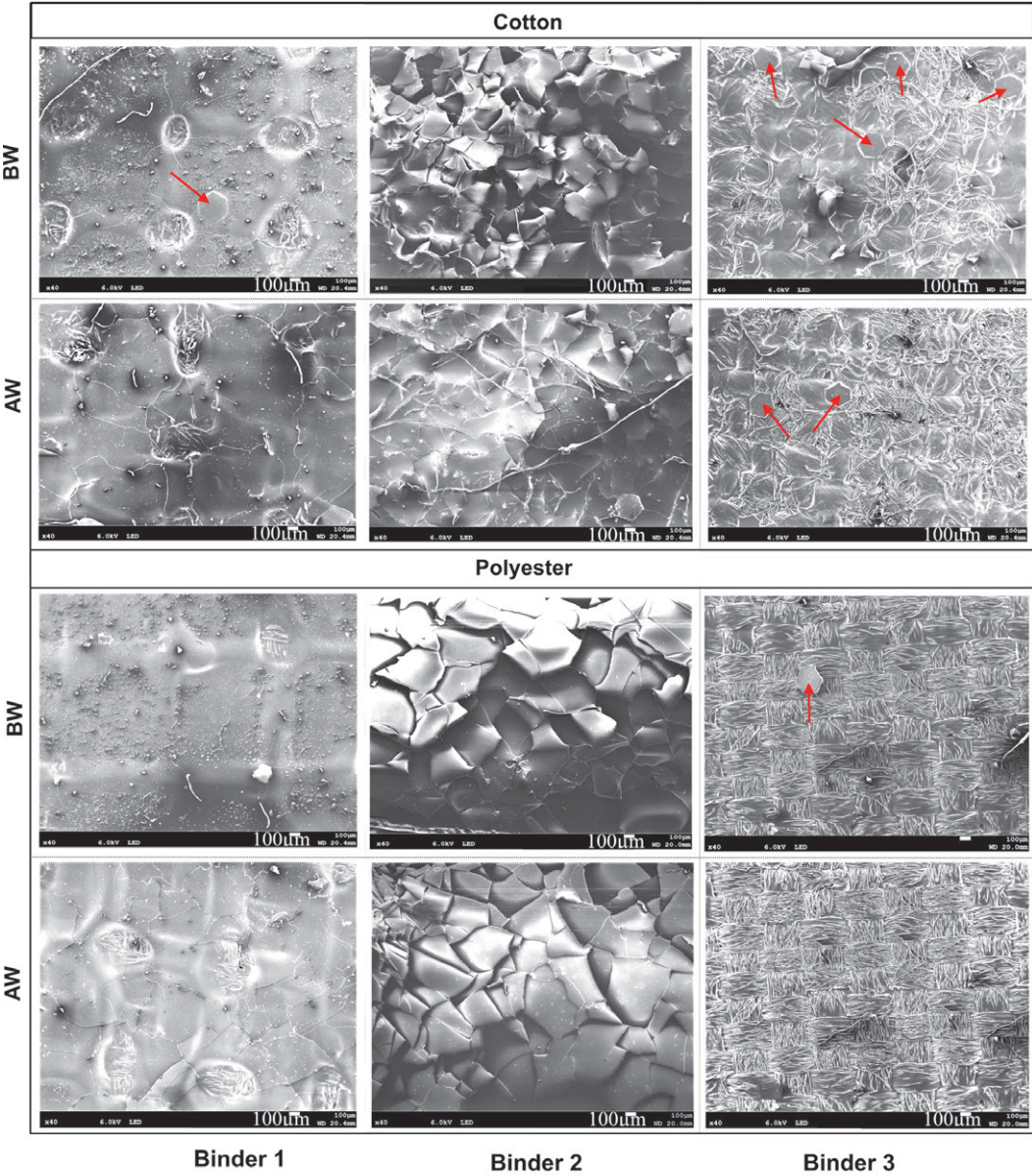


Fig. 12 SEM images of the surface of textile substrates after screen printing, before and after wash

surface tension of binders. Table 4 summarises the results from these experiments.

Values from Table 4 were combined to get the work of adhesion (W_a) between different binders and textile substrates.

It can also be inferred from Fig. 8 that although made from different materials (cotton and polyester), the surfaces of textile substrates have similar surface tension values and were behaving alike with the same binder.

Besides the surface roughness parameters calculated from profilometer for both textile substrates were also very similar with $(S_a, S_q) = (0.020, 0.056)$ for cotton and $(0.023, 0.029)$ for polyester (refer Appendix Table 6 for detail). The W_a value for binder 1 (vinyl acrylic copolymer) was found to be highest with a value of 121.7 mN/m with the polyester textile substrate and 118.1 mN/m with the cotton textile substrate. As explained above, according to the thermodynamic mechanism of adhesion, polymer system, in a neutral environment (like air) attempts to reduce the surface free energy by aligning the surface into non-polar regions of the polymer. In case of the polymer textile substrate and binder 1 the surface tension value is almost equal and comparatively higher than others material; hence, they combine to form an equilibrium at the interface and high adhesion [41]. Binder 3 (styrene acrylic copolymer) has the second highest W_a value, 81.0 mN/m with the polyester textile substrate and 78.6 mN/m with the cotton textile substrate. Finally, we obtained the lowest W_a for binder 2 (silicones) as 67.0 mN/m with the polyester textile substrate and 65.0 mN/m with the cotton textile substrate. These can be due to a comparatively high difference between the surface tension of the binder 2 and the textile substrates (refer Table 4).

4.1.2 Peel resistance values

Test specimens were placed between the jaws of the tensile tester approximately 50 mm apart, one at a time. The recording device continuously recorded the peeling or separation force at a separation speed of 100 ± 5 mm/min. Mean value of the peel resistance (force) is calculated (rounded to nearest 5 N) throughout the peeling process, neglecting the reading from first and the last quarter of the total reading.

Results of the peel test experiment as shown in Fig. 9, indicate that binder 1 has the highest peel adhesion force value for both types of textile substrates with a mean values of 73.75 N (for cotton) and 58.44 N (for polyester). This is followed By Binder 2 that has a mean values of 33.86 N for cotton textile substrate and 36.62 N for the polyester textile substrate. Finally, binder 3 has shown the lowest peel adhesion force with polyester textile substrate equal to 9.55 N and slightly higher value of 26.79 N for the cotton textile substrate. Unlike the work of adhesion value, binder 2 has a slightly higher peel resistance compared to binder 3. The possible answer to this behavior can be the low solid content (38%) of binder 3 compared to binder 2, which has 100% solid content. On the other hand, vinyl acrylic copolymer-based binder 1 had around 60% solid content and also (OH) group that shows high affinity with cellulosic fibre (cotton textile substrate), thus resulting in highest peel resistance value.

After experimental adhesion characterisation, secured tag samples were printed, using binders (mixed with microparticle) on the textile substrates. These samples were tested for abrasion and wash durability along with surface interaction investigation using SEM images.

4.2 Results of secured tag analysis

4.2.1 Abrasion resistance value

In case of abrasion resistance test, secured tag samples printed with binder 1 using a screen of mesh size of 10 threads/cm on both textile substrates (cotton and polyester) and mesh size of 24 threads/cm on polyester, proved to be the most durable. They could withstand 7500 abrasion cycle with an erosion

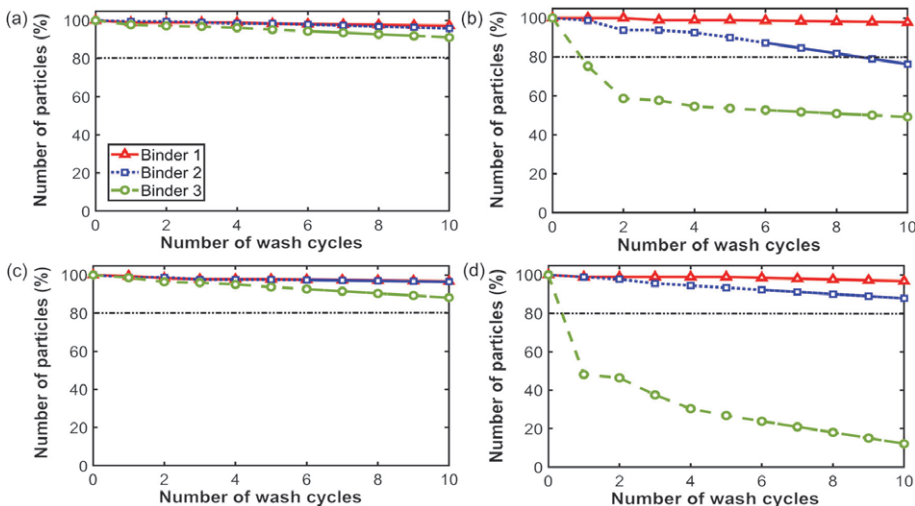


Fig. 13 Washing test results. a Cotton 10. b Cotton 24. c Polyester 10. d Polyester 24

Table 5 Result summary: a comparative analysis (I = first rank, II = second rank and III = third rank)

Binder	Textile substrates and screen type	Work of adhesion	Peel adhesion force	Abrasion test	Washing test
Binder 1	Cotton 10	I	I	I	I
	Cotton 24			II	I
	Polyester 10	I	I	I	I
	Polyester 24			I	I
Binder 2	Cotton 10	III	II	III	I
	Cotton 24			III	II
	Polyester10	III	II	II	I
	Polyester 24			II	I
Binder 3	Cotton 10	II	III	II	I
	Cotton 24			II	III
	Polyester10	II	III	III	I
	Polyester 24			III	III

of less than 20% of the total particles. This proves that the secured tag, when printed with binder 1, can withstand high abrasion. The secured tag will be durable when printed on the similar textile substrate and can be validated successfully without hampering the code (or random particle distribution). In fact, polyester 24, although printed with a lower rate of binder deposition was durable against abrasion. A further investigation using SEM image (as shown in Fig. 10) shows the possible reason to be the smooth and even deposition of binder (with low friction) on the surface of polyester and the cotton textile substrate. The binder seems to have completely covered the particle, preventing it from possible exposure to the abradant. Detailed abrasion resistance results for all type of binders and substrates are shown in Fig. 11. Binder 2 was found to be less durable against abrasion due to the scaly and rough surface formed on the textile substrate after print—that can be observed in Fig. 12.

4.2.2 Wash test results

In the case of wash test, secured tag samples printed with combinations of cotton 10 or polyester 10 with all the three types of binders showed good resistance to washing. These samples withstood 10 wash cycles with particle erosion as low as 2% for binder 1 and around 10% for binders 2 and 3. In case of cotton 24 and polyester 24 due to the lower rate of binder deposition, the wash durability was found to slightly lower for binder 1 and binder 2 and very low for binder 3. Figure 13 graphically represents the number of particles (in percentage) remaining on individual secured tag sample after each wash cycle.

Figure 12 further shows the SEM analysis (surface interaction) of these samples before and after wash. In accordance with the wash test results, the images indicate the reasons for

the low durability of a certain binder. For example, in the case of binder 3, the particles are not completely covered with printing paste and visible on the surface of the textile substrate. This results in easy erosion of micro-particle during washing and surface abrasion, resulting in lower durability. Similarly, made with hydrophobic silicon material, binder 2 has a good wash resistance. Values from the profilometer analysis of different samples can be found in Appendix Table 6 that further indicates the possible reasons for low durability among the samples.

Finally, Table 5 summarises all the results and presents a comparative analysis of different binders and textile substrates. It ranks different samples based on their performance in comparison to others, taking into consideration the 20% threshold values for particle erosion (under which the secured tag code would work successfully). It can be observed that secured tag samples that were printed with binder 1 using a screen of mesh size 10 threads/cm give the best results for both the textile substrates in all the different durability tests. For the polyester substrate, a secured tag can even be printed using a screen of mesh size 24 threads/cm, which showed a high durability against washing and abrasion.

5 Conclusions

The study presents a new secured tag for textile product authentication and traceability in T&C supply chain. The secured tag is realised by printing randomly distributed microparticles on the textile surface through an uncontrolled screen printing mechanism. Thus, the obtained randomness in particle distribution is unclonable and acts like a unique signature for each product. In addition, this secured tag can be easily read and verified using a smartphone camera, thereby imparting additional functionality

to the textiles. The study systematically explains the development process of the secured tag (including design, fabrication and encoding/validation algorithm) followed by an in-depth investigation of different raw materials (in form of three binders and two textile substrates) and their interaction. Tests such as abrasion and wash resistance have also been performed to examine the durability and readability of the tag during textile use phase. Finally, all results were compared to determine the optimum combination.

It has been observed that secured tag printed with binder 1 (vinyl acrylic copolymer) performs best among all performed tests, whereas binder 2 (silicones) performed better in wash resistance. On the other hand, binder 3 (styrene acrylic copolymer) does not prove appropriate for the secured tag fabrication. Since the performed tests simulate the real-use condition of garments, therefore, it is anticipated that the fabricated tags can sustain the various use conditions of textile.

It should be noted that the current study is a proof-of-concept of a new traceability tag. Therefore, for the initial exper-

imental validation, two widely used textile substrates (100% cotton and 100% polyester) with relatively stable woven structure were selected. In the future, different fibre blends and textile structures (including knits and nonwovens) will be selected for experimental validation. The tags can be further tested for dry cleaning and other chemical cleaning processes. Future study can also focus on lifecycle analysis of binders 1 and 2 to explore the most sustainable alternative. A piloting of the developed system in real industrial scenarios would be the next step to explore further challenges and their solutions at the manufacturing stage.

Acknowledgments The authors would like to thank Mr. Christian Catel from ENSAIT/GEMTEX, France, for his time and help.

Funding This work has been comprehended in the framework of Erasmus Mundus Joint Doctorate Project—SMDTex (Sustainable Management and Design for Textiles), which is financed by the European Commission.

Appendix

Table 6 Profilometer reading for different specimen

Adhesive type	Treatment	Sample	Sa	Sq	Sp	Sv		
No binder	Before wash	Cotton	0.0203	0.0256	0.209	0.0132		
		Polyester	0.0237	0.0294	0.123	0.112		
Binder1	Before wash	Cotton10	0.038	0.051	0.252	0.178		
		Polyester 10	0.0361	0.0467	0.358	0.181		
		Cotton 24	0.0426	0.0511	0.217	0.176		
		Polyester 24	0.0286	0.0383	0.265	0.114		
		Cotton 10	0.0362	0.0454	0.204	0.196		
	After wash	Polyester 10	0.0292	0.0371	0.18	0.175		
		Cotton 24	0.0532	0.0679	0.322	0.185		
		Polyester 24	0.0381	0.0501	0.235	0.135		
		Binder2	Before wash	Cotton10	0.0449	0.0555	0.272	0.156
				Polyester 10	0.0302	0.0356	0.178	0.0873
Cotton 24	0.0259			0.0332	0.248	0.125		
Polyester 24	0.0283			0.0334	0.155	0.0949		
After wash	Cotton 10		0.0395	0.0499	0.255	0.146		
	Polyester 10		0.0351	0.0492	0.238	0.117		
	Cotton 24		0.0481	0.0615	0.285	0.215		
	Polyester 24		0.0232	0.029	0.134	0.14		
	Binder3		Before wash	Cotton 10	0.0727	0.0888	0.33	0.212
				Polyester 10	0.0421	0.0516	0.184	0.172
Cotton 24		0.077		0.0911	0.336	0.191		
Polyester 24		0.0285		0.0362	0.164	0.125		
After wash		Cotton 10	0.0642	0.0801	0.295	0.25		
		Polyester 10	0.0433	0.0522	0.152	0.169		
		Cotton 24	0.0386	0.0497	0.239	0.159		
		Polyester 24	0.0417	0.0506	0.181	0.151		

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Paper V

Agrawal T. K., Kumar, V., Pal, R., Wang, L., Chen, Y (20xx) Blockchain-based framework for traceability- A case example of Textile and Clothing supply chain. *Computers in industry* (Submitted)

BLOCKCHAIN-BASED FRAMEWORK FOR TRACEABILITY – A CASE EXAMPLE OF TEXTILE AND CLOTHING SUPPLY CHAIN

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ABSTRACT

Supply chain traceability has emerged as a prime requirement for multi-tier supply chains. It not only enables the supply chain visibility but also caters to the consumer requirements related to transparency, quality assurance, and production tracking. Textile and clothing supply chain is one such example that particularly requires traceability implementation due to prevailing problems related to information asymmetry and opaque structure. Customers find it difficult to access product data that can facilitate ethical buying decision-making or assure product authenticity. Conversely, it is challenging for supply chain partners to share all the competitive information in the unsecure environment. In this context, this study investigates blockchain technology, which uses a shared and secured data infrastructure to keep track of information about assets and requires no central authority to function. It further proposes a blockchain-based traceability framework that explains supply chain partner interaction and network architecture at organizational level and smart contract and transaction validation rules at the operational level. In order to validate the applicability of the framework, the study presents a simulated example of an organic cotton supply chain through a blockchain program with customized smart contract and transaction rules. The proposed system can build a technology-based trust among the supply chain actors, where the distributed ledger would be used to store and authenticate of supply chain transactions. Since the blockchain relies on no central authority, the blockchain-based traceability would provide a unique opportunity, flexibility, and authority to all supply chain actors to trace-back their supply chains and create transparent and sustainable supply chain network.

1. INTRODUCTION

Complexity and requirements in the manufacturing industries have exponentially increased in the past few decades. Escalating global competition, market volatility, desire for customized products and declining product lifecycles pose a serious challenge to the industries (Mehrabi et al., 2000). Besides, due to illicit trades, unethical production practices, and fragile supply chains, industries are under immense pressure from consumers and governments to follow sustainable production means, to be transparent in their functioning and enhance visibility at the operational and organizational level (Guercini and Runfola, 2009; Jansen-Vullers et al., 2003). Textile and Clothing (T&C) industry is one such example that is facing serious issues due to unstable consumer demand, escalating competition, unaccountable product recalls and counterfeits (Alves et al., 2013; Corbellini et al., 2006; Kumar et al., 2017). It is also been subjected to strong criticism for unfair labor practices and use of toxic materials, largely because of its opaque supply chain. Catastrophic events in recent past have further intensified the demand and called for immediate actions (Algayerova, 2017; Assmuth et al., 2011; Hoque et al., 2016).

In this direction, adopting a blockchain-based traceability system have emerged as a possible solution that can counter the above-mentioned challenges (Dobrovnik et al., 2018; Mandolla et al., 2019; Wang et al., 2019). Blockchain-based traceability can ensure safe and seamless information sharing; facilitate product quality monitoring/control, operation monitoring/control, real-time data acquisition, transparency and visibility throughout the supply chain (Kshetri, 2018; Queiroz and Fosso Wamba, 2019; Treiblmaier, 2018). Traceability, as defined in the United Nation Global compact and Business for Social Responsibility (2014) report, is “ the ability to identify and trace the history, distribution, location, and application of products, parts, and materials, to ensure the reliability of sustainability claims, in the areas of human rights, labour (including health and safety), the environment and anti-corruption”. Information is the key element of a traceability system and the system rely on recorded identification using a unique authentication code associated with each traceable recorded unit (TRU) (Olsen and Borit, 2018). Blockchain technology in this context can help in documenting the trail of each product and related attributes (information) - at all transformation stages-, associating it with unique code while preventing fraudulent transactions and incorrect data entry through the supply chain (Abeyratne and Monfared, 2016; Dobrovnik et al., 2018). With its decentralized and immutable data storage system, blockchain can ensure technology-based trust among a group of untrusted supply chain partners interacting with each other thus facilitating

transparency and visibility in the supply chain (Queiroz and Fosso Wamba, 2019). Likewise, it can help to maintain the integrity of the industries while preventing leakage of sensitive business information that can be a source of competitive advantage. (Dobrovnik et al., 2018; Sikorski et al., 2017; Treiblmaier, 2018).

Blockchain technology has been introduced in the most appropriate period of time when the supply chains globally are facing huge customer demand in the form of product sustainability assurance. Customers are eager to know if the product they are buying is authentic, complies with all standard, legally sources and manufactured, with quality assurance. Blockchain-based traceability has the potential to identify counterfeit or fake transaction, tracking/tracing product origin, and supply chain activities at the same time can ease paperwork processing (Kshetri, 2018; Tu et al., 2017). With its smart contract and digital ledger characteristics, it can better assure product quality, improve compliances, payments, and pricing processes. With its interlinked hash function, blockchain technology can help in examine and trace the trail of the product (Zhao et al., 2019). All these characteristics will be discussed in detail in the later section of this paper. In fact, blockchain is one of the Industry 4.0 technologies that ensure the integration of cyber-physical system (CPS), and internet of things (IoT) in the supply chain (Hofmann and Rüsch, 2017). It can operate the IoT, ease real-time data collection and exchange using sensors and electronics (Tian, 2016).

Blockchain-based traceability has huge potential in revolutionize supply chains and solves many outstanding issues. Nonetheless, in order to make an impactful contribution and solves these issues in different supply chains, it is also important for researchers in all domains to understand the full potential and functioning of the blockchain technology (Umeh, 2016). This would help them to apply their core competence to customize domain-specific rules (smart contracts), partners' interactions, networking, the extent of information sharing/securing, record keeping (ledger) and develop use case examples for various supply chain scenarios (Konovalenko and Ludwig, 2019). For instance, one of the practical case example developed by Caro et al.,(2018) for the agri-food supply chain. Considering this, the current paper presents a blockchain-based traceability framework for the supply chain with a case example of Textile and Clothing (T&C) industry. It provides an overview of the T&C supply chain, blockchain technology and further introduces a framework for information traceability using commissioned or private blockchain network in T&C supply chain. The framework explains the information/material exchange, supply chain partners interaction, distributed ledger arrangement and smart contract development taking into account the particularities of the T&C

industry. In order to support the framework, the paper develops and demonstrate an example blockchain with customized smart contract and ledger-updating rules for the T&C supply chain. The example is an initial step for customized blockchain development and can be further complicated by adding more interaction and network rules. It can be noted that, although the example blockchain is developed for the T&C industry, it can be incorporated for any supply chain with certain modifications.

2. BACKGROUND

2.1. T&C Supply Chain and need for traceability

T&C supply chain is a complex network with numerous materials, many possible permutations with several different and complicated processes. Due to dynamic consumer preferences and volatile trends, T&C products have a short shelf life with multiple styles and collections every season (Kumar et al., 2017; Thomassey, 2010). This discourages adoption of modularity and thus complicate the manufacturing systems. The supply chain partners are usually widespread in different parts of the world and the journey from fiber to the finished product is remarkably long and complicated (Muthu, 2017). The supply network is linearly arranged with several partners that are linked together in a logical network according to their contribution to the product's transformation stages. Fashion brands, which are typically the retailer are the focal partner in the T&C supply chain, which, procure finished textile products from upstream suppliers and sell them to customers through different outlets. These brands decide the upstream partners, supply chain model, and rules based on various factors, including low-cost manufacturing location, suppliers' track record and consumer market (Kumar et al., 2017, 2016). In general, the fashion brands do not own any production facility and act as a reseller. Therefore, most of the interaction in the T&C supply chain occurs at B2B (business to business) level and it is a brand who interacts with the customer at B2C (business to customer) level. As illustrated in Figure 1, the T&C supply chain starts with a fiber producer that can be a cultivation company growing natural fiber (e.g. cotton) or industry producing petroleum-based chemical fibers (e.g. polyester). These fibers are then proceeded into yarn by the yarn-manufacturing units using spinning process and later converted into fabric by fabric manufacturing units through weaving, knitting or nonwoven processes. The fabrics thus generated are passed to apparel manufacturing (stitching) industries where they are shaped into fashion clothing, accessories or home furnishing products. It is noteworthy that Figure 1 is just a simple illustration of the T&C supply chain to demonstrate the material flow, in fact, it is a complex network with multiple actors at each production stage, each catering procuring raw material

from multiple upstream suppliers, processing them and transferring the process product to the next downstream buyer. Besides, the main actors there are also various sub-suppliers and contractors involved in the supply chain providing add-on (e.g. buttons, threads, etc.) and processing services (e.g. chemical treatment, embroideries, etc.). These upstream suppliers—mainly involved in manufacturing - are usually located in developing countries with low wage rates and easy raw materials availability. The downstream buyer and consumers are mostly located in the developed part of the world with customers having higher disposable income.

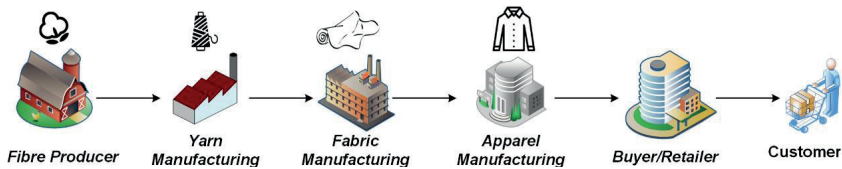


Figure 1: A typical T&C supply chain

Due to this complex structure with the large geographical spread of the supply chain, partners especially the focal firm, often find it difficult to track and locate all the involved supplier, contractors, and sub-suppliers (Egels-Zandén et al., 2015; Guercini and Runfola, 2009). Taking advantage of this, the upstream manufacturers often follow unsustainable means of production to reduce cost and maximize the profit. Information asymmetry, low-visibility, and security escapes are major challenges in the T&C supply chain that had contributed to many catastrophic events and scandals (a most tragic example being Rana Plaza). Besides, counterfeits and uncountable product recalls posing a serious threat to economic and consumer health. According to OECD/EUIPO (2019) report, due to counterfeits EU industries losses almost €26.3 billion direct estimated sales every year, with the biggest effect on the retail and trade sectors with an estimated loss of €10.8 billion in sales per year. On the other hand, inefficient product recalls management causes significant financial losses and jeopardizes brands reputation (Chen et al., 2009). As per the report by Rapid Alert System (RAPEX), textile, clothing, and fashion products are among the top five most notified products, contributing to almost 22% of the total recall notification in 2010 to 2017 (European Commission, 2018). Most of these recalls go unaccountable due to lack of traceability.

Adoption of a blockchain-based traceability system is one of the possible solutions to address these challenges and ensures seamless information among supply chain partners. This system can track and record all the information related to each stage of product transformation and while safeguarding crucial and sensitive data throughout the supply chain.

2.2. Blockchain Technology

2.2.1. *History and types of blockchain*

While Haber and Stornetta (1991) introduced the concept of time-stamping digital document – the core mechanism behind blockchain, the blockchain technology formally gained its popularity from the Bitcoin (a cryptocurrency application of blockchain) that was released in January 2009 with the first miner under the pseudonym of Satoshi Nakamoto (Nakamoto, 2008). Bitcoin blockchain relies on the anonymous exchange of cryptocurrency – Bitcoins - on the public and distributed network without involvement of a centralized bank or financial authority. These Bitcoins are generated as a reward for mining process, during which a miner (a pool of processing system) validations set of transactions occurring on the blockchain and predicting a random answer of a mathematical cryptographic hash function (Antonopoulos, 2014). Such a blockchain network is public and open to all individuals with access to the internet. Anyone can anonymously trade bitcoin/cryptocurrency and can view all the blocks with their recorded transactions. Pertaining to these features public blockchain are very complex, consume enormous energy, with low efficiency but high security. The transaction once validated and recorded on the database is immutable (Kshetri, 2018). However, business blockchain need not be public. As business transactions involve confidential information and mainly take place among known parties with a certain degree of trust, therefore the business blockchain is a private network. Such private blockchain is comparatively less complex, with customized transaction rules and network design. Table 1 gives a brief differentiation among the public and private blockchain network (Zheng et al., 2017).

Table 1: Difference between public and private blockchain

Property	Public blockchain	Private blockchain
Determining Consensus	All miners* (*interconnected node/pool of systems using their computing power to validate the transaction.)	Only a selected set of nodes or even a single node representing an organization
Permission	Public	Customized accessibility depending on the role and authority in the network
Immutability	Almost impossible to tamper	Could be modified
Efficiency	Low	High
Centralized	No	To a certain extent
Consensus process	Permission-less	Permissioned

The present trends and developments in blockchain technology to some extent resembles the initial days of internet adoption, which was slow and full of speculations until the commercial potential was completely realized with the mass-scale adaption of the World Wide Web (Treiblmaier, 2018). It was only after the mass acceptance, businesses and individuals better recognized positive and negative aspects of the internet (Kambil, 1995). In a similar fashion, the companies are now investing to develop blockchain-based solutions that have the potential to revolutionize the market. It is anticipated that the blockchain market will experience exponential growth at a compound annual rate of 61.5 percent to become a US\$2,312.5M economy by 2021 (Markets and Markets, 2018). According to the study by IBM, almost one-third of organizations are considering or actively participating in blockchain technology. Most of the experts and executives acknowledge the usefulness of the blockchain technology and at the same time experiencing ripples of ‘passive’ disruption from customer and partners due to possible ‘change in the game-rules’. On the other hand, the interest from an academic researcher in blockchain can be interpreted from the facts that a simple query on the scientific database, Scopus (in January 2019), with term ‘Blockchain’ displays more than 3000 related literature. Interestingly ~65% of the literature published in the year 2018 alone, and ~10 % of the literature is related to the ‘supply chain’ or ‘logistics’. Additionally, substantial literature can be found in the form of white paper that critically explores the blockchain technology in the supply chain context. However, it is also important to recognize the fact that blockchain technology is not relevant to all scales of industries and securing all sorts of databases. It has a huge potential when multiple partners are involved with a distributed network; however, it is less relevant for intranet or small network among trusted parties.

2.2.2. Components and mechanism

As defined in the book ‘Blockchain for Dummies’ by IBM, *Blockchain is a shared, immutable ledger that facilitates the process of recording transactions and tracking assets in a business network. An asset can be tangible (a house, a car, cash, land) or intangible (intellectual property, patents, copyrights, branding). Virtually anything of value can be tracked and traded on a blockchain network, reducing risk and cutting costs for all involved* (Gupta, 2018). The term ‘blockchain’ is derived from the way in which the blockchain technology stores the transaction data. It consists of a sequence of blocks that are linked in the form of a chain. As shown in Figure 3, each block holds set of the transactions in a Merkle tree form (Tx_Root) using a cryptographic function that helps in easy verification of individual transactions without having to compare and evaluate all the previous versions of the complete database. Other than

this, the block contains ‘timestamp’ of the formulation of the block, a hash of previous block (Prev_Hash), a block ID/Number and a proof of the consensus mechanism (Nonce) (Swan, 2015). These blocks are logged into the distributed ledger based on the consensus rules agreed on by the network partners. In order to understand blockchain mechanism and the proposed framework it is important to understand the four crucial components of blockchain technology i.e. distributed shared ledger, smart contract, permissions, and consensus:

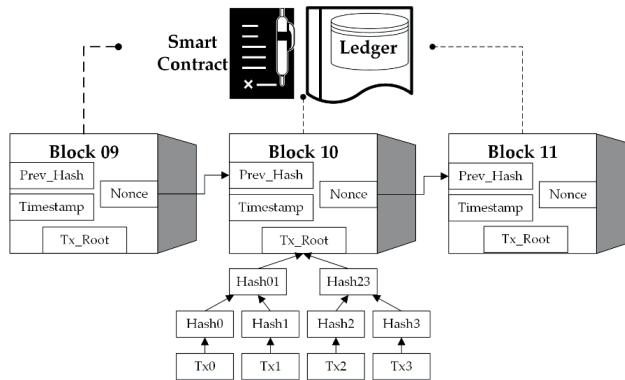


Figure 2: A typical blockchain representation

a) Distributed Shared Ledger

A ledger is simply the record of transactions. It is been used in double-entry bookkeeping since ages. In blockchain technology, these ledgers do not only records all the transactions but are also shared within the authorized partners, thus termed as distributed. Additionally, these ledgers are made immutable by binding it with a cryptographic hash function and linking it with the hash of the previous block (Swan, 2015). Hash is a combination of random digits generated by passing the block information (transaction detail and a hash of the previous block) in a cryptographic hash function (e.g. SHA-256 in Bitcoin). These functions produce a new hash of the desired length (e.g. 256 bit for SHA-256) for the current block. Due to its randomness, it is extremely difficult to predict the input information using the resulting hash value. Two identical inputs will always provide the same and unique hash, but a slight variation in the input data changes the hash significantly. Moreover, as the hash of a new block is generated using hash of previous block (which in turn contain a hash of trailing block) as shown in Figure 2, so any modification in the transaction of the previously registered block will alter the hash of all the subsequent blocks. Additionally, on distributed shared ledger each transaction is recorded and

shared only once thus eliminating the risk of duplicate entry or double spending (Gupta, 2018; Swan, 2015). The ledger holds the current state of the network (record and track of all tangible and intangible asset that is being traded over the blockchain since its installation) and chain of transactions. Being an append-only system, it serves as a single source of truth. Therefore, the shared ledger is one of the most important blockchain components that facilitate the traceability of products and information and creates a technology-based trust among a group of untrusted parties interacting in an unreliable network without any centralized authority.

b) Smart contract

Smart contracts set the rules for the ‘game’ that governs the business transactions. They are extensively important and need to be customized for different asset type and/or in accordance with the requirements of individual businesses. In blockchain technology, smart contracts are hard-core programmable logic with strict implementation conditions. Each transaction is verified against the rules set by the smart contract before they are recorded on the shared ledger and each valid transaction is associated with a block (Luu et al., 2016). There are two popular transaction validation and record-keeping methods widely used in blockchain networks: Unspent Transaction Output (UTXO) and Account/Balance model. In the account/balance model, each address (ID of the trading partners) is considered as an account with a certain balance, and transactions are transfers of asset or value from one account to another. In case the sender has the asset balance equal or more than what has been agreed while trading – associated with their address – than the transaction will be validated and recorded on the blockchain, else it is discarded. In the UTXO model, there is no essential notion of the account associated with ID/ address of trader but the transactions inductively trade and spend outputs (assets) generated by previous transactions and create a new log of unspent outputs (assets). Both methods have their respective pros and cons. A detail explanation can be found in work by Zahmentferner (2018). In the context of the T&C supply chain, these methods can be adopted in accordance with the asset sharing and tracking rules.

c) Permissions

A private blockchain network consists of a known partner with a certain degree of trust. An address that in turn associated with a public-private key pair identifies each partner. A detail explanation with an example of public-private key encryption can be found in the study by Zyskind et al (2015). This identity determines the type and extent of access an individual partner have to the transaction details and shared ledger on the private blockchain network. It helps to

set the network rules and partners' interaction policies. Unlike a public blockchain, where the address (or ID) comprises of a random string, in the private blockchain, it can be a well-defined string that can easily identify the supply chain partner name and type. However, to maintain security the private key is always confidential and only known to its respective owner. Through this functionality, it is easy to comply with data protection regulation, maintain data privacy, trace the history of the product, identify the source of the defect and have better control on the data that are appended on the blockchain (shared ledger).

d) Consensus

While dealing with a shared ledger, it is also important to have a mechanism to avoid what is called the Byzantine fault (Castro and Liskov, 2002). In simple terms, it is a wrong ledger entry, done by mistake or due to the presence of a corrupt partner in the network. Before recording a set of transactions on a block, each transaction is verified against the current state of the shared ledger. This validation is done by a single peer (validating peer) on the blockchain that is randomly selected, each time during the block formation, based on the type of consensus mechanism. This safeguards the ledger from a wrong entry and enables the location of its origin. Along with the transactions data and other information, the address of the validating peer is also saved on each blockchain. The Bitcoin uses a proof-of-work (PoW) consensus mechanism that makes bitcoin blockchain highly secured from attacks. In PoW, the miners (pool of processing systems) compete with each other to solve a complicated mathematical puzzle in order to get the chance to write the new block and earn the reward as bitcoins (the process is known as mining). It is also one of the most expensive methods in terms of energy because a lot of processing power is utilized during the mining process and not all miners get a chance to validate and create the new block. In a private blockchain, the same can be replaced with mechanisms such as Proof-of-Elapsed Time, Byzantine fault tolerance, etc. where the validating miner is chosen randomly based on a set mechanism with minimal energy utilization. A detailed explanation can be found in work by Viriyasitavat and Hoonsopon (2018).

3. BLOCKCHAIN-BASED TRACEABILITY FRAMEWORK FOR T&C SUPPLY CHAIN

As mentioned above, a blockchain designed for business and supply chain application is quite different from that of the widely recognized bitcoin or cryptocurrency applications. As compared to the public bitcoin network, blockchain for supply chain need to have a certain level of privacy with restricted access. It should be private with authorized and identifiable partners.

Besides, there should be a customizable level of visibility and accessibility for each partner. At the system level, the blockchain will record and secure all the different required data to ensure traceability, however, depending on the accessibility level of each partner only a certain set of information will be made visible to them. This structure would not only ensure a technology-based trust and transparency in the supply chain but at the same time enables easy implantation of the government rules and policies. Similarly, each individual partner can also maintain their competitive advantage without disclosing all the trade secrets and strategies to the competing firm. For instance, product-costing data from a different supplier can be accessed only by the buyer but not among the suppliers themselves. Despite this, the blockchain – including all transaction data – should remain auditable and verifiable at any given by an authorized third party (Gupta, 2018; Korpela et al., 2017). This would help in resolving conflicts and identifying responsible partners in case of supply chain audit by the government.

For a clear understanding, the introduced blockchain-based traceability framework is described at an organizational and operational level. At organizational level, it explains the supply chain configuration in private blockchain network, partners interaction, methods for defining customized accessibility of different partners based on their roles and responsibility, and mode for accessing the blockchain network and input/report the transactions. Whereas at the operational level, it explains how the smart contract rules and transaction validation mechanism for blockchain be configured for supply chain traceability application and how information associated with different product transformation stages can be captured and stored on blocks. At all these stages, the study highlights and explains how the different blockchain component along with the network configuration can ensure information traceability and security in the supply chain.

3.1. Organizational level

As explained previously, in the T&C supply chain fashion brand or the retailer usually act as a dominating partner or focal firm that forecast the market demand and places order to the upstream suppliers. Each retailer sells a vast variety of product through different outlets, (all) round the year. These products line frequently changes depending on the season and fashion trends. In order to fulfill such a diverse set of products, as a standard practice, individual retailer procures from different apparel manufacturer. Similarly, each apparel manufacturer also caters to different retailers and at the same time source from different upstream suppliers. Hence, in an idealistic scenario, with blockchain-based traceability system adaptation throughout the

T&C supply chains, every individual partner would involve in multiple blockchain networks. Each of this network will have a different set of shared ledger and one or multiple smart contracts. Figure 3, shows the transformation of linear T&C supply chain shows in Figure 1 into a distributed blockchain network.

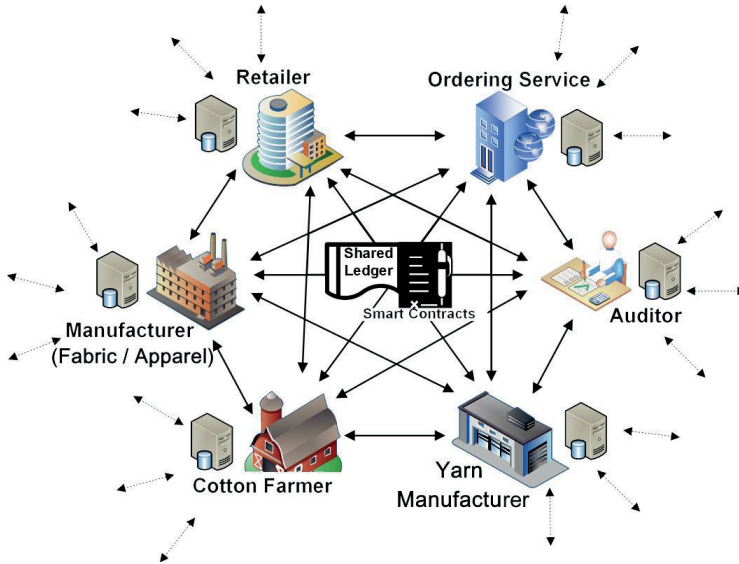


Figure 3 Blockchain-based decentralized network for information sharing

The transformation affects the information sharing mechanism, the material flow will remain linear based on product transformation stages. Further, the dotted arrows linked with each partner and moving outward shows the other possible blockchain network with which a partner can be associated. There are two additional partners (Ordering service and Auditor) in the network whose role is described in the following section. A blockchain network can be initiated and maintained by any supply chain partner. In this proposed framework, we have considered T&C retailer – who is usually the focal firm - as the initiating partner that invest (with a major stake) and maintain the blockchain network. The retailer interacts with different clusters of upstream suppliers and connect each cluster with an individual channel or set of channels. Each cluster consists of the individual supply chain or supplier network starting from fiber manufacturer to clothing manufacturing unit, involving logistic partners, auditors, and certification agencies. In comparison to a public blockchain, multiple customizations can be made in a private blockchain network to match the requirements of the trading partners. This customization and configuration can ease the functioning of blockchain, accelerate the processing, and at the same time maintain privacy and transparency in the network. Based on

the same logic we propose a blockchain-based traceability system while configuring the supply chain structure and partner interaction rules. Following are the main component of the blockchain-based traceability network at an organizational level.

3.1.1. Channels

Channels are subdivisions of the network, acting as a data partitioning mechanism. Each channel has its independent blockchain (chain of transaction) that are stored over a distributed shared ledger. These shared ledgers are governed by a smart contract or even a set of contracts. A cluster of the upstream suppliers (partners) - usually dealing with a particular product - can connect to one channel or even a set of channels, each made for the different type of transactions. For example, all material and production related transactions for one cluster could run on one channel and financial transactions from the same cluster can run on another channel. This would facilitate data privacy and subdivide the network in multiple blockchain (unlike voluminous Bitcoin blockchain). Each partner over a given channel is bonded by individual channel rules and common rules of the whole network. These rules include trading and access rights of individual partner and the extent the partner can interact over the particular channel. For instance, an auditor can only access the channel with a read-only request (for the ledger) to approve transactions, however, they cannot add or modify them.

3.1.2. Peers

Peers are processing system that host the smart contract and/or shared ledgers on them. They facilitate generation, endorsement and/or validation of transaction depending on their role and contribution. In informatics, peers are different nodes that are connected together to form the network. Determined by the contribution, only the main partners of a supply chain (cluster) should host peer systems, as it involves investment and maintenance of the system. Rest other partners can simply access the ledger through an application. For example, sub-suppliers with a minimal contribution to the T&C supply chain need not invest in hosting a peer. They can just run the application on any device (smart mobile or PC) to access the blockchain. During the transaction validation process, peers are randomly selected based on the consensus mechanism to validate and endorse the transaction.

3.1.3. Applications

Applications are usually user-friendly interface (software) that can be used to make an input or any formal request on the blockchain. The can be a simple request- to read transactions, a post request - to add transaction or amend request - to read and change the transactions. Each partner can possess multiple devices that can run the blockchain application on it, however, they can only perform limited activities based on their access rules. Even an RFID or QR code reader can be directly connected to a channel to post traceability code and track/trace history of a particular product. A customer's application can connect the customer to the blockchain network to access publicly shareable information concerning the product.

3.1.4. *Ordering service*

They are typically third-party service provider, responsible for maintaining the network. They do not host any ledger, smart contract or generate/endorse/verify a transaction. Their main task is to collect a set of transactions that are requested at a given time on the blockchain, arrange them in a logical sequence, register it on a block and convey to the validating node. Once validated, it will forward and append the block to the shared ledger within that channel. Ordering service is also required to resolve a conflict in the form of 'fork' (Zamyatin et al., 2019).

3.1.5. *Membership services*

In a private blockchain network for a supply chain, membership services generate and provides a unique public-private key pair to each participating partner. These key pair determine the type and extent of accessibility of each individual partner on the blockchain network depending upon their role and responsibility.

Figure 4, is a simplified representation of the proposed blockchain network for the T&C supply chain. It shows a simple network with two channels, each for a particular set (cluster) of supply chain partners including the retailer (RE). In this example retailer is the focal firm that initiates the blockchain and hosts multiple channels for various clusters of the supplier. Each cluster of supply chain partners - trading in a particular asset - interact on an individual channel (Channel 1 and Channel 2). Partners' interaction on channels is governed by the individual channel rules (C1 and C2) and by common channel rules (CN). There are multiple peer systems (e.g. P1a and P1b for Channel 1 and P2a and P2b for Channel 2) associated with single channel that can host single smart contract and ledger (e.g. P1a hosting S1 and L1) or multiple smart contracts, and multiple ledgers (e.g. PC hosting S1 and L1 at the same time S2 and L2) . A1a and A1b are

applications to access Channel 1; similarly, A2a and A2b to access Channel 2. AC, on the other hand, can access both channels and ACus is an application for the customer.

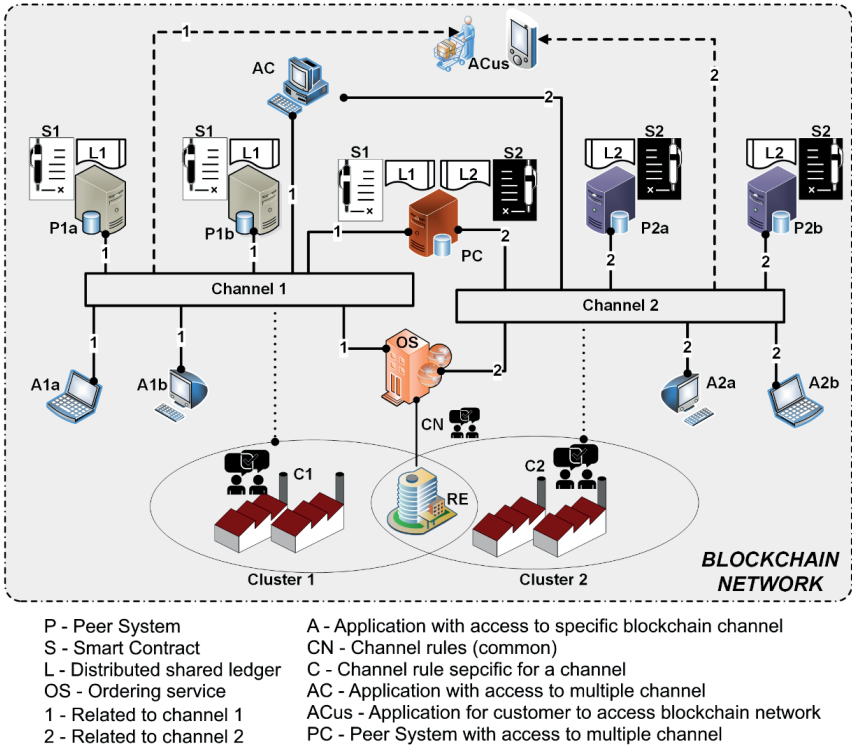


Figure 4 A simplified representation of the proposed blockchain network for T&C supply chain with the retailer (RE) as the focal firm initiating the blockchain

3.2. Operational level

For designing blockchain-based traceability framework, it is equally important to analyze and relate it to the operational level. Especially in case of the T&C supply chain, that involves multiple operations on the tangible fashion products. These products form the core of the T&C supply chain and traceability is all about data management of these products throughout the supply chain. Hence, a blockchain-based framework at an operational level includes planning, gathering, arranging, and exchanging the traceability information.

In T&C supply chain – except retailer and few mediators, most of the partners take raw materials as input from an upstream partner(s); perform various operations on it to make the

final product that passes to the next downstream partners (Kumar et al., 2017). This process replicates repeatedly until the product reaches the retailer. As a result, a significant amount of information is generated at each supply chain stage that required proper collection and management. This information acts as a critical component of the supply chain and each partner works towards controlling its flow and protecting the confidential information. However, not all of this information should be recorded on the shared ledger of a blockchain-based traceability network. This will make the network slow, cumbersome and inefficient. Thus, a blockchain implementation also requires advance planning and classification of the essential traceability information that can go on the shared ledger through consensus of each partner (Agrawal and Pal, 2019). In addition, it is also necessary that this information should comply with the obligation of the next downstream partner(s), accrediting agencies (like ISO), local government, an international association and/or third parties associated or monitoring the supply chain. To reduce the complexity, as proposed by Kumar et al. (2017), one of the effective solutions would be to divide the traceability information into four sets: Private shareable, public shareable, secured, and linking information.

3.2.1. *Private shareable information*

It is crucial among B2B partners, a specialty for the next downstream partner(s) for performing business operations. However, they are secured and cannot be accessed by a third party or customer.

3.2.2. *Public shareable information*

It can be shared with the customer and with any third party. They are some of the essential information that should be recorded and shared at all stages of product transformation in order to comply with the accreditation and regulations from the local government. The extent of collection and sharing of public shareable information would determine the transparency level of a supply chain for its customer.

3.2.3. *Secured information*

It is encoded information that can only be accessed by an authorized partner within the channel. This secured information is sensitive and confidential. It can include financial data, IP data and various other information that can be a source of competitive advantage.

3.2.4. *Linking information*

It is most crucial for the functioning of the blockchain. It is the information that would be validated during each transaction against the shared ledger that is governed by the smart contract. This would contain four value field and a combination of all this would be confirmed against the global state of the shared ledger to validate the transaction. These four value fields are:

- ***Traceability ID or Lot ID*** is a unique identification code differentiating each TRU from the other similar TRUs. It is a crucial element of traceability and essential to bind each TRU with the traceability information. It also facilitates tracing of asset lots even after they are divided, mixed or recombined. These IDs could be generated through a time-based function to ensure its uniqueness.
- ***Public Key*** is like the identity of the authorized partner performing that transaction. This key is a crucial element to trace and verify the claim. During transaction validation, as a first step, the public key of the trading partner is checked against the shared ledger to verify if he/she has sufficient balance of asset in their account i.e. equal or more than what he/she is transferring.
- ***Transaction signature*** is a combination of the public key, private key and the ID or address of the authorized partner pair that has initiated the transaction. It ensures whether the transacting partner has the right to perform a transaction on the blockchain and check if the partner actually possesses the asset that they are trading.
- ***Asset Value*** is the amount of asset been traded on the supply chain.

After planning and organizing, an effective capturing and recording of the information at each stage of the supply chain is equally important. As stated above, each supply chain partner can access the blockchain through applications and input transactions. The transaction signature will define the type of accessibility. In fact, to automate this process various sensors can also be directly linked with blockchain that can record data and get a response. As a final step, data exchange and record keeping model like UTXO and Account/balance model (explained in section 2.2.2) can be adopted based on the asset and its transaction.

4. BLOCKCHAIN-BASED TRACEABILITY OF ORGANIC COTTON – A USE CASE EXAMPLE

We demonstrate the application of the proposed framework through an example blockchain program written in Python 3.7.2, HTML and Flask (Python-based web framework). The blockchain is formulated taking into account one of the possible channels in T&C supply chain dealing with a cluster of partner trading with organic cotton. The supply chain starts with organic cotton supplier and passes through all the textile product transformation stages until the retailer gets a final textile product (or garment) made 100 % organic cotton composition. From here on, we will refer to this product (or garment) as ‘organic product’ in our study. The example demonstrates the application of the blockchain-based framework in tracking and tracing each transaction and collect crucial traceability information associated with this organic product. It should; (i) restrict an unauthorized transaction on the ledger that can result in a fake, non-organic or foreign product entering the supply chain, (ii) allows customer and/or a third party (based on their accessibility) to access the public shareable information related with the organic product and (iii) build a technology-based trust among the supply chain partners. Following are the main components of the example blockchain.

4.1. Supply chain partners

In this example scenario, we define the following partner:

- i) ***Organic Cotton producer/supplier (OCS):*** This is a certified cultivator or supplier (with several organic farms) of pure organic cotton with a trustworthy track- record. The OCS is the only actor in the supply chain that has an authority to add and transfer organic cotton mass on his/her blockchain account, rest other partners can just transfer the mass. In other words, OCS is the only partner that has the right to make both input and transfer entry on the shared ledger. This organic cotton mass is constantly monitored based on the production capacity of the OCS. Thus, the OCS can only trade up to a certain mass in a given time period. In addition, the farms are regularly inspected by a certifying agency that provides a time-bound certificate of authentication, which implies that the OCS can add mass on the shared ledger until the validity period of his/her certificate. After adding organic cotton mass in his blockchain account, OCS perform transfer operations on the blockchain. Each transaction contains a certain mass of organic cotton (in forms of bales) which is transferred to downstream partner (in this case yarn manufacturer) with a time-based unique Traceability ID.

- ii) **Yarn Manufacturer (YM):** is a fiber-spinning mill that receives/buys these bales (mass of organic cotton fiber) from the OCS and convert them into cones of yarns. YM further divide these yarn cones into different batches (each with certain mass) and transfer them to next partner (in this case fabric manufacture) through their blockchain account. Each batch is assigned with a new time-based Traceability ID that includes an impression of previous Traceability ID of the cotton fiber provided by OCS.
- iii) **Fabric Manufacturer (FM):** is a weaving mill that receives a certain mass of organic cotton - in form of yarn cones - from YM (physically and in their blockchain account) and manufacture fabric with them. FM divides this yarn batch into fabric rolls and further mark them with time-based Traceability ID that includes an impression of previous Traceability ID of the cotton yarn batch provided by YM.
- iv) **Apparel Manufacturer (AM):** receives a certain mass of organic cotton fabric of cotton (in rolls form) and constructs them into a finished organic product. AM makes organic products and assigns them with new Traceability ID that includes an impression of previous Traceability ID of the fabric provided by the FM.
- v) **Retailer (RE):** receives the finished and ready-to-sell organic product from AM. Now By connecting with the blockchain network and accessing the shared ledger, the RE can track and trace all involved supply chain partner, know the history of the organic product and ensure the origin and authenticity of organic cotton.

4.2. Smart contract

In our example, to authenticate the transactions, we follow the concept of ‘mass balancing’ to keep track of the mass of organic cotton generated by OCS and transferred to all other downstream partners until it reaches the RE. It is a widely used logic for the conservation of mass in a physical system, which states that mass cannot disappear and neither can be created spontaneously. Mass balancing accounts the material entering and exiting along with the current mass accumulated in the system. Each trading (including splitting) of amounts is tracked and recorded with the corresponding transaction within the blockchain system. Double trading or transfer of the same amount/asset is almost impossible in a mass balancing system (Wills and Finch, 2016). In mathematical terms:

$$\text{Input} = \text{Output} + \text{Accumulation}$$

Where, 'input' is the total balance of asset in the trader's account which he/she has received from another partner or generated of his/her own (like in case of OCS), 'output' is the amount he/she has transferred in all transactions and 'accumulation' is the balance left after transfers. Therefore, each transaction will be validated with the mass balancing logic to check the organic cotton being traded origin from a genuine source. The algorithm checks whether the transferring partner actually possesses the mass of organic cotton (in forms of fiber, yarn, fabric or finished product) he/she is trading and if the asset being traded acquired from a genuine source. The mass being traded should also come from a traceable lot(s) with a trail of authentic and unique traceability IDs. For record-keeping, we have followed the Account / Balance method. The algorithm keeps track of the asset balance in each partners' blockchain account as a global state in the shared ledger. Unlike UTXO (use in Bitcoin), the Account / Balance method is more effective for record-keeping when the same blockchain has to deal with multiple types of assets. A possibility that is not considered in this example could be the case where a single partner can supply various type of fiber (e.g. polyester, acrylic, rayon, etc.) and in the later stages, these fibers are blended during the product transformation in the supply chain.

4.3. Permission

As stated before, in private blockchain each partner has a unique ID that is associated with a public and private key pair. In our example, the private and public key pair for each partner is generated using the RSA (Rivest-Shamir-Adleman) algorithm (Rivest et al., 1978). Likewise, in the blockchain application, while doing a transaction; a transferring partner will input his/her unique ID, private key and the unique ID of the recipient. The web interface developed for the public and private key generation is shown in Figure 5. Using the RSA algorithm it developed interrelated public and private key pair on every click. This can be used by Identity or Membership service to generate and assign unique key pairs for all partner and for new partners joining the blockchain. This public and private key for each supply chain partner can be further linked with his or her KYC (Know Your Client) information for better visibility and transparency in the supply chain. These key pairs determine the access rights of each partner on the blockchain network.

Identity Service Provider

Click on the button below to generate a unique public/private Key pair for a supply chain partner

[Generate Public/Private Key](#)

Unique ID:

Public Key:

30819f300d06092a864896f70d010101050003818d0030818902818100a2d6daa39aa236dcb768552136ddf4596f2ccb9e9
9db988a00363897084422a9eb0889bde2c048dc952874b19e9fe9ca5a17253344721954c50c9f8cc3540566d7b61e0a8c1
c6f31ebcf82c6a4d96 e9ce03208deef514fd07f990f69bd7102ba76e1e01a017853895b5ee3dae0ffc20988c4606373de9c9
41980df5f6dcc530203010001

Private Key:

3082025e02010002818100a2d6daa39aa236dcb768552136ddf4596f2ccb9e99db988a00363897084422a9eb0889bde2
c048dc952874b19e9fe9ca5a17253344721954c50c9f8cc3540566d7b61e0a8c1c6f31ebcf82c6a4d96de9ce03208deef51
4fd07f990f69bd7102ba76e1e01a017853895b5ee3dae0ffc20988c4606373de9c941980df5f6dcc5302030100010281801
ba3c470c8aa880d66c43aceec753828860a6075874012e039b0fa62087128411737d7c9775794067cfae4f3d12ceb8e01
44b477c3426ab24cd01bb4d4e2ca17a96357cc81270c9f9d61e4ba98f772da57646299c7bf381cb8e513fa08eda6e544aa
1c01c044a6b99948c71daef73a017480c2a77921367a4d07b97c9b0d4108102a100c546fa49940b18a2f02a276f68a4c676e6

[Save the Identity](#)

IMPORTANT

- **WARNING !:** Don't share your private key with anyone!

Figure 5 Web interface for the public and private key generator

4.4. Consensus:

The example blockchain program runs on two peer nodes on a single computer system. The first peer generates all the transactions; the second one validates them against the shared ledger. If validated, the transactions are written on a block that contains block ID, a hash of the previous block, transactions (along with the traceability information) and address of the validating peer. For demonstration purpose, the proof-of-work consensus mechanism is followed with a very low difficulty level to generate the nonce value for each block.

4.5. Transactions:

The example blockchain demonstrates a simple scenario of trading and transfer of organic cotton from fiber supplier (OCS) to retailer (RE) in sequential order i.e. simulating the material flow as it actually happens in a T&C supply chain. However, in practice, there are multiple partners at each supply chain stage that can be simultaneously connected on the blockchain network initiated by a single retailer, over different channels (as explained earlier). In addition, an individual partner can receive an asset from one or more upstream suppliers, and similarly can transfer the asset to one or more downstream partners. A complex T&C supply chain network is as shown in Figure 6.

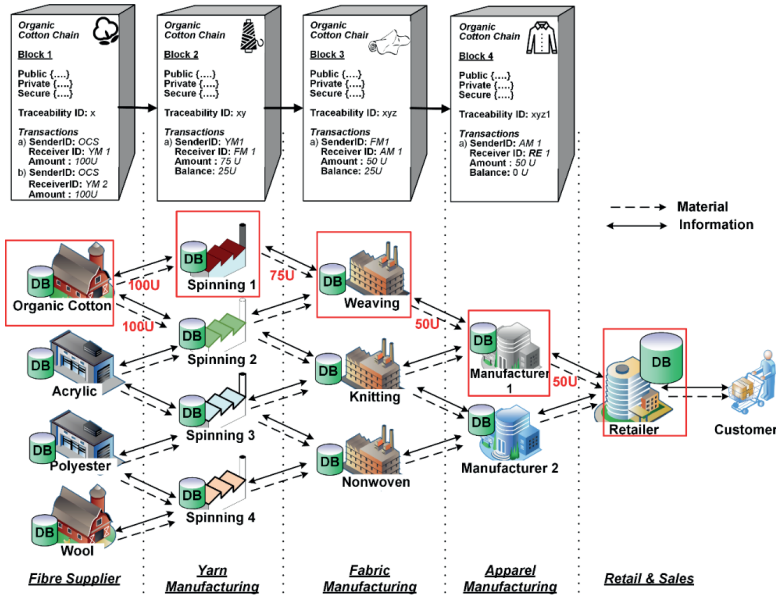


Figure 6 A complex T&C supply chain network with a marked partner involved in the example scenario

It can be observed that a single RE can have multiple suppliers at each supply chain stage, with many possible permutations. However, for ease of understanding and explanation, in this example, only one channel is considered and only four sets of transactions are performed and recorded on the shared ledger. Each transaction set is performed by a particular supply chain partner using the 'Trade Organic Cotton' interface as shown in Figure 7, and later verified and recorded as a single block on the blockchain. The interface collects sender Unique ID, sender Private key and recipient unique ID, and as an initial step verifies if the traders are legitimate partners on the blockchain network. Then it cross-checks the available balance of the asset (organic cotton mass) in the sender's blockchain account on shared ledger with the amount he/she is transferring on the interface. If found valid, the transaction is written on the blockchain and the amount is updated in the traders account on the shared ledger.

Trade Organic Cotton

Enter transaction details and click on "Transfer" button to transfer your asset

Sender Unique ID:	
Sender Private Key:	
Recipient Unique ID:	
Amount to Send:	

[Transfer](#)

Figure 7 Web interface to perform transactions

Being a fiber supplier, only OCS has the permission to add the new mass of organic on the shared ledger and subsequently in the supply chain. Therefore, as demonstrated in Figure 6, OCS uses his/her public/private key, generate the genesis block (Block 0) and adds 200U (U stands for units) of organic cotton on his/her account on the shared ledger. This block is hashed and act as a starting point of the blockchain. OCS perform another transaction in which 100U of organic cotton is transferred to yarn manufacturers (YM1 and YM2) respectively. This is recorded on Block 1, which is hashed and balance is updated on the shared ledger. After this, YM1 transfers 75U of organic cotton (in the form of yarn) to fabric manufacturer (FM1) and retain a balance of 25U. The transaction is again validated against the shared ledger, recorded on new Block 2 and hashed. Subsequently, FM1 makes fabrics from the obtained 75U of organic cotton (in the form of yarn) and transfer 50U of it to apparel manufacturer (AM1). The transaction again follows the same validation steps and forms a new Block 3. Finally, AM1 construct organic product from these 50U organic cotton (in the form of fabric) and transfer it to the retailer (RE). This transaction is validated and recorded as Block 4.

4.6. Supply chain traceability

At this stage, the Retailer (RE) can trace all the subsequent transaction on the blockchain by accessing the shared ledger entries and validate the authenticity of the cotton in the organic product. A snapshot from the web interface is shown in Figure 8 that shows all the transactions that occurred in the example scenario along with the timestamp. The figure shows details related to each transaction with traders' Unique ID, amount traded, and the validator node with the time of transaction. This would enable secured traceability in the supply chain with a technology-based trust. A snapshot of the full blockchain is presented in Figure 9 and 10 that

shows all transactions and block data as they occur and are recorded in different blocks. Highlighted are the actors involved in the transaction (trading partners), value being traded, previous hash, nonce, timestamps and most importantly how the blocks are linked with the previous and next block forming the chain of transactions.

Show entries Search:

#	Recipient Address	Sender Address	Value	Timestamp	Block
1	30819f300d06092a864886f7...	30819f300d06092a864886f7...	200	Feb 10, 2019, 5:49:39 PM	0
2	aa90ea9de7bf4fc68afe87e6...	THE VALIDATOR	0	Feb 10, 2019, 5:49:39 PM	0
3	30819f300d06092a864886f7...	30819f300d06092a864886f7...	100	Feb 10, 2019, 5:52:02 PM	1
4	30819f300d06092a864886f7...	30819f300d06092a864886f7...	100	Feb 10, 2019, 5:52:02 PM	1
5	aa90ea9de7bf4fc68afe87e6...	THE VALIDATOR	0	Feb 10, 2019, 5:52:02 PM	1
6	30819f300d06092a864886f7...	30819f300d06092a864886f7...	75	Feb 10, 2019, 5:53:19 PM	2
7	aa90ea9de7bf4fc68afe87e6...	THE VALIDATOR	0	Feb 10, 2019, 5:53:19 PM	2
8	30819f300d06092a864886f7...	30819f300d06092a864886f7...	50	Feb 10, 2019, 5:54:19 PM	3
9	aa90ea9de7bf4fc68afe87e6...	THE VALIDATOR	0	Feb 10, 2019, 5:54:19 PM	3
10	30819f300d06092a864886f7...	30819f300d06092a864886f7...	50	Feb 10, 2019, 5:54:59 PM	4

Figure 8 List of transactions as they occur on the blockchain



Figure 9 Blockchain for organic cotton traceability (Part1)



Figure 10 Blockchain for organic cotton traceability (Part I)

5. CONCLUSIONS

Blockchain is a distributed ledger which works without a central authority and allows creating decentralized and immutable storage of data which is verifiable and traceable. Due to these unique features, it has been explored for various applications mainly in the financial sector. Recently, a shift has been observed in terms of exploiting novel application in the supply chain context, particularly to create transparency and traceability.

In this direction, this paper presents a blockchain-based traceability framework for the supply chain with a case example of the T&C supply chain. It provides a critical discussion on various essential components of blockchain for information/material exchange, supply chain partners' interaction, distributed ledger arrangement, smart contract development and information/material traceability and security in a commissioned or private blockchain network with restricted access to the supply chain partners, based on their roles and responsibilities. To support the proposed framework, the paper further develops and illustrates an example blockchain with mass-balancing based smart contract to authenticate the blockchain transaction and update the shared ledger. Although the blockchain-based traceability framework has been proposed for the T&C sector, it can be further adapted for similar supply chains.

The future research can be focused on formulating the sector-specific smart-contact formulation which accommodate the supply chain actor specific activities and requirements. Furthermore, the roles of certifiers should be identified and accommodated in the smart contract for blockchain-based traceability. Nonetheless, the present paper provides a comprehensive understanding to design blockchain-based traceability for a complex scenario.

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