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Exploring fully integrated textile tags and information systems for implementing traceability in textile supply chains

Exploration de marqueurs textiles entièrement intégrés et de systèmes d'information pour la mise en œuvre de la traçabilité dans la chaîne d'approvisionnement des textiles

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Abstract

Exploring fully integrated textile tags and information systems for implementing traceability in textile supply chains

Traceability, in general, refers to keeping track of information to a certain degree. The concept of traceability is considered important to verify the various aspects of products in different industries and their global supply chains. Textile industry is among those which are accused time-to-time for opaque supply chains and unsustainable practices. Particularly, the aftermath of a series of industrial catastrophes, customers and non-government organizations have started to scrutinize the brands to bring transparency in their supply chains. In this direction, traceability has been identified as a tool for organizations to trace their supplies throughout the supply chains and collect relevant information to ensure transparency and claim validation. Traceability has been further acknowledged as a competitive element and often acts as a decisive factor in purchase process. Moreover, the textile products are one of the most counterfeit-prone items around the world. As a result, the demand for traceability has been intensified for supply chain monitoring and security, and product authentication.

The principal aim of this thesis was to address the implementation of traceability information systems in the textile supply chain. Further, it investigates the feasibility of yarn-based integrated tracking tags as a means to impart traceability in textiles. It has been pursued through several independent studies in the domain of textile manufacturing, supply chain management and information systems. The appended papers in this thesis address various aspects of traceability implementation in the textile supply chain and how traceability information can be encoded into the textiles using yarn-based coding.

Traceability consists of two components namely information system and tagging. The latter component is used to uniquely identify the product in the supply chain which assists in recalling and/or storing the relevant traceability data from/in the information system. Different actors in the supply chain manage the traceability data in their information systems, therefore traceability tag acts as a linking agent for information exchange. In this direction, this thesis introduces the concept of yarn coding and yarn coding-based integrated tags which can be potentially used in future for textile traceability applications. In addition, a framework is proposed for the implementation of traceability information system in the textile supply chain. The work highlights various elements which can play a significant role in promoting and/or implementing traceability. Regardless of perspective or viewpoint, traceability is interwoven between technical and managerial aspects; therefore traceability implementation requires a techno-management approach to obtain an optimal solution.

Keywords: Traceability, Textile, Yarn coding, Integrated tag, Supply chain management

Abstrakt

Utforskning av integrerad textil märkning och informationssystem för implementering av spårbarhet i den textila försörjningskedjan

Spårbarhet brukar generellt hänföras till att följa information till en viss grad. Konceptet spårbarhet anses betydande för att kunna verifiera olika slags aspekter gällande produkter i diverse industrier och deras globala försörjningskedjor. Textilindustrin är en industri som ibland anklagas för att ha en så kallas "ogenomskinlig" försörjningskedja samt ohållbara verksamheter. I synnerhet, till följd av en rad av katastrofer inom industrin, har konsumenter och frivillighetsorganisationer börjat rannsaka varumärken att öka transparensen i deras försörjningskedjor. Transparens har genom detta blivit ett verktyg för organisationer att spåra deras produkter genom hela försörjningskedjan samt samla in relevant information för att kunna garantera spårbarhet och hävda validitet. Spårbarhet har även blivit erkänt som en konkurrensfördel och kan även vara avgörande i en köpprocess. Textila produkter är en av de mest förfalskade produkterna här i världen. Som följd av detta har efterfrågan av spårbarhet ökat för att kunna övervaka och säkerställa försörjningskedjan regeluppfyllnad samt verifiera produkters autentiserat.

Syftet med denna avhandling är att adressera implementeringen av spårbarhetsinformationssystem i den textila försörjningskedjan. Vidare, att även undersöka möjligheten för en fullt integrerat garn-baserat spårningsmärkning som ett hjälpmedel spårbarhet i textila produkter. Detta gjordes genom flera självständiga studier inom textil tillverkning, försörjningskedjan samt informationssystem. I denna avhandling finns det bifogade artiklar som behandlar olika aspekter gällande implementering av spårbarhet i den textila försörjningskedjan och hur information av spårbarhet i textil kan överföras till data genom att använda garn-baserad kodning.

Spårbarhet består av två komponenter, informationssystem och informationsbärare (tag). Taggen används för att identifiera produkten i försörjningskedjan vilket också bistår i att återkalla och/eller lagra relevant spårbarhetsdata från/i informationssystemet. Olika aktörer i försörjningskedjan hanterar spårbarhetsdata i deras egna informationssystem och därför kan spårbarhetsmärkning agera som länkande element för informationsbyte. Denna avhandling introducerar garn-kodningskonceptet och en fullt integrerat garn-kodningsbaserad märkning som i framtiden skulle kunna användas för textila spårbarhetsapplikationer. Ett ramverk föreslår informationssystemkomponeter för implementering i den textila försörjningskedjan. Avhandlingen betonar olika element som kan spelar viktiga roller för implementering av spårbarhet. Oavsett perspektiv eller synpunkt, spårbarhet är sammanvävt mellan teknologiska och organisatoriska aspekter; därför kan implementering av spårbarhet kräva en så kallad techno-management synsätt för att kunna anskaffa optimala lösningar.

Nyckelord: Spårbarhet, Textil, Garn-kodning, Integrerad märkning, Hantering av försörjningskedjor

Résumé

Exploration de marqueurs textiles entièrement intégrés et de systèmes d'information pour la mise en œuvre de la traçabilité dans la chaîne d'approvisionnement des textiles.

La traçabilité, en général, fait référence à un suivi de l'information jusqu'à un certain point. Le concept de traçabilité est considéré comme un élément essentiel pour vérifier les divers aspects des produits dans différentes industries et leurs chaînes d'approvisionnement mondiales. L'industrie textile est parmi celles que l'on accuse de temps en temps d'un défaut de transparence dans leur chaîne d'approvisionnement et faisant parfois appel à des pratiques insoutenables. C'est plus particulièrement après une série de catastrophes industrielles que les consommateurs et les organisations non-gouvernementales ont commencé à s'intéresser de près aux marques avec le souci que les entreprises apportent plus de transparence à leur chaîne d'approvisionnement.
Dans cette logique, la traçabilité a été identifiée comme un outil permettant aux entités de tracer leurs approvisionnements tout au long de la chaîne de transformation et de collecter des informations pertinentes afin d'assurer la transparence et de répondre dans la mesure du possible, aux attentes. La traçabilité a été reconnue comme un avantage compétitif qui agit souvent comme un facteur clé dans la décision d'achat. De plus, les produits textiles font partie des biens les plus contrefaits dans le monde. Par conséquent, le besoin de traçabilité s'est intensifié en ce qui concerne la surveillance et la sécurité de la chaîne d'approvisionnement tout autant que pour l'authentification des produits.

L'objectif principal de cette thèse est d'aborder la mise en œuvre des systèmes de traçabilité de l'information dans la chaîne d'approvisionnement textile. En outre, elle interroge la faisabilité d'un traçage basé sur l'intégration de marqueurs de suivi à l'échelle des fils, comme un moyen d'insérer une traçabilité dans les textiles. Cet objectif a été mené à travers plusieurs études indépendantes dans le domaine de la fabrication du textile, de la gestion des chaînes d'approvisionnement et des systèmes d'information. Les documents annexes à cette thèse apportent divers éclairages sur l'intégration d'une traçabilité dans les chaînes d'approvisionnement textiles et sur comment une information traçable peut être codée à l'intérieur de textiles via l'utilisation d'un codage basé sur le fil, échelle intermédiaire entre les fibres et les étoffes.

La traçabilité se divise en deux parties, à savoir le système d'information et le marquage. Ce dernier point est utilisé pour identifier de manière unique le produit dans la chaîne d'approvisionnement et aide à rappeler et / ou à stocker les données de traçabilité pertinentes dans le système d'information. Différents acteurs de la chaîne d'approvisionnement gèrent les données de traçabilité dans leurs systèmes d'information, de sorte que le marqueur agisse comme un élément de liaison pour l'échange d'informations. De ce point de vue, cette thèse introduit le concept de codage des fils et de balises intégrées pouvant potentiellement être utilisé dans le futur pour des applications de traçabilité des textiles. De plus, un cadre général est proposé sur l'intégration d'un système d'information sur la traçabilité des textiles dans la chaîne d'approvisionnement. Ce travail souligne différents éléments pouvant jouer un rôle significatif dans la promotion et/ou la mise en œuvre de la traçabilité. La traçabilité lie intimement les aspects techniques et organisationnels. Elle requiert donc une approche technico-managériale pour garantir une solution optimale.

Mots-clés : Traçabilité, Textile, Codage du fil, Balise intégrée, Gestion de la chaîne d'approvisionnement

摘要

面向纺织工业链可追溯性实现的封闭集成纺织标签及其信息系统开发

可追溯性，通常指的是对信息持续的追查。可追溯性的概念被认为在验证各种工业产品的各个方面及其全球供应链是重要的。纺织产业被归为前期不透明的不可持续的产业。特别是在一系列的工业灾难之后，顾客和非政府组织已经开始仔细审视品牌，促使其供应链增加透明度。从这个角度来说，可追溯性已被确定为一个为组织跟踪其整个供应链的供应，并收集相关信息，以确保透明度和索赔验证的一个工具。此外，纺织产品是世界上最容易伪造的物品之一。因此，对可追溯性的需求主要为了加强供应链监控和安全，以及产品认证。

本论文的目标是为了解决纺织品供应链中可追溯信息系统的具体实现。并且，以追踪纱线集成标签为技术基础来构建追溯方法为实现纺织品可追溯性提供了可能性。此技术涉及几个独立的研究领域：纺织制造、供应链管理和信息系统。在本文的附件中提供了在纺织供应链各个方面实现可追溯的实践情况，并且展示了这些可追踪的信息是怎样通过纱线为基础编码到纺织成品的编码。

本文中的可追溯性技术，包括两个组成部分，即信息系统和标签化。后者用于在供应链中唯一标识产品，它帮助在信息系统中召回和存储相关的可追溯数据。在供应链中的不同角色让在信息系统中的数据追踪成为可能，因此可追踪标签在信息追踪中作为连接元素出现。从这方面来说，本文介绍了纱线编码的概念和基于纱线编码的集成标签而且这可能在未来纺织可追溯性方面有所应用。此外，还提出了实现纺织供应链可追溯信息系统的框架。在推动和实现可追踪性中充当重要角色的各种元素是工作的重点。无论从哪个观点,可追溯性在技术和组织方面相互交织，因此可追溯性的应用需要技术可控才能完美解决问题。

关键词：可追溯性，纺织，纱线编码，集成标签，供应链管理

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Suzhou, China

Vijay Kumar

List of appended papers

Paper I:

Kumar, V. and Ekwall, D. (2016), "Macro-Scale Indicators Based Analysis of Textile Product Recalls in the EU". *In proceedings of Nofoma*, Turku, Finland

Paper II:

Kumar, V., Koehl, L. and Zeng, X. (2016), "A fully yarn integrated tag for tracking the international textile supply chain". *Journal of Manufacturing Systems*, vol. 40, 76-86.

Paper III:

Kumar, V., Koehl, L., Zeng, X. and Ekwall, D. (2017), "Coded yarn based tracking tag for textile supply chain". *Journal of Manufacturing Systems*, vol *42*, 124-139.

Paper IV:

Kumar, V., Hallqvist, C. and Ekwall, D. (2017), "A framework to implement traceability in the textile supply chain". *Systems*, vol. 5, issue 2, 33.

Paper V:

Kumar, V., Ekwall, D. and Wang, L. (2016), "Supply chain strategies for quality inspection under a customer return policy: a game theoretical approach". *Entropy*, vol. 18, issue 12, 440.

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1. Introduction

This chapter presents basic concept of traceability and its scientific, economic and social relevance. The focus of discussion will be based upon the technology and management driven aspects of traceability and their impact on manufacturing, supply chain relation, and end-users. The outcome of the discussion will pave a way for the research process and methodologies selected in this Ph.D. research.

1.1. Overview of textile industry and its supply chains

The textile industry is one of the first industries to adopt globalization in its supply chain. It is often considered as a typical starter for export-oriented industrialization and a facilitator for the economic development of countries with large semi-skilled or unskilled labour (Fernandez-Stark et al. 2011; Morris and Barnes 2008). Textile industry that we refer to in this thesis is an expression used for a group of industries primarily concerned with activities for the conversion of fibre into a finished garment and retailing to the end-user. In this context, the term *textile supply chain* is used to describe the chain of actors acting suppliers to each other, which is formed in the process to organize abovementioned activities (Kaya and Öztürk 2014). Textile industry plays an important role as a manufacturing sector in the World economy. World Trade Organization (WTO) registers a total global export of $797 billion of textile and apparel in 2015, which is 4.3% of total world merchandise trade in 2014 (World Trade Organization 2016). Developing countries account for three-quarters of the world clothing export (Fernandez-Stark et al. 2011). Besides this, the textile industry contributes to a significant employment in developing as well as developed countries. McNamara (2008) reported the worldwide employment of more than 40 million people in this sector and ~45% of which is only in China. Further, countries such as Cambodia and Mauritius have more than 70% of employment in all manufacturing industries is in the textile industry (McNamara 2008).

At the macro scale, textile industry can be divided into multiple sectors. Figure 1.1 shows an overview of various actors in the textile industry. The supply chain for apparels or clothing items, includes the raw materials sector – dealing with natural and synthetic fibres, yarn spinning mills – converting fibre into yarns, weaving and knitting mills – weave or knit fabrics from the yarns, chemical processing or fabric finishing industries – dealing with chemical processing, functionalizing and dyeing the fibres or fabrics, apparel manufacturers – cutting and sewing the fabrics into final garments and the retailers – retailing the garments in the markets and dealing with the end-users (Giri and Rai 2013). Similarly, the section of the industry is serving for non-apparel products such as home textiles and technical applications including geotextiles, medical textiles and other special purpose textiles have certain variations regarding actors and supply chains. In general, apparel or clothing sector is termed as conventional textile sector while sector targeting the non-apparel are termed as a non-conventional textile sector. All these sections are backed by different other industrial sectors for the functioning as shown in Figure 1.1. In this thesis, the focus is explicitly given to the supply chain leading to clothing or apparels. Therefore the term 'textile sector' or 'textile supply chain' here implies the apparel supply chain.

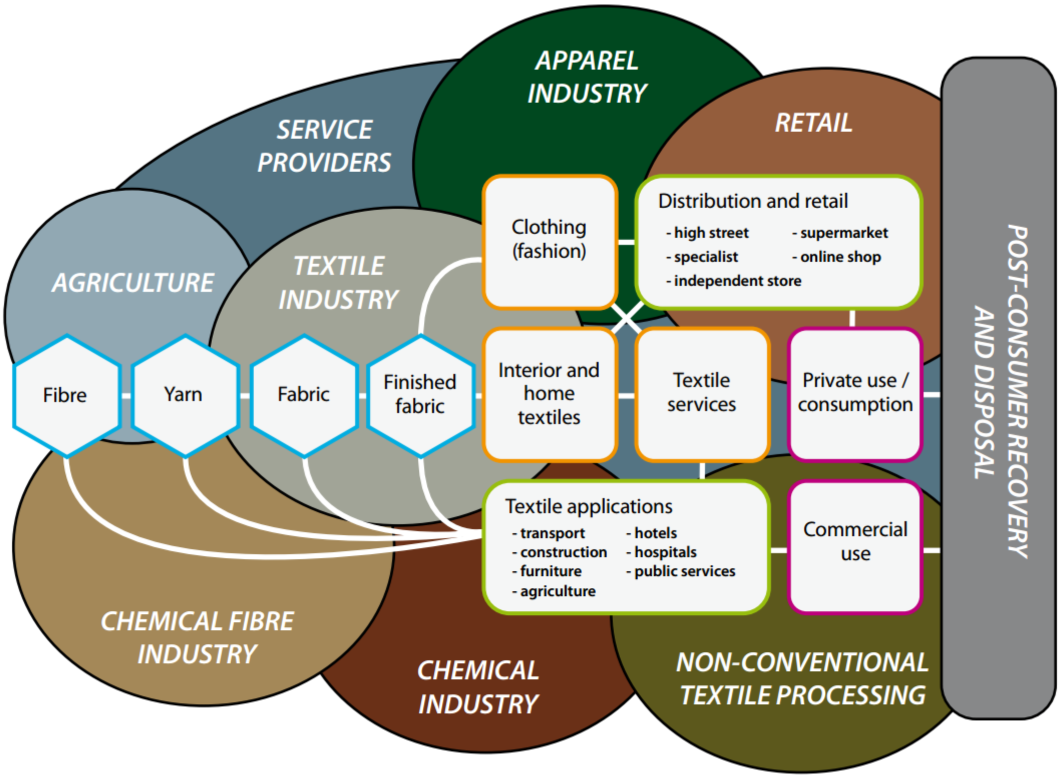


Figure 1.1 An overview of textile sector and its supply chains (Allwood et al. 2006)

The actors in textile supply chain distinctly differ in their operations and specializations, who are located in different geographical locations (Nordås 2004). Subsequently, the modern textile industry has a relatively long, complex and fragment structure. Furthermore, in the intensified global competition, the focus of a supply chain management from production efficiency perspective is preferred to follow customer-driven approaches and synchronization of various activities, which inevitably requires a high level of collaboration and communication among various supply chain actors (Jain et al. 2009). While, from the context of textile industry, the transparency and sustainability are some of the major customer concerns that have recently gained considerable attention, informational integration of different actors is the prime focus for synchronizing the various supply chain activities while meeting the market demands. In efforts to meet the abovementioned requirements, traceability has emerged as a prerequisite which not only facilitates in establishing the links to exchange critical information among various stakeholders but also keeping track of products and activities, thereby improving the supply chain visibility.

1.1.1. Characteristics of the textile sector

The textile industry has seen transformations in terms of actors' integrations, supply chain strategies and major area of development in past few decades. According to Appelbaum (2004), textile trade was historically dictated by the trade agreements until the WTO abolished the agreement on Textile and Clothing (ATC). In the '70s the textile supply chain was primarily driven by synthetic fibre manufacturers, and the business objectives targeted to low-cost products, high volume, and utilization of capacity (Rigby 1992). The features of supply chain included weak seasonal pattern and linear buying relationship, while the primary focus of innovation was synthetic fibres, dyeing, and finishing (Rigby 1992). Customers were less sensitive towards design and fashion. In the '80s, the sector was retailer driven, and the driving forces were increasing consumer demand for fashion besides many other factors. The textile supply chain features included more product variety, increased fashion seasons, while the focus of innovation of is on distribution systems, automation, and control (Rigby 1992). In the '90s and afterward retailers began to expand their range, and the static fashion became a seasonal phenomenon with more product variety and shortened product life (Rigby 1992; Tartaglione and Antonucci 2013). The customer evolution, technological advancements, the internet, and globalization have changed the arena including industrial delocalization, mass customization, fast fashion, and increased demand.

The present textile market is characterized by rapid and volatile demand, short product lifecycle, increased fashion seasons and variation within individual seasons, large product varieties with targeted customers (such as occasions, age-group, specific individuals, etc.), more customer buying impulse (Bhardwaj and Fairhurst 2010). For the textile markets of '80, Johns et al. (1987) defined the apparel in US domestic market in three categories – fashion, seasonal and basic with their market shares of 35%, 45% and 20% respectively. The first two categories have product life of 10 and 20 weeks, respectively. However, in 2007, Masson et al. (2007) reported the average product lifecycle is 3-6 weeks and ~15% of the total items in a retail store are newly introduced every week. Therefore, the retailers often need to have updated information about their stock levels and product sales profile to reduce the possible lead-time and engaging the customers with up-to-date products.

From the manufacturing aspect, the present textile sector is more focused on the mass customization, small orders to capture specific customer demands and integration of the supply chain. Customer oriented approaches are being adopted in which firms can interact their customers and supply chain actors continuously. Firms look for a competitive edge based upon fast-responsive techniques including just-in-time, quick response and agile supply chain (Bhardwaj and Fairhurst 2010). As the retailers outsource most of their production offshore to minimize the cost (or maximize the profit) of the final supply, it has led to a significantly long lead-times, limited supply chain visibility, complexity and inconsistency in processes at both ends of the chain (Bruce et al. 2004; Bruce and Daly 2006). According to Christopher (2000) and Choi (2007), the demand uncertainty and limited visibility have long been a challenge in supply chain management. Therefore, the present complexities have forced the industry to adopt various techniques to collaborate strategically and informationally integrate different actors to increase the supply chain visibility and generate fast and accurate information about the supplies in globally spread supply chain networks.

Characteristically, the supply chains are now becoming more open in terms opting information sharing techniques. Inter-organizational information systems including electronic data exchange (EDI) systems have gained popularity for exchanging a vast range of data ranging from simple invoicing information to complex transactions such as shared technical databases (Holland 1995). Furthermore, information technology (IT) is widely recognized as a critical component for assessing the performance as well as the competence of single actor as well as supply chain as a whole (Jin 2006). Information is an intangible component for a customer, and not only a significant section of the end-users has their buying preferences linked with this intangible component, but manufacturer/retailers have also identified this as a characteristic that can provide a competitive advantage (Guercini and Runfola 2009). For example, clothing brand Nudie Jeans Co. shares the information about suppliers with their sustainability practices which not only make their suppliers accountable to their practices but also assures the end-users that they are aware of the level of transparency in the products' manufacturing (Egels-Zandén et al. 2015). Therefore, the textile sector can be characteristically termed as transforming sector, progressing from slowly varying to a dynamic segment where, like many other sectors, IT is playing a critical role in not only transforming but also integrating it as a whole.

1.1.2. Division of textile sector

Depending upon the market segment they serve, Nordås (2004) categorized the textile supply chain actors into two groups – labour intensive and low-wage group as the first group, and dynamic, innovative and well paid as the second group. The actors serving to high-end fashion market are described as modern, dynamic industry with relatively well-paid workforce and mostly limited to developed countries. The actors of this group in the supply chain compete in term of demand forecasting and introducing fashion trends thus act as demand creator in the supply chain (Guercini and Runfola 2004). As brand-named merchandisers and trading companies (collectively called as retailer) work as trendsetter and order originator for upstream actors, according to Gereffi (1994), they play a pivotal role in creating a decentralized production network. This control over the market and demand generating capacity provide them dominance in the supply chain (Thomassey 2010).

The industrial segment with limited power, involved in the mass production and standard products mostly use semi-skilled with low-wage workers and primarily located in developing countries (Nordås 2004). The actors compete with each other on the basis of their ability to adopt the fashion trend imposed by the former group and supply the product with minimum possible lead-time (Guercini and Runfola 2004). The actors in the second group are often situated in geographical locations where they can be more economically efficient, have reliable access and can ship the supplies conveniently. For instance, the actors dealing with labour-intensive activities such as yarn spinning and weaving have seen a rapid migration towards Asia or the Far East where inexpensive workforce and availability of sub-suppliers help them to provide a competitive edge (Lam and Postle 2006). While the requirement of semi-skilled or unskilled labor making the textile industry as a vital industry for many less-economical developed countries, the ease of transportation and reduced production cost have driven them to compete with domestic suppliers located developed countries. As a result, the western countries have witnessed a substantial increase in import of textiles and clothing, mainly after the elimination of quota implied in the agreement on textiles and clothing (ATC) by world trade organization (Adhikari and Yamamoto 2008). Nevertheless, the textile supply chain is buyer-driven and main dominance remains with the big retailers irrespective of their location. To maintain the textile industry, western counties are further being forced to upgrade into high-value segment while the supply chain has become global.

1.1.3. *Information sharing and textile sector*

The availability of the information has been increasing at an exponential rate, and the digital communication is the backbones of almost every industry (H. P. Choi 2010). Information has become an integral part of the supply chain management where it provides possibilities and opportunities for various actors to improve the efficiency of the supply chains. According to Štorga et al. (2011), organizations would like to take the leverage of information irrespective of its source, which can help them to innovate or compete. Sharing information plays a crucial role coordinating actions and informed decisions by the actors in a supply chain (Solanki 2015). The textile supply chain is a long and complex network of actors, whereas the fashion market is volatile and unpredictable thus there is a need for high visibility in the supply chain (T.-M. Choi 2007). The actors are often distantly located to each other, which involve different laws, regulations, and standards according to the local jurisdiction (Boström et al. 2011). Therefore, information plays an important role not only in supply chain decisions and strategies but also in binding different actors to comply with local regulation as well as with the suppliers to comply with respective regulations. Furthermore, textile manufacturing involves chemical based processes including fabric dyeing and finishing. Use of any inappropriate or inferior quality chemical, or use above the permissible limit could lead to undesirable consequences. For example, a recent Swedish report claimed to found around 10 percent of the chemical used in clothing could pose a high human risk (Roizen and Oz 2015). Similarly, multiple brands' soccer clothing were found to contain hazardous chemicals (Siemers 2014). The use of chemicals is often regulated by local or regional (such as EU) regulations. As the textile supply chain is globally dispersed with most of the manufacturers located in Asia, while the buyers or brand owners located near to western countries (such as the EU member states and the US), the chemicals used by the suppliers or manufacturers need to comply with regulations of buyers' countries and conversely buyers should be aware of used chemicals with their quality and quantity. Inability to control the use of chemicals could lead to product recall besides other business consequences such as negative brand image, financial losses, the cost associated with the corrective actions, and so on. As a result, information about suitable/permitted chemicals and permissible usage limit play a pivotal role in the textile supply chain from suppliers' as well as buyers' perspectives. In fact, European regulations have put the responsibility on the industry to manage and evaluate the risk of chemicals; therefore, the supply chain actors (such as dyers and chemical processors) dealing with chemicals need to duly manage the information of chemicals they import or handle (Alves et al. 2014).

Besides the business functioning need, information is a key component when the transparency of the supply chain is concerned. The textile sector is long criticized for lack of transparency in its business (Khurana and Ricchetti 2016). The history of the textile industry is full of cases with unsustainable practices, such as involvement of child labor, marginal salaries to the workers, use of inferior chemicals and raw materials to increase the profit are to name a few. In fact, big brands were revealed to be indulged in these activities. Going back in 1990s, Nike was accused for involvement of child labor in its manufacturing process, which the founder and chairman, Phil Kinght admitted in 1998 (Khurana and Ricchetti 2016). In the year 2013, the eight-storey garment factory collapsing incident in Bangladesh – infamously known as Rana Plaza incident – left over one thousand dead and many more injured (Burke 2014; Clean Clothes Campaign 2013). Moreover, many famous fashion brands were sourcing their products from factories located in Rana Plaza building (Clean Clothes Campaign 2013). These events have raised the consumers' concerns over how transparent the textile supply chains are (Goswami 2014; T. Zhang and Kraisintu 2011). Pressed by the criticism from customers, regulatory authorities and non-governmental organizations, companies need to develop their strategies which imply to fulfill the local regulatory requirements to minimize the social and environmental risk (Gobbi and Massa 2015). In this context, information sharing is considered as a critical component in the textile supply chain.

1.2. Traceability

A growing number of organizations are looking for efficient and reliable solutions to follow-up the products, production activities and gather the related information to manage their business activities efficiently and comply with regulations. In this context, traceability has gained a considerable attention. The term traceability originates from the word 'traceable' which means capable of being traced. Cambridge dictionary describes traceability as the *ability to discover information about where and how a product was made* ("Traceability" n.d.). In the industrial context, traceability was defined internationally as *the ability to retrieve history, use or location of an entity by means of recorded identifications* in 1987 (ISO 1994). It was introduced in the context of food industry to increase the security and safety throughout the food chain. Over the decades, traceability has been emerged as a requirement in almost all sectors and 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; T. Zhang and Kraisintu 2011). According to Bechini et. al (2008, p. 342), *traceability is a needed strategic service in any production context*, which can be used in quality controlling, counterfeit protection and management of the complex supply chains.

In the past, traceability has been used differently in different sectors. In logistics, traceability refers to the track and trace the shipments in the supply chain using different serial numbers (Shamsuzzoha and Helo 2011), while the sectors including supply chain, food and forest, refer traceability as collection, documentation, maintenance, and application of information to comply with regulatory and convey the material source, safety, ethical and sustainability information to the consumers (Opara 2003). The above-stated aspects have been used in many other sectors, including textile, by different firms (Egels-Zandén et al. 2015; Egels-Zandén and Hansson 2015). Software industry uses a particular term 'Requirement traceability' to track various stages of software development and evolvement of requirements (Pinheiro 2004). Despite the different applications, the core notion of traceability is probably defined in the best term 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, p. 354).

The primary focus of the thesis is from textile supply chain perspective, so emphases are given to information about the product and processes. According to an expert panel set by European Commission (Informal Product Traceability Expert Group - Final Report 2013), traceability management uses the association of flow of information with the physical product. In this context, Figure 1.2 illustrates a general configuration of traceability using two consecutive actors S1 and S2 in the supply chain, which will be used later in the thesis. Here, S1 serves as an upstream supplier to S2 while S1 has its own suppliers from whom it imports or gathers the inbound materials. In the context of traceability, it is imperative that when these actors exchange the physical products, they also exchange of product-related information. Within this context, Figure 1.2 shows two channels i.e. one for the information flow and one for physical product flow. The channels are connected by the traceability tags, which act as information mapper and remain with the physical products, thus make links of physical product with the information. While the goal of traceability implementation is systematically managing the information about the lots (i.e. products) and activities (or processes) which essentially relies on data models with lot and activities as key entities, traceability tags maps these key entities with the physical product or Traceable Resource Unit (TRU), thus segregate or substantial each TRU uniquely in the supply chain.

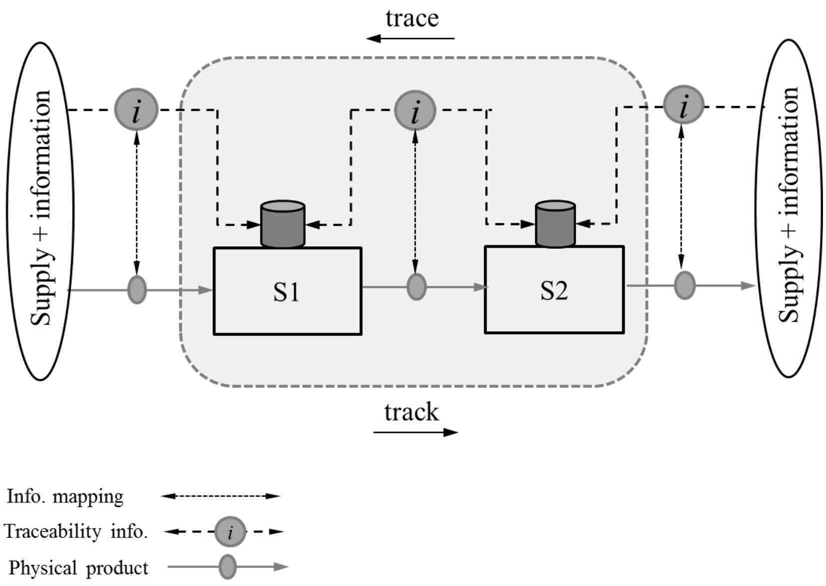


Figure 1.2 Traceability in supply chain

The configuration of S1 and S2 in Figure 1.1 can be seen as two immediate actors in the textile supply chain, such as yarn manufacturer (i.e. *yarn* stage in Figure 1.1) and fabric manufacturer (i.e. *fabric* stage in Figure 1.1), where former acts as an immediate supplier to the latter.

1.2.1. Definitions of traceability

Traceability has been widely defined in literature from different perspectives. Some of the widely used definitions are described in this section.

ISO 8402:1994 (ISO 1994) defines traceability as

> *[…] the ability to trace the history, application or location of an entity by means of recorded identifications.*

Another definition which is highly cited in the literature belongs to Moe (1998, p. 211), which states,

> *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).*

GS1 Global Traceability System (Ryu and Taillard 2012, p. 13) 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.*

In addition, according to van Dorp (2002), the definition of traceability varies based on organizational context and targeted application. Schwägele (2005) defined traceability in two components as track and trace, where former can be stated as *the ability to follow the path of an item as it moves downstream through the supply chain from the beginning to the end*, whereas the latter is stated as *the ability to identify the origin of an item or group of items, through records, upstream in the supply chain*. However, there is another viewpoint which addresses traceability as *generation of information on products and production processes, examining the way this information is shared among different actors* (Guercini and Runfola 2009, p. 883).

The research work presented in this thesis was intended to investigate the traceability from its operation perspective in the textile sector; therefore we comprehend traceability from its operational or basic functioning aspect and follow the definition proposed by Djatna and Ginantaka (2014, p. 354) as,

> *[…] the capability (and implementation) of 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.*

As product and information are two inseparable components in a traceability system, the implementation of a traceability system should not only include a mechanism for storing and interrelating the information but also assuring through certain authentication mechanisms that the traceability information belong to a specific product, thus preventing the use of traceability information with counterfeit goods.

1.2.2. Basic components of traceability

Traceability is a multi-facet concept, which combines technological and managerial attributes. It requires encoding of information pertaining to the product and processes, which requires the management of information in collaboration with multiple supply chain stakeholders (Guercini and Runfola 2009). While keeping the track of every product and traceability data collection incline on the technical capabilities including information technology (IT) and traceability tags (such as RFIDs, barcodes, QR codes and other labels), the extent of information sharing, data sharing policies, and targeted objectives rely on managerial part (Gobbi and Massa 2015). From the implementation perspective, the structure of a traceability system obviously varies depending upon the extent of information to capture and communication among the supply chain actors. Nonetheless, a traceability system enables the rapid intervention to correct or prevent errors in the product life cycle; therefore traceability is regarded as a strategic element in any production context (Bechini et al. 2008; Gobbi and Massa 2015).

Moe(1998) defines the structure of traceability systems in following components.

- **Structure of system**

The structure of the system underlines the basic procedures to identify the products uniquely and the required degree of traceability. It involves the route and means of identifications of products to identify in the supply chain.

- **Core entities**

Core entities define the products and set of essential descriptors that must be incorporated to secure ideal traceability. Based upon the organizational requirements and the required degree of traceability, the descriptors can be related the quality attributes, environmental loads, processing, material handling, and buying and selling attributes.

- **Traceable resource unit (TRU)**

Traceability resource unit (TRU) defines the minimum number of units which can be uniquely identified. It can be a single item or batch of items with exactly same attributes and characteristics that are uniquely recognizable by the procedure defined in the Structure of system. For instance, polyester fibre bales manufactured in one batch may be called as a TRU when they are transported together to the fibre spinning industry. As the materials may be split and combined at different industrial processes to form the final product, the new TRU form should be assigned a new identification. However, if the TRU remains the same before and after the process i.e. undergoes without splitting, the identity before the process can be used after the process.

- **Retrospective analysis**

A traceability system should able to retrospectively recall the recorded traceability information related to the TRU at any point in the supply chain. This is particularly relevant to during the application phase when the downstream actors in the supply chain request the TRU information.

Furthermore, as textile supply chain consists of multiple supply chain actors, therefore implementing traceability is affected by multiple factors, including the perception and understanding of each actor for traceability, local regulations, and lack of common approach (Informal Product Traceability Expert Group - Final Report 2013). Nonetheless, the followings are enlisted as some of the best practices while implementing traceability in a multi-actor supply chain network (Informal Product Traceability Expert Group - Final Report 2013),

Best practice 1: written procedures addressing the full traceability process

Best practice 2: minimum labelling information

Best practice 3: minimum data to record

Best practice 4: automation of traceability systems

Best practice 5: use of global standards to ensure interoperability

Best practice 6: self-assessment of traceability systems

The most of the abovementioned practices are self-explanatory in nature, focusing on aligning the different supply chain actors regarding technology and goals to provide a streamline implementation and functioning of the traceability.

1.3. Relevance of traceability to the textile industry

As stated previously, traceability is a growing concern in almost all industrial sectors. The application of traceability varies for different supply chain stakeholders based upon the products they handle and/or their position in the supply chain. For instance, while retailing brands use traceability as a tool to be able to provide information such as the history of products to the end-users or consumers, the upstream suppliers use traceability for claim verifications and other supply chain applications. In fact, the market value of apparel is decided not only by the real worth of the product but greatly influenced by the associated brand name or value. According to Keller and Lehmann (2006), "for customers, brands can simplify choice, promise a particular quality level, reduce risk, and/or engender trust." In this context, how brands maintain their positive image plays a significant role in their market performance (Keller and Lehmann 2006). One important aspect of building or maintaining a positive branding is establishing transparency in the supply chain – which essentially relies on how efficiently one can trace the origin of the products when following an upstream path in the supply chain and access relevant information supporting transparency claim. In this direction, traceability is a basic requirement, which not only supports the abovementioned objective by storing the information about the product at all levels in the supply chain but also supports other supply chain activities. Following subsection broadly describe the relevance of traceability in different contexts.

1.3.1. Marketing tool/value creation

Marketing or advertising plays a major role in present marketplaces. With the advancement in IT and move towards globalization, while it has become easier for brands to reach the customers, the competition has intensified due to vanishing international borders for businesses. Moreover, customers' demands are no more limited to product's quality and cost. They are now more concerned with social and environmental impacts of the products (Goswami 2014). Textile sector has mainly encountered a strong public outcry particularly after the media or non-government organizations (NGOs) highlighted incidences related to unethical practices (such as the use of harmful chemicals, child labor, poor work conditions, etc.) at various stages of the textile production (Boström and Micheletti 2016). Hence, addressing above aspects during marketing or selling can potentially provide a competitive edge. The abovementioned sustainability and transparency aspects are, in fact, information based where brand owners need to ensure that they have a proper verification mechanism before making such claims. Absence or inability to verify the claim can generate negative brand impression when customers identify the claim to be false or not verified properly. For instance, the organic cotton farming – which was used by fashion brand Victoria's Secret – involved child labor as Phelan (2011) reported, which is criticized widely by the media and resulted in the negative branding. The crux of the abovementioned issue lies in verification, where the brand owner could not verify the source of the raw cotton. Traceability in the abovementioned scenario is a basic requirement to recall the information related to the product, therefore helps in verifying the informational claims. Moreover, traceability is a marketing tool where brand owners can highlight the transparency of supply chain while allowing the customers to trace various degree of information about the product using traceability system. Moreover, customers feel more confident to buy a product if the traceability information is available with it (Du Plessis and Gerrie 2012). As a result, traceability contributes to the positive branding (Yang and Fryxell 2009) with claim verification (Norton et al. 2014), which inevitably provides a competitive edge to the concerning brands (Guercini and Runfola 2009).

One important characteristic, which influences the customer's purchase intention, is 'made in'. Many customers prefer to buy apparels which are manufactured locally as it is easier for them verify the transparency of the manufacturing process. Therefore, previous studies (Gobbi and Massa 2015; Goswami 2014; Guercini and Runfola 2009) suggest that 'made in' is an aspect which can be utilized by local businesses, to compete with overseas brands. 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 individual raw materials utilized in the product can be conveyed to the consumers. Thus the traceability information on 'made-in' becomes more useful than that of conventional labels (Goswami 2014). It is also reported that consumers prefer to pay more if they can trace the product history (Dimitri Soverini 2014). In this direction, companies have started to exploit traceability as a marketing tool. For instance, All American Clothing Co. provides traceability information about the source of fibre used in production (Egels-Zandén et al. 2015). Similarly, Levi Corporation conveys the company's initiatives for environment 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.

1.3.2. Execution of product recall

Product recall is a process of removing or withdrawing products from the customers and/or markets due to safety or quality issues originated from their noncompliance with the government regulations. Product recall is, in fact, has gained more attention due to strict government regulations and buyer interests on product safety. According to Chen et al. (2009), a product recall can damage the brand equity developed over the years and spoil the company's reputation besides contributing in financially loses. Product recalls can further cause a loss in investor confidence, impact the customer's future purchases severely and affect the business in short as well as long terms. For example, a Wisconsin-based clothing company has reported 28% less revenue in the fourth quarter of 2014 following the announcement of recalling 173,000 units of children's sleepwear which was partially attributed to recall (Advisen Ltd. 2016). Therefore, it is important for the companies to prepare themselves handling the product recalls and prepare themselves from the negative image that could generate from a product recall. Although a product recall is practically not a good occasion for a company, the damage resulting from a recall can not only be minimized, but it can also yield unexpected opportunities if a recall is proactively managed (Craig and Thomas 1996). It can be an opportunity for the company to project itself as a socially responsible by underlying its sincere concerns to the customers and gain their confidence (Magno 2012). Therefore, to convert disastrous product recalls into an opportunity or mitigate the risk, the companies need to be prepared with appropriate strategies to execute a product recall such as precise information about the affect products, their distribution information and ability to identify the source of error, which has caused the recall for further rectification. In this direction, traceability is a tool which is widely used in different sectors to execute recalls (Bechini et al. 2008; Schröder 2008; Thakur and Hurburgh 2009). Traceability data allows the precise identification of recalled products and locating them in the supply chain and markets. Further, consumers can trace back if their products are recalled using the traceability systems. As a result, experts describe traceability as a fundamental requirement for effectively managing the recalls (Informal Product Traceability Expert Group - Final Report 2013). Moreover, a single product recall can be enough for completely spoiling the company. Hence traceability is a required strategical element in any manufacturing sector including textile.

1.3.3. Supply chain visibility

Visibility in the supply chain is often playing an important role in for a company to make informed decisions (Chapman 1995). Visibility is of particular relevance when supply chain actors are globally located, and their actions affect each other. For example, textile supply chain has a global geographical spread where labour-intensive production activities are carried at locations with inexpensive labor (Egels-Zandén and Hansson 2015). The globalized supply chain has resulted in extending the supply chain length and complexity and diminished the transparency (Goswami 2014; Guercini and Runfola 2009). Further, the increased length and complexity of supply chain creates more risk and provides some level of autonomy to offshore suppliers to opt their policies or standards, which would not be visible to the buyers (Christopher and Lee 2004; Ekwall 2009a). Due to this autonomy and opaqueness in the supply chain, the offshore buyers are occasionally found indulged in malpractices such as child labour, marginal salary, poor working condition, and so on. For example, the fashion brand Victoria's Secret has been accused of using child labour in the farming of organic cotton (Phelan 2011), which is the result of opaque supply chain. Similarly, many other cases recently highlighted incidents such as Rana Plaza collapse in Bangladesh (Burke 2014) and fire incident in a garment factory in Pakistan (Walsh and Greenhouse 2012) is a result of the opaque supply chain. Egels-Zandén and Hansson (2015) further argued that the complex supply chains even make it challenging for the lead firms name their suppliers. It can be empirically related to the statistics presented by Nimbalker et al. (2015) – which analyzed 59 clothing brands in Australia and found only about 10% of the brands had complete information about the fibre suppliers, while the remaining either partially knew about them or did not have any information at all.

In this context, traceability a vital role in creating visibility and transparency in the supply chain, which not only helps in managing the information about processes, production activities and the chain-of-authority but also enforces inter-actor communicating for exchanging critical important. Traceability system allows tracing each component to its origin, which makes supply chain actors more accountable to their claims and practices, thus creating more visibility in the supply chain. Further, from the operational perspective, traceability 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; Töyrylä 1999). The manufacturing processes – which take a long lead-time needs synchronous functioning of involved actors (Thomassey 2010) – is benefitted by the supply chain visibility where supply chain actors can make a decision in advance before receiving the product based on the traceability information. From the post-selling phase, traceability is deployed as a tool for creating visibility to the consumers (Goswami 2014).

1.3.4. Sustainability

In the simplest term, sustainability can be stated as endurance or ability to be maintained at a certain rate or level from ecological, economic and social aspects (Brown et al. 1987). Textile sector is heavily interweaved with environmental, social and economic aspects. As a result sustainability is one the widely recognized concern in the textile supply chain. Growing of fibres (cotton and other natural fibres) and textile manufacturing processes contribute to a large environmental impact due to the consumptions of substantial amount of water, chemicals fertilizers (for fibre growing) and release of effluents, greenhouse gases and other toxic/harmful by-products originating from different processes (Pedersen and Andersen 2015). EIPRO study estimates 2–10% of lifecycle impact originating from clothing alone in the EU-25 (Tukker et al. 2006). From the social perspective, various reports indicate the socially unsustainable practices that are followed in the textile sector. This includes marginal salary to the workers, unhealthy working conditions, employment of the child labor and so on. In this context, sustainability has become a priority from government regulations and fuelled by the consumer expectation (Goswami 2014; Goworek 2011).

Within the context of sustainability, traceability is an invaluable tool, which not only helps the organizations for sustainability claim verification but supports other aspects which help in progressing sustainability goals. According to Norton et al. (2014), traceability ensures "the reliability of sustainability claims, in the areas of human rights, labour (including health and safety), the environment and anti-corruption". Various supply chain actors can be held responsible for their sustainability practices using the traceability information. Moreover, sustainability is not only limited to manufacturing phase; for example, in the case of cotton fibre based apparels, more than 70% of the total energy consumption arises from the use phase (such as washing and drying) (Yasin et al. 2016). Therefore, in order to progress sustainability, the contribution from the end users would be required who need to select appropriate conditions for washing and drying suitable for minimizing the environmental impact. Hence, traceability can not only allow the end user to evaluate the sustainability of the product from raw materials or manufacturing perspective, but the end user can also use the traceability information to select the best possible strategies to minimize the use phase environmental impact.

1.3.5. Regulatory compliance

Regulatory compliance is a mandatory component for the functioning of any business. Functioning of a business involves multiple aspects including social, ethical and environmental concerns, which are monitored or occasionally audited by the regulatory authorities. In sectors, such as food grain (Thakur and Hurburgh 2009) and pharmaceutical, traceability is a regulatory requirement, where the companies are required to be able to trace their supplies in order to ensure the safety of products. Moreover, in case of quality-crisis, companies may need to organize government-mandated product recall to remove harmful products from the markets. In this direction, government regulates particularly those sectors, which are critical from safety point of view, for implementing traceability. Although, general danger level in textile sector may or may not be compared with sectors such as food and medicines, some actors in textile sector deal with materials which require due diligence. Therefore government regulates them for traceability. For instance, as described in Section 1.1.3, the European regulations mandate the industries dealing with chemicals (such as dyes) to be able to trace their imported supplies so as to manage the risk associated with them (Alves et al. 2014). Moreover, recently European parliament has voted for compulsory 'made-in' label where all non-food items would require labelling of country of origin information and a good produced in more than one country would require labelling of the country as origin where "the last substantial, economically justified processing" was carried out (European Parliament News 2014). Global supply chains are not unusual in textile manufacturing. Therefore some level of traceability would be required to justify above-stated labeling claims. As a result, implementing traceability indirectly becomes a regulatory requirement for companies working in European single market. Similarly, there are other nation-specific requirements, which are directly or indirectly supported by traceability; as a result, implementing traceability becomes regulatory compliance.

1.4. Issues with current traceability practice

As stated previously, the core notion behind traceability is the *capability (and implementation) of 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*. The information can vary from simple applications such as recording the product footprints to sophisticated applications such as communication critical product information in the real-time. Therefore, the backbone of a traceability system is IT, and supply chain actors capture and exchange the required traceability data for realizing the targeted goals. In this process, firstly, the identification information is encoded on the products with the help of traceability markers and then supply chain actors manage and exchange product information with reference to the encoded identification. As the supplies move through a number of globally spread supply chain actors, there exist multiple issues from implementation perspectives, as described below.

1.4.1. Technical limitations of traceability tags

The most common forms of traceability tags in the textile supply chain are plain written labels, printed barcodes, QR-codes, and RFIDs. As stated previously, information is encoded in/on these tags, which is used for product identification, tracking, and information exchange. They are attached to the product or external packaging to record the product's footprint with the help of encoded information, which also acts as a reference to store and retrieve the product information. Therefore to realize traceability, it is important that traceability tag accompanies the product (Agrawal et al. 2016; Corbellini et al. 2006; Ekwall 2009b; Informal Product Traceability Expert Group - Final Report 2013). Moreover, traceability becomes limited to the point traceability tag remains with the product. From the application perspective, as traceability has application throughout the product lifecycle, therefore ideally the tag should accompany the product as long as the product exists. Besides this, traceability tag plays a significant role in counterfeit detection as it acts as product identifier (Corbellini et al. 2006). Within this context, if the traceability tag is cloned (i.e. encoded information of the original tag is implemented on another similar tag) and attached to a counterfeit product, it becomes difficult for the end user/customer to differentiate among genuine and counterfeit products. This is because the cloned tag would authenticate the product because it contains the encoded information same as that of original tag. Therefore, the first necessary conditions for implementing traceability is an association of the product to be traced with the traceability tag until the point traceability is required, and the second condition is the protection of tag from tampering or copying. Generally used barcodes, printed labels and simple RFIDs are easy to copy therefore; they provide minimum security to the product. Moreover, RFIDs respond with the stored alphanumeric codes to almost every RFID reader; this can lead to unsolicited tracking the user having an RFID-integrated product. A ultra-high frequency RFID tags have a readability range up to 12 m from the reader, which can be even increased with a high-gain antenna (Probst et al. 2015). To avoid the tracking, RFIDs either are removed or disable at point-of-sale. Subsequently, the traceability with existing tags is mostly limited until the point-of-sale (POS). Moreover, RFID-chip is an electronic waste; therefore RFIDs-integrated textiles create concern during the recycling process (Köhler et al. 2011; Wyld 2010). Therefore, the existing traceability markers are easy to copy and provide traceability, which is limited to the POS.

1.4.2. Data sharing

Traceability is an inter-organizational concept, where different supply chain actors share the product-related data. However, the level of product details shared by the product owner with other actors can increase the competitions, financial and legal risk (Informal Product Traceability Expert Group - Final Report 2013). Therefore, a common challenge for all supply chain actors while implementing traceability is to protect the elements of information or data, which provide them a competitive edge. Textile sector is a market demand-based industry where retailers place the order to upstream actors based upon the forecast and subsequently the upstream suppliers add a substantial portion of the value creation. The upstream suppliers develop their competitiveness by specializing and developing processes whereas the retailers or brand owners develop their competitiveness by market trend forecasting and introducing the products on appropriate time. Also, the suppliers and intermediaries play an important role in the success of a retail brand, which adapt to product designs, materials, and other related aspects required according to forecasted demand. In case, the opponents obtain the sourcing details of a product or retailer; they can quickly erode the competition by opportunistically hiring the same or similar suppliers. Similarly, if the upstream suppliers disclose their production strategies or practices, the opponents can copy them. Therefore, the supply chain actors are often skeptic to share information, even with their collaborators to avoid any risk of unsolicited data release to competitors. Therefore, issues with data sharing and protection often play a hindrance factors in traceability implementation, and limited data sharing does not completely satisfy the purpose of the implementation of traceability.

1.4.3. Data interpolation

Traceability is an inter-organizational concept, where different supply chain actors share the product-related data. Communication of the data is generally carried out using e-business messaging such as EDI, which essentially relies on data interpolation. This uses some definitive semantics to interpret the data on the sending and receiving ends. However, due to the absence of strict guidelines or framework for traceability in non-food sector, actors use different (or non-standardized) semantics – which creates problem in data interpolation or exchange. It is estimated that up to 70% of the EDI transactions contain wrong or incomplete information (Hunter and Valentino 1995). Moreover organizations sometimes uses different systems based upon their suppliers (Lam and Postle 2006), which inevitably increases the cost and complexity.

1.4.4. Absence of global regulations

Traceability is a larger concern not from the industrial perspective, but also from consumer perspective such as to prevent counterfeit and execute an efficient product recall. In this context, government regulations play an important role in its implementing by providing clear guidelines and frameworks. Furthermore, traceability is an inter-organizational concept, which seeks collaboration from all actors to share and build the traceability. For example, traceability is a legal requirement in the food sector in the European Union, which mandate that every firm must be able to trace their products in all manufacturing stages (Alfaro et al. 2015), subsequently each supply chain actor responsibly maintain minimum traceability level. As a result, traceability is food sector is considered one of the most effective implementation (Probst et al. 2015). However, textile industry does not have any mandatory regulations for traceability (except for selected supply chain actors), which act as a big hindrance in the implementation of a complete traceability. Nonetheless, as discussed in section 1.3.5, government guidelines are indirectly mandating the traceability.

1.5. Purpose

It is evident that traceability is a growing concern in various sectors for managed and visible supply chains. As highlighted by Goswami (2014), Guercini and Runfola (2009), Henninger (2015) and others, textile industry has seen a significant transition from the supply chain as well as market demand perspective, therefore traceability has become a growing concern to the sector as a whole. Further it acts as a value creating tool which provides a competitive edge to the local businesses, particularly those located in the western countries and are facing a great competition from the offshore suppliers (Goswami 2014; Guercini and Runfola 2009). As stated previously, traceability is a phenomenon of collecting and sharing the information so that a product can be traced in the supply chain product and it is achieved by attaching a traceable marker (or tag) which helps in uniquely identification of the product. As a result, traceability is limited to the point the product is accompanied by its traceability tag. In this direction, this research is intended to explore the traceability from integrated traceability tags in textiles and information sharing in the supply chain perspectives. Unlike the existing RFIDs or printed barcode labels, the integrated traceability tags are expected to physically integrate into the textile structure so that it cannot be simply removed from it thus provide extended traceability. This is achieved through several experimental and theoretical investigations devoted to develop a traceability solution and effect of traceability on supply chain. This uses three research questions (described in the future section). Within this context, in this thesis, a portion is devoted on the development of new integrated form of traceability tag for the textiles using lab-based experimentation for controlled environment and checking the feasibility of the concept.

1.6. Limitations

Traceability is an inter-organizational concept, which relies on technical competences, organizational policies and government regulations. The context of this thesis is on the scope of traceability by using integrated tagging from the research perspectives and the conclusions are made on data analysis gathered from secondary sources and lab-based experimentations. Therefore, the due diligence would be required from existing government regulations and standardizations to generalize them in the any real application scenario. Moreover, the integrated tagging has been pursued from feasibility aspect; therefore, the practical implementation of the developed tagging would require the further development considering the manufacturing processes, materials, and other technical and organizational aspects.

1.7. Research questions

This thesis introspects the traceability in the textile supply chain. Therefore, three research questions (RQs) (shown in Figure 1.3) that are broadly identified as traceability implementation issues are described in this section. RQs will be followed in the subsequent chapters.

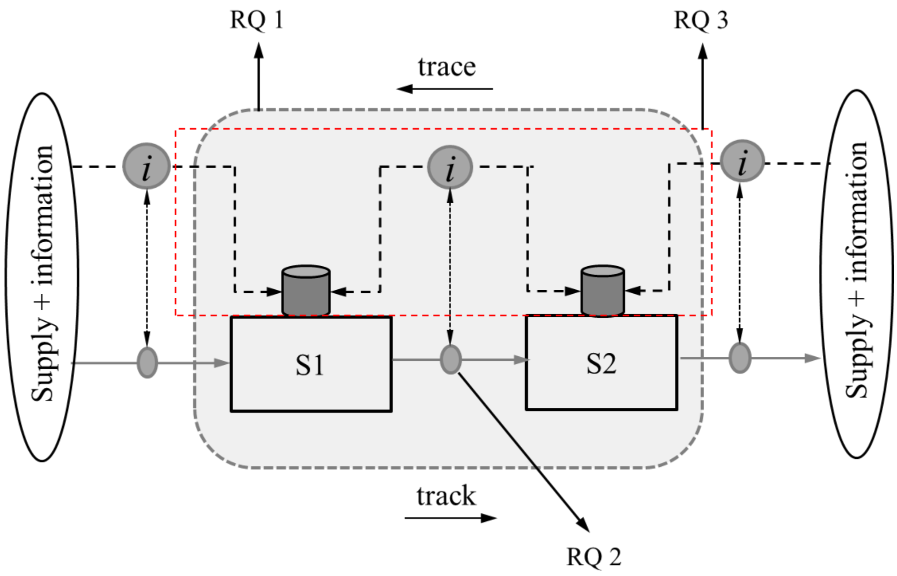


Figure 1.3 Component of framework with respect to research questions

RQ 1 How is traceability relevant to the textile supply chain?

Traceability is a wider concern not only to the industry but also to the consumers and government. Therefore, this question explores its relevance from a broader perspective to various supply chain stakeholders.

RQ 2 How can traceability be implemented without using external tags?

As described in Section 1.4, the current traceability practice utilizes the traceability tags which lack in providing proper security and integration to the product. On the other hand, traceability heavily relies on these tags, therefore, it is of utmost importance to use robust traceability tagging. In this research question, the author investigates for an alternate approach to address traceability, which uses yarn-based fully integrated textiles tags.

RQ 3 How can traceability information be managed and exchanged in a multi-actor textile supply chain?

Traceability is an inter-organizational exchange and management of the information. Therefore, this research question can be interpreted as an investigation for information systems to implement traceability in a multi-actor environment or supply chain.

1.8. Outline of the thesis

Chapter 1 provides the background of the research and emphasizes the aim and practical relevance of this thesis. It presents a broad overview of the textile sector and its supply chain, and a brief relevance of traceability. Furthermore, Chapter 1 proposes the research questions (RQs) which are pursued in this PhD work.

Chapter 2 lays down the frame of reference for the thesis. It provides a theoretical foundation for the required features of traceability systems and traceability tags, and how they are related to different manufacturing and supply chain management aspects. Further, this chapter explains common tags used for traceability in the textile industry.

Chapter 3 compiles the methodological framework followed in this thesis to achieve various objectives in the research. It further classify different appended papers according to the methodology, research procedure and scientific reasoning behind them.

Chapter 4 presents the results obtained from the independent papers, which are appended in this thesis. This chapter includes a summary of the five papers, which forms the thesis and describe their linkage to each other and the RQs.

Chapter 5 analyses the appended papers and answers the RQs presented in Chapter 1.

Chapter 6 derives the conclusions of the thesis. Here the analysis is made in terms of applicability of the proposed traceability tags and traceability system and the contributions from theoretical and practical point of views.

Chapter 7 presents some recommendations for the future research.

2. Frame of reference

The purpose of this chapter is to give insights into the relevant literature and provide a frame of reference to the thesis.

The focus of the thesis can be categorized into two parts i.e. technical and strategical. This follows the argument presented by Gobbi and Massa (2015) which is based on the study of (Pigni et al. (2007) that traceability can be distinguished into two type of systems namely technology-based and non-technology-based. Technology-based traceability is technology-driven and uses traceability markers such as electronic tags, hidden markers, cloud computing, and information technology to integrate the supply chain actors. The non-technology based traceability deals with the managerial aspect of the supply chain, which ensures that information is exchanged between the various actors. It involves the strategies for communication, reflection, regulatory compliance and other supply chain concepts, which interact with the traceability (Gobbi and Massa 2015). Nonetheless, the two components of traceability complement each other, as they are interdependent. For instance, the selection of a traceability technology would require tunings in the management strategies of the organization and supply chain, while the strategical aspect of traceability would require considering the limits of the traceability system for supply chain or organizational changes or goals. The components of the theoretical framework are presented in Figure 2.1. The strategical traceability focuses on the supply chain concepts and their relevance to the traceability while technical traceability discusses the technically driven aspects.

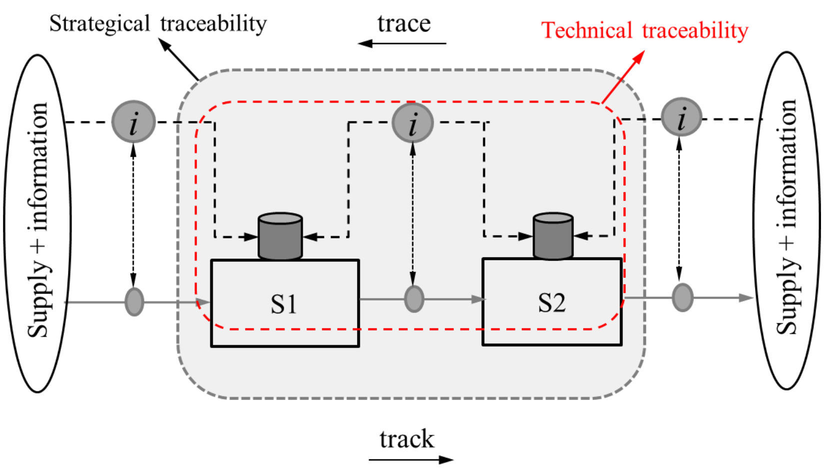


Figure 2.1 The components of theoretical framework

2.1. Supply chain management

The main focus of the thesis is on traceability which implies to extend the informational boundaries of a supply chain stakeholder beyond its organizational or administrative scope. (Christopher 2005, p. 17) defines supply chain as, *the network of organizations that are involved, through upstream and downstream linkages, in the different processes and activities that produce value in the form of products and services in the hands of the ultimate consumer*. Therefore, the stakeholders include different supply chain actors and the customers. A supply chain begins with the preparation of the raw materials and finishes with the end-user. Subsequently, the framework of a supply chain can be divided into three parts namely the supplier, the buyer and the consumer. Lambert and Cooper (2000) split the supply chain into three elements namely, network structure, business processes, and management components. The first element deals with supply chain linkages such as organizational and geographical relationships. The activities in the supply chain are related to the second component while the last component deals with supply chain network integration into the business process. Further, the supply chain network consists of multiple actors and integrating them is not only a complex issue but also counter-productive since all the members are not equally important. In this context, Lambert and Cooper (2000) describe that the suppliers can be divided into mainly four categories, namely, managed process links, monitored process links, non-managed process, and non-monitored process links. The first two categories are the most relevant links to which a buyer mostly rely for competitiveness; subsequently, they are directly managed by the buyer. The remaining two links are not that important. Therefore, they are managed by random audits or not monitored at all.

In the context of the supply chain, the term *supply chain management* is used for planning and coordinating all the operations in the supply chain. As companies create competitiveness through their capability to innovate, produce and deliver to the end users, the supply chain management plays a vital role (Halldorsson et al. 2007). The textile sector consists of multiple actors, dealing with distinct raw materials and specialized in different operations (Giri and Rai 2013). Although retailers act as the main driver of the textile supply chain (Thomassey 2010), the most of the value creation takes place outside the vicinity of the retailer i.e. with the upstream actors. Subsequently, the collaborative actions of supply chain actors decide the level of success. According to Halldorsson et al. (2007), the value creation outside the boundaries of individual firms induces numerous complexities in collaboration, decision making, structure of the operations, and so on. Nevertheless, for the successful supply chain management, the operations and information should work together (Ekwall 2009a). Rich and Hines (1997) further describe the supply chain management at two levels, internal supply chain management – management at intra-actor level, and external supply chain management – management of inter-actor and customers' relations. As the textile supply chain are spread globally, information acts as an integral part of coordinating the activities and synchronous functioning of different supply chain actors (Elwan Ibrahim and Ogunyemi 2012). In this context, this thesis follows the definition of supply chain management proposed by Lam and Postle (2006, p. 267),

All the activities involved in delivering a product from raw material through to the customer including sourcing raw materials and parts, manufacturing and assembly, warehousing and inventory tracking, order entry and order management, distribution across all channels, delivery to the customer and the information systems necessary to monitor all of these activities.

Information sharing helps in the integration of supply chain actors (Gobbi and Massa 2015) and according to Elwan Ibrahim and Ogunyemi (2012), a well-integrated supply chain is particularly required to compete in the market and act as a key factor for the success. It is further argued by Gobbi and Massa (2015) that the focus of supply chain management – which traditionally meant for managing the flow of materials, has moved towards coordination through information exchange to achieve the sustainable development. Because textile supply chain is a relatively long and complex global network, integration through information helps the companies to closely monitor the supply-demand balance, make an informed decision and reduce the lead-time (McNamara 2008). The information in supply chain management is further an important aspect from regulations perspective. For instance, government regulations mandate the due diligence for chemical suppliers in the EU to keep the traceability information about the suppliers (Alves et al. 2014).

2.1.1. Relation paradigm in the supply chain management

The supply chain management is an inter-organizational management and sometimes it is referred as intermediate type of relationship within *a spectrum ranging from integrated hierarchy (vertical integration) to pure market* (Harland 1996). Relationship refers to the activities by different actors to establish, maintain and develop relational exchanges (Morgan and Hunt 1994). The globalization has fragmented the textile sector (and many other sectors) to different geographical locations with a clear separation into those who manufacture (i.e. upstream suppliers) and those who sell (retailers). However, the success of supply chain heavily relies on how different actors coordinate with each other. The buyer-suppler relationship in the supply chain acts as important component for different strategies of the involved organizations (Hoyt and Huq 2000; Youssef 1992). It can vary from simple to complex based upon the kind of products or services involved in the supply chain (Hoyt and Huq 2000). The traditional concept of supply chain relation is based on arms-length agreement with limited commitment and leveraging the supply chain for minimum purchase price (Hines 2004). Vertical integration of supplier-buyer was mostly adopted in early 20th century when cost was a main decisive factor, while material specifications were much more standard (Handfield and Bechtel 2002). However, dynamics of relation has changed over time due to changing characteristics of the industry. For instance, globalization has increased the overall competition; therefore many firms started to focus on their core business while outsourcing their production activities. Furthermore, the outsourcing of manufacturing activities helps the clothing retailers to reduce risks by not owning any production facilities (Margretta 1998; Xie et al. 2011). Nevertheless, the lead firms are becoming more dependent to the upstream supplier; subsequently, they have started to realize the importance of trust (Hoyt and Huq 2000) and relationship (Sahay 2003) Christopher, 1992; Slack, 1991; Schonberger, 1986). Moorman et al. (1992, p. 315) define trust as *a willingness to rely on an exchange partner in whom one has confidence* whereas Anderson and Narus (1990, p. 45) define trust as *firm's belief that another company will perform actions that result in positive outcomes for the firm as well as not take unexpected action that result in negative outcomes*. While the role of trust is identified for mitigating the risk (Hines and Samuel 2004), Sherman (1992) reported that around one-third strategic alliances failed due to the trust deficit. Kwon and Suh (2004) further state that trust and information sharing-based planning plays a prime role in successful supply chain management. Harland (1996) states the relationship in a wide spectrum ranging from vertical integration to pure market, and trust and power asymmetries among the supplier and buyer decide the type of type of relation (Cox 2001, 2004). While partnership as a complex concept which depends upon trust and duration of relation, it is difficult to shift from adversarial to cooperative relationship in scenario of mistrust among supply chain actors (Wilding and Humphries 2006). In addition to this, Moberg et al. (2003) outline diverging goals and lack of transparency in information systems as obstructions in the cooperation in the supply chain. Factors behind the mistrust includes the information asymmetry and perception of opportunistic behaviour in the supplier-buyer relation (Ekwall and Sternberg 2014; Michalski et al. 2013; Morgan and Hunt 1994). Textile supply chain has the components of mistrust – for example, the imperfect quality inspection. As quality inspection of textile products is a complex task due to technological and monetary constrains, the imperfect quality inspection provides opportunistic prospective to the suppler to provide defective or low quality products (Cheng et al. 2013), which results in information asymmetry between the buyer and supplier. The difference in information influences the bargaining power and decision making process, and generally have a negative impact on medium and long term supply chain relationships (Michalski et al.

2013). Nonetheless, cooperative strategies act as a tool to develop competitive edge without sacrificing customer satisfaction. Further, it helps in reducing the production lead time, quality improvement and mitigating the risk arising from demand uncertainties.

2.1.2. Game theory in supply chain management

As discussed in Section 2.1.1, supply chain involves situation of cooperation and conflict based upon the behaviour/goals of different involved actors. Several researchers have addressed these actors as players in the game, each making decision to achieving certain goals (X. Zhang 2014). As a supply chain is a network of actors working together, the decisions of different actors affect the welfare of other actors and efficiency of the supply chain. To understand the behaviour of actors in situations, a great deal of interest has increased for modelling and analysing the conflict and cooperation in the supply chain (X. Zhang 2014). In this context, game theory has emerged as a modelling technique to study the conflict and cooperation in the supply chain. According to Moitre (2002, pp. 153–154), game theory can be defined as *the study of mathematical models of conflict and cooperation between intelligent rational decision-makers.* In a typical supply chain game, a typical game consists of three basic elements, namely, actors, payoff functions and the strategies (Fudenberg and Tirole 1991). It relies on basic assumption that the involved actors make rational decisions in the supply chain and these decisions can be expressed as in some mathematical functions. Further, the actors are interdependent and their strategies affect each other. Broadly, the games in game theory can be divided into two categories namely cooperative and non-cooperative (Geisler 2014; Papapanagiotou and Vlachos 2010). Cooperative game deals with the situations when the supply chain actors collaborate each other in achieving the goals and divide the supply chain profit in an *equitable* manner. On the other hand, non-cooperative game concerns the situations when the actors do not work for each other; rather they try to maximize their own welfare in the supply chain. Further, a differentiation is made on the basis of type of information available with each player, which includes perfect (or symmetric) and imperfect (or asymmetric) information (Geisler 2014). The former case concerns the situations with outcome of an action or all actors in the supply chain know decision, therefore they have symmetric information. As the actions and their outcomes may not be easy to correlate or observe by all the actors, it creates an information asymmetry in the supply chain, which is known as imperfect or asymmetric information game scenario.

2.1.3. Traceability as a strategic element in supply chain management

Information is an important aspect of the supply chain, which not only helps in supply chain integration but also benefits the involved actors to make informed decision. As aforementioned, a supply chain is a network of inter-dependent actors and the decision of one actor affects the welfare of other actors and the supply chain profit. In this context, traceability – which is fundamentally the sharing of information – plays a strategic role in the supply chain management. Bechini et al. (2008) further state *traceability as a needed strategic service in any production context* (p. 342). By implementing traceability simply implies providing a means to the supply chain actors to informationally overlap with each other, thus they acquire more knowledge than that of without traceability. Textile supply chain, which – in most cases – is managed by the retailer, involves a number of upstream suppliers located in different global geographical locations; subsequently, it is a complex network. Further, fashion market is characterized by as rapidly changing marketplace where trend changes and becomes obsolete quite quickly. Therefore, a retailer needs to provide a constant stream of innovation (including product design and functionality) to retain the competitive edge. As for a retailer, most of the value addition takes place with upstream suppliers – which sometimes act as a supplier to multiple retailers; therefore the retailer needs to pay due diligence for securing and sharing the information with the upstream suppliers otherwise it can provide an undue advantage to the competitors. Moreover, aspects such clothing design are not generally covered with the copyright protection, therefore if the rival players acquire the traceability information about sourcing and other supplier details, they can access the same or similar resources and potentially erode the competition by introducing the similar products. Subsequently, implementing traceability and the way information is shared become a strategic supply chain element. Moreover, the upstream suppliers deal with specialized activities, where they create competitive edge by specializing operations, materials, processes and chemical recipes, which are sometimes kept secret or shared with specific supply chain actors. Therefore, traceability implementation stands for negotiating with the different actors to share the critical information in a strategic way so that it benefits without jeopardizing the relationship of actors.

2.1.4. Traceability vs socio-economic and regulatory relevance

Traceability is a wider social as well as governance concern in transparency, sustainability, providing safe products, and to minimize the impact of harmful products, which are identified during the advanced stages of marketing, distribution or use. Further, increasing complexities of supply chain risks and economic opportunities that generate from traceability have increased the attention of the industrial actors to adopt traceability practice (Verzijl et al. 2015). In this context, interplay of private sphere (i.e. expectations or objectives of industrial actors) and public sphere (i.e. government policies) perform as an important protagonist for traceability implementation (Clarke 2010). Regulatory interest and enforcement of the traceability for a sector or supply chain actor depends upon the material, processes and products they handle. For instance, food sector has attracted probably the highest attention from the government regulatory agencies of various countries after the events like mad cow disease and issues resulting from genetically modified crops (Goswami 2014; Hobbs 1996; Loader and Hobbs 1996). Textile sector has seen one of the highest product recalling cases in the EU countries as reported by the RAPEX, many of which are considered dangerous to the end users (Kumar and Ekwall 2016). They include products with inappropriate clothing design (such as use of inappropriate lacing in children/kids clothing which can lead strangulation or choking), use of inappropriate chemicals (including banned dyes and chemical finishes) (European Commission 2015). Subsequently, it is of utmost important for the companies to comply with the safety standards and as any failure to adhere with such quality standards can be lethal to the end users; it is of paramount importance to immediately identify and recall such products from the market or distribution system. In this context, European regulatory agency for chemicals (REACH) has catalogue for the forbidden chemicals (including chemicals used in textile dyeing and finishing) and it further directs the industrial actors that they should be able to trackback their manufactured or imported chemicals (Alves et al. 2014). Furthermore, regulations addressing the issues like minerals extraction from conflict zones require due diligence from the supply chain actors to comply with the regulations (Norton et al. 2014). This also concerns to track or quantify the use of the natural resources in order to avoid their unnecessary exploitation. Furthermore, textile sector has seen great social concerns from consumers relating to the environment and society; subsequently the traceability has been sought for providing transparent and sustainable products (Goswami 2014). While textile sector has seen an intensified demand for sustainable products (Khurana and Ricchetti 2016), according to (T. Zhang and Kraisintu 2011) traceability is established an unprecedented element in the textile industry which was not the same decades back.

Cheek (2006) further argue that, although firms are aware of the benefits of traceability, the implementation is deterred by the cost factor. Textile supply chain consists of many small actors with limited profit margin; particularly for them the financial investment plays a deterring role. Without the participation of all the involved actors, a complete traceability cannot be achieved. Nonetheless, regulatory authorities play an important role by providing the guidelines for each individual actor to maintain the desired level of traceability; hence decide the success of full supply chain traceability. This can be empirically related to the fact that food sector which has a strict guidelines has probably the most successful traceability at present. In fact, government efforts have been seen recently in setting up the regulation at an international level (i.e. involving two or more countries) (Cheek 2006).

2.1.5. Different types of traceability

- **Internal traceability and external traceability (Ryu and Taillard 2012)**

Internal traceability refers to the management of the information which is generated within the vicinity of a supply chain actor. It involves the event of combining one or more traceability units in a process to generating new traceability units. It includes the handling of the traceability information of inbound raw materials, final (outbound) product and the process information such as movement (i.e. movement of raw materials within the vicinity of one actor), transformation (i.e. change in (physical) characteristics of input raw materials into the outgoing product), storage (information about storing the traceability unit within the organization), usage (i.e. information about using the traceability unit) and destruction (information about the disposal or destruction of the traceability unit).

External traceability relates to instances when a traceability unit is exchanged between two actors therefore, the scope of traceability information goes beyond the single actor. This is generally implemented using traceability tags which act as a linking element between two actors for the information exchange.

- **Product traceability and logistical traceability (Gencod-EAN France 2001)**

Product traceability refers to the *'qualitative follow-up'* of a product which includes information concerning to the product in the supply chain. It deals with the processes and material aspects (such as quality, technical details, etc.). On the other hand, logistical traceability refers to the *'quantitative follow-up'* and deals with the geographical location of the product. It deals with information related to the physical movement of the product in the supply chain.

This thesis majorly focuses on the product traceability in the supply chain.

2.2. The technical perspectives of traceability

Technically, traceability implies the ability to trace back the history by means of technology that maps the physical product with the relevant history. History is an informational aspect, which is collected, stored or shared by means of technology. Furthermore, the whole systems i.e. selection of technology to capture information, storage and extent of information sharing is influenced by the supply chain strategies and external regulations, which provides clear guidelines. Gencod-EAN France (2001) describe traceability as a four component procedure as shown in Figure 2.2. It includes Identify, Communicate, Record data, and Manage links.

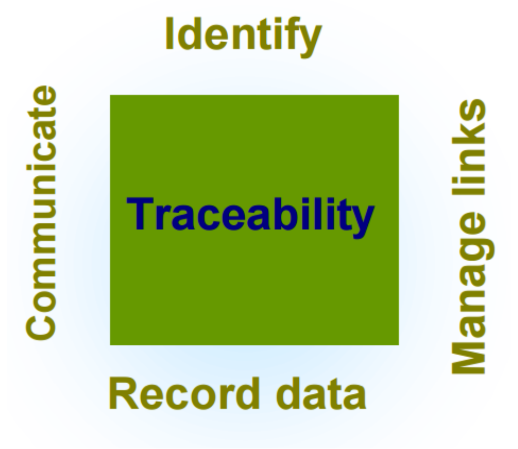


Figure 2.2 Key underlying components of traceability (Gencod-EAN France 2001)

The component *identify* is the most critical component of foundation of any traceability system. As a supply chain actor performs different operations on incoming raw materials to convert them into the final product, it creates a large amount of information regarding processes, materials, information about the suppliers and so on. From the traceability perspective, it is important to preserve this information as any part of the information may be relevant to the next actors or from the perspective of government regulations. *Recoding data* and *communication* come after identify the traceability information. It involves the appropriate technical means to record and store the traceability information and communicate it in the supply chain. *Manage links* denotes the maintain the different supply chain links with the appropriate information which fulfils the internal organization policies of the traceability information sender while fulfilling the needs of the receiver and comply with the regulations. For example, government regulations for food sector in the EU provide the guidelines for one-up-one-down traceability and minimum required traceability level, therefore each actor needs to comply with the regulatory requirements while implementing traceability.

2.2.1. Traceability data

Traceability can be seen as the information about anything that happened to the product, from the perspective of manufacturing, packaging and distribution which includes different standpoints raw materials, processes, assessments, human labour involved, environmental impact, and so on (Sarpong 2014; Fredi Schwägele et al. 2009). Furthermore, it acts as auxiliary practice for the proper function of a production system or the use of a product, which uses the traceability information for different strategies during production or security during the use-phase of the product, in addition to government regulations. Therefore, for the efficient utilization of traceability system, traceability data should comply with the requirements of each of the stakeholders. In a broader sense, GS1 (Ryu and Taillard 2012) defines traceability data with the following components,

Who? Party [Identification + data elements]
Where? Location [Identification + data elements]
When? Date / Time
What? Traceable item [Identification + data elements]
What happened? Process or event [Identification + data elements]

In fact, the type of Gooch and Sterling (2013) proposed the data requirements for the food sector with different terminology but with almost similar interpretation. The above stated data components generally define the traceability information; however identification of elements in each component is a complex task. For instance, each actor in the supply chain performs handful operations on the products and each operation uses different raw materials thus create a large amount of traceability information. Ideally, all this information should be captured, however handling of all this information is complex seeing the volume of data and its utility. As traceability is an inter-organizational concept, therefore when the abovementioned information model is expended between the multiple businesses, it enables value chain traceability (Gooch and Sterling 2013).

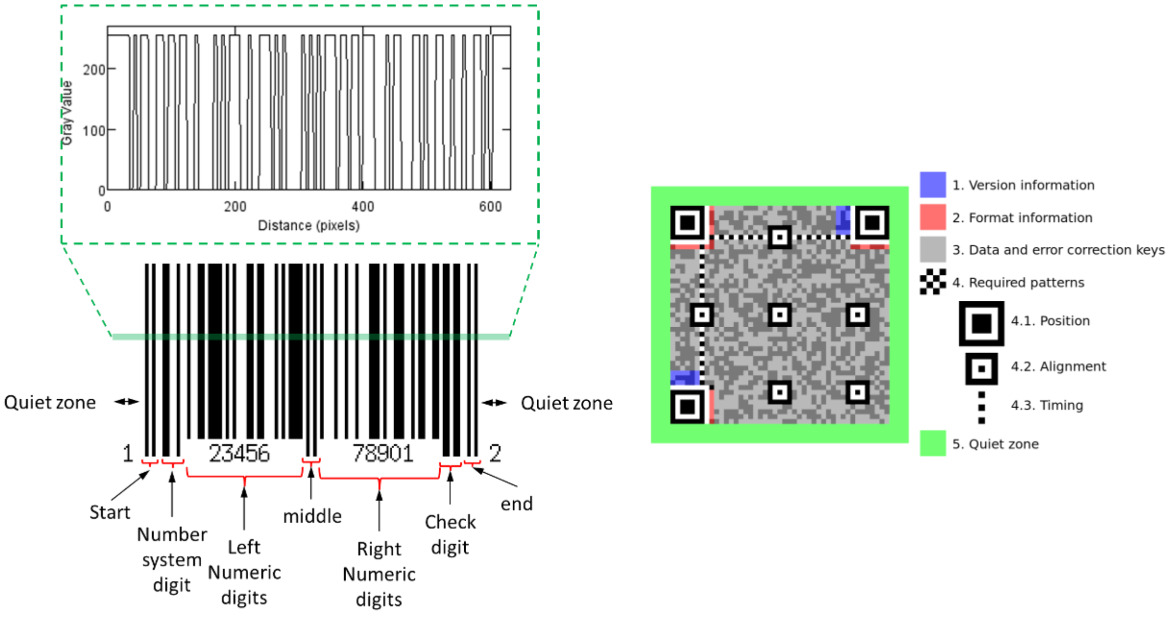
2.2.2. Traceability tags

Traceability tag is the component which maps the physical product with the traceability information. It consists of a unique identity number or feature which helps in identifications of the attached product in the supply chain. As traceability has multiple functionalities including, product security, tracking and counterfeit detection, the characteristics or information on the traceability tag varies based upon the targeted functionality. A tag can have number or any other trace which points to another source of information or features which indicate the authenticity. The following subsections describe the most commonly used traceability markers in textile sector.

- **Printed Barcodes**

A barcode is an image that contains information encoded in the form of geometric shapes. The type of information varies from numeric to alpha-numeric based upon the type of barcode, and the capacity of information that can be encoded in the barcode is decided by the density of geometric shapes used for information encoding.

The first barcode was developed by IBM with name 'Universal Product Code' (UPC) which is capable of encoding 95-bit information. These classical barcodes contain parallel back strips and white spacing. A combination of strip width and inter-strip white spacing represents a digit in the barcode. As the decoding is carried out by analyzing the width and spacing along a width-wise line, they are also known as linear barcodes. The barcodes are decoded by the image pattern recognition where some inherent strips-based features are detected to decode the information. For example, UPC-A contains initial and final strips with predefined width and spacing (also called module) to identify the start and end of the barcode (as shown in Figure 2.3(a)). Similarly, there is predefined 'quiet zone' which contains only free spacing. Further, the information is decoded by analyzing the strip width and spacing by analyzing the black and white variation along a line in the barcode, as shown in Figure 2.3(a). Additionally, there is a number system digit and a check digit where former identifies the number system of the barcode, while latter is used for verifying if the decoding is correct.



(a) (b)

Figure 2.3 Barcodes and their features (a) linear barcode (UPC-A) (b) 2D barcode (QR code) (Wikimedia Commons 2013).

2-dimensional (2D) barcodes are an advanced version of 1D barcodes where information is encoded in both *x* and *y* directions, which enhances the data storage capacity. Figure 2.3 (b) shows a 2D barcode (also known as QR code) with some predefined features. In addition to high data capacity, 2D barcodes have a high error correcting capacity, which allows restoring of the information even if a part of the tag is hidden or damaged. Due to increasing popularity and ease of decoding using smartphones camera, barcodes have developed in a large variant following different standards and widely used for tracking and warehouse application in the supply chain.

- **Radio Frequency Identification (RFID) Tags**

RFID is an electromagnetic field based identify marker used for product tagging, where the information is stored electronically. Therefore, a RFID tag can be read even if it is not visible or hidden inside the product, and unlike barcodes, multiple RFID can be read and decoded simultaneously. A typical RFID contains an electronic microchip and antenna coil. Electronic chip holds the memory of the tag, where information is encoded. Antenna coil helps in powering the chip by electromagnetic mutual induction coupled with the receiver or decoder and transmits back the identity encoded in the memory. RFID tags can be classified based on the type of power source and information coding.

Power source based RFID tags have categories namely active and passive. A passive tag is the simplest form of the RFID tag, which has no source of energy and the mutual electromagnetic induction acts as a powering source to the tag. On the other hand, active RFID tag has an inbuilt-in source of energy. Thus, the latter can transmit the tag information from a much larger distance than the former. Further, the RFID tags divided based on information coding include read-only and read-and-write RFIDs. The read-only RFID contains a microchip, which can be recorded only once; subsequently, the information cannot be changed if the microchip is encoded once. On the other hand, data in the read-and-write RFID tag can be modified multiple times and based upon the requirement, the process can be designed to automatically capture and modify the data. For example, Thakur and Forås (2015) use the temperature and humidity sensors embedded RFID tags to store the temperature and humidity during the frozen food transport.

- **Miscellaneous tagging**

As traceability defines the ability to trace the history, it does not always imply to tag the products with a unique numeric tracking code. Traceability also signifies to the product authentication (Ekwall 2009a), which is a highly relevant in the counterfeit prone textile sector. As the RFIDs and barcodes are easy to replicate, there is always a possibility of using them with the counterfeit product. This has naturally directed to devise other anti-counterfeit techniques which tag the product with some un-clonable/un-replicable/special features; thus protect from cloning and help the buyer or consumer in product authentication. Occasionally, the tag fetures mentioned above are used along with RFIDs/barcodes, where they are used for counterfeit detection/protection. Whereas, the RFID or barcode tag is used for uniquely identify the product in supply chain. These anti-counterfeit techniques include holograms, Microtaggent®[1], botanical DNA[2], fibres with special features (J. Zhang and Ge 2011), specific light responsive patterns (Shamey 2009), etc. A typical hologram is a photographic recording of a light field, which forms a 3D visible impression of an object on a 2D substrate and can be observed with naked eyes. Companies usually print logos as hologram adhesive strips which are directly laminated on product covering or labels. Microtaggant® developed by 3M is another tagging technique, which relies on the arrangement of highly cross-linked melamine

[1] www.microtaggant.com

[2] http://adnas.com/supply-chain-certainty-textiles-apparel/

plastic particles with multiple stratified layers of different colors (Shamey 2009). The counterfeit detection is carried-out by generating the numeric identity from a combination of melamine plastic particles arranged in different layers (Shamey 2009).

2.2.3. Traceability data management and communication interoperability

For a successful realization of traceability, all supply chain actors need to systematically comply the mapping of relevant traceability information with a physical product in the supply chain (Bechini et al. 2008; Thakur and Hurburgh 2009). In this context, standardization of technology and directives play a major role, which act as a guide for different actors (Bechini et al. 2008). The various sectors have different regulatory requirements and standardizations to attain a minimum level of traceability. As textile industry does not have standardized guidelines, organizations often end with following multiple standards and semantics for information exchange, which makes the process more complicated (Lam and Postle 2006). Nonetheless, European regulations are more directed to towards standardization of the technology to minimize the barrier (Verzijl et al. 2015). As the supply chain traceability is an interplay of multiple actors who exchange the relevant traceability information with the physical flow of product, adoption of appropriate data management play a major role. In this context, the following traceability data management models has been identified (Informal Product Traceability Expert Group - Final Report 2013),

- One-up one-down model

In this model, each involved actor is responsible for linking the traceability record with immediate upstream and downstream actors. Subsequently, each actor is responsible for matching with the traceability requirements of immediate actors. The European Commission has mandated this kind of traceability management in the food sector (Thakur and Hurburgh 2009).

- Centralize database

Centralize database model uses a central database (generally managed by the third party) and each supply chain actor communicates the traceability data to it. This system needs data standards and procedures to communicate, maintain security and privacy of the data. According to Bechini et al. (2008), central arrangement is neither realistic nor efficient in real scenario due to complexity, scale, and other related concerns.

- Traceability Network

This model relies on sharing traceability key instead of sharing the data. The key acts as a reference for information retrieval from the particular actor. According to (Informal Product Traceability Expert Group - Final Report 2013), the transactional or traceability network model is simple and the most efficient model, which supports anti-counterfeiting policies with the ability for complete retrace product information. Nonetheless, supply chain actors should follow a specified data format for assigning the traceability key so that other supply chain actors can identify the respective traceability data owner to retrieve traceability data.

- Cumulative tracking

As the name specifies, cumulative tracking model follows the transfer of complete traceability information to the downstream actor as the product is transferred. Therefore, the complete traceability data follows the product. However, it faces a challenge regarding cost, data security and implementation due to a scale of data, which grow substantially as product advances in the supply chain.

Bechini et al. (2008) further discussed the traceability data model as *pull* and *push* models which use a common (external) actor acting like an *escrow* for multiple companies. According to the authors, each actor will maintain his private database to store the traceability information; therefore, he is responsible for the protection of confidential data, security, and maintenance of the database. The database will have two parts, traceability number, and product data, where the former part will act as a unique reference to the latter part. All supply chain actors share the first part of the traceability data i.e. the unique traceability numbers with the common actor, which keeps the map of traceability numbers with their respective suppliers in a common repository. Subsequently, in order to recall the traceability information, client sends the unique reference number to the common actor, which recalls the identity of the supplier and points the request to the supplier's database. Then the supplier responds with the relevant data to the common actor and the common actor replies to the client with the traceability data. In this model, the common actor knows only the traceability numbers and suppliers' information, but he has no product data. Subsequently, the supply chain actors pull the traceability information from the respective supplier when the client places a request. Hence, this model is called as *pull* model. On the other hand in *push* model, the supply chain actors *push* their product data to the common repository, and the common actor serves to the traceability request without contacting the respective supplier as the common repository holds the product data to serve the client's request.

The implementation of aforementioned traceability models relies on the communication or exchange of traceability data, which requires common semantics to understand the data and intercept the data request (Bechini et al. 2008; Thakur and Hurburgh 2009). In this context, communication techniques including Electronic Data Interchange (EDI) have been developed and widely used as a fast and reliable computer-to-computer information exchange between the supply chain actors (Alves et al. 2014; Bechini et al. 2008; Informal Product Traceability Expert Group - Final Report 2013; Probst et al. 2015). Nonetheless, it requires sophisticated IT capabilities between the information exchanging partners (Bechini et al. 2008; Thakur and Hurburgh 2009) and unavailability of a skilled workforce to handle technology acts as a major deterring factor for its implementation (Verzijl et al. 2015). Another paradigm for information exchange includes eXtensible Markup Language (XML), which has been widely used in many business activities.

2.2.4. Implementation steps

Norton et al. (2014) identified the following seven key steps for practical application of traceability for attaining sustainability as given below,

a) *Identify the key commodities*
b) *Gain a full understanding of all relevant sustainability issues to those commodities and identify whether traceability is the best way to mitigate those risks*
c) *Develop the business case for traceability*
d) *Take traceability action*
e) *Engage internally with key staff, and develop solid internal practices and processes.*
f) *Engage with suppliers*
g) *Stay the course*

The implementation steps can vary based on the type of business, commodity or product, relation with suppliers, etc. Nonetheless, as Norton et al. (2014) highlights, implementation of traceability particularly requires the identification of the goals one wants to achieve through traceability and secondly, the engagement with the suppliers to attain those goals. Probst et al. (2015) further argue that lack of skilled workforce to implement or maintain traceability act as deterring factor from the implementation perspective.

3. Methodological framework

This chapter aims to give an overview of the scientific approach followed in this Ph.D. thesis. It describes the methodological framework and elaborates the tools used in collecting, processing, and analysis of the data. It also describes the chronology of the research process.

3.1. Research procedure

According to the Advanced Learner's Dictionary of Current English, research is described as *a careful investigation or inquiry specially through search for new facts in any branch of knowledge*. It is considered as a systematic approach with iterative steps to understand, examine and explore a particular topic to generate or refine information or test hypothesis. A research process contains different steps which include defining and redefining problems, formulating hypotheses or suggested solutions; collecting, organizing and evaluating data; making deductions and reaching conclusions (Kothari 2004). The selection of a particular approach is determined and influenced by research objectives, type of data, funds and the background of the researcher (Peterson 2012). In general research approach is divided into three categories – qualitative/quantitative, deductive/inductive and mixed. A qualitative research approach mainly emphases on the concept, definitions, and descriptors, while quantitative research is about quantities and measurements (Berg 2004). According to Denzin and Lincoln (2008), the qualitative research stresses on the relation between the investigated problem and the researcher, whereas quantitative research investigates the cause-effect relationship based upon measurements. Furthermore, objective of the research is considered of great importance in quantitative research. The second category of research, i.e. deductive/inductive, is identified based upon the relationship between the theories, the reasoning of the argument or validation of the hypotheses. The deductive approach is a *top-down* approach, which goes from more general to specific, and involves the narrowing down to specific hypotheses (Creswell and Clark 2007). Moreover, the arguments are based on laws, theories and principles (Soiferman 2010). On the other hand, inductive approach emphasizes to the generalization of specific observations or findings (Soiferman 2010). Subsequently, it is considered as a *bottom-up* approach (Creswell and Clark 2007). Further, it is more open-ended and exploratory, and the arguments are mainly based upon experience or observations. The third category, as the name specifies, combines the above mentioned approaches to address the research questions.

The proposed research questions were approached using a mixed method design which relies on inductive reasoning and does not require a hypothesis at the start. The main methods include in this thesis to investigate the research questions are a quantitative approach based – where the data is obtained mainly from the experimental approach and publically available secondary data sources, and qualitatively based upon scholarly and non-scholarly open literature.

3.1.1. Experimental research approach

The experimental research approach is a quantitative approach utilized to study the effect of a certain set of known causes by intentionally varying them and then analyzing the reflected variations in the output (Christensen 1997). This allows investigating the correlation between dependent and independent variables. It is further divided into classes – laboratory and field experiments (Tierney 2008). The former uses the simulated environment to control the dependent variables, and thus it allows the replications of the experiments. However, it is sometimes problematic to generalize the findings to realistic scenario since the data is generated from controlled simulated conditions that may not be so controllable in a realistic scenario. On the other hand, field research relates to experimentally examine the hypothesis in real world natural settings. Although the field experiment is considered to have higher external validity than laboratory-based experiments, it witnesses a more possibility of irregularities as the controlling of the variable is not as robust as that of laboratory-based experimental setup. The initial development of the prototypes is carried-out by laboratory research.

A major part of this thesis has focused on the development of the textile integrated tag for traceability, which needs more control in experiments to check the initial feasibility of the concept. Therefore, the laboratory experiment research was followed for the development of the yarn coding (i.e. Paper II) and yarn coding-based traceability tags (i.e. Paper III).

3.1.2. Case study-based approach

A case study is a method to systematically develop a concept by analyzing the phenomena as they occur without any significant interference of the investigator (Fidel 1984). It is defined by several statements in the past. For instance, Bromley (1990) defines a case study as *systematic inquiry into an event or a set of related events which aims to describe and explain the phenomenon of interest,* while Yin (2014, p. 18) calls it as *an empirical inquiry that investigates a contemporary phenomenon in depth and within its real-life context, especially when the boundaries between phenomenon and context are not clearly evident.* Further, multiple terms are interchangingly used the literature including case study, case review and case reports to state the same term (Zucker 2009). Yin (2014) emphasis on conducting a case study with steps *the question to study; its proportion, if any; the unit of analysis; linking data to proposition; and interpreting the findings.* Further, the case study-based research uses either primary data or secondary data. Primary data includes the results from experiments, statistical data or any observations related to specific subject made by a researcher, whereas secondry data is collected by the researcher from a source which is not directly managed by the researcher (Rabinovich and Cheon 2011). In this thesis, Paper I is a case-based study, investigating the textile product recalls in the EU member states. It analyses the recall data obtained from the single european recalling agency known as RAPEX (acronym used for Rapid Alert System for dangerous non-food products) and correlating with different macroscale indicators of respective EU member state and insinuates the importance of traceability which is of particular relevance in increasing number of product recalls.

3.1.3. Phenomenological approach

The phenomenological approach is a method to investigate or identify the phenomena through the way it is perceived (Lester 1999). Lester (1999) further emphasises that *epistemologically approaches are based in a paradigm of personal knowledge and subjectivity, and emphasise the importance of personal perspective and interpretation* (p.1). There are two papers i.e. Paper IV and Paper V following this approach. Paper IV proposes a generic framework for implementing traceability in the textile sector – including traceability information collection, management, and exchange. As textile supply chain contains a different set of arrangements based upon the final product, the traceability implementation varies based upon nitty-gritty of the specific setup. To avoid any specificity, this article draws the common characteristics of a textile supply chain from the literature and then proposed the traceability framework. Further, Paper V describes a textile manufacturer-retailer network where traceability is used as an ex-post quality control. It uses a game-theoretic approach to model the interaction between the above mentioned actors.

The classification of appended papers according to the research approach is given in Table 3-1.

Table 3-1 appended papers details

Paper	Case study	Phenomenal	Experimental
I	X		
II			X
III			X
IV		X	
V		X	

3.2. Research process and chronology

The research process started in September 2013 as an Erasmus Mundus Joint Doctorate project. It had fixed and pre-decided mobilites to spent in three Universities/institutes including École Nationale Supérieure des Arts et Industries Textiles (ENSAIT)/ Université Lille 1 - Sciences et Technologies in France (18 months i.e. from Sept. 2013-Feb. 2015), University of Borås in Sweden (18 months, i.e. from Mar. 2015-Aug. 2016), and College of Textile and Clothing Engineering, Soochow University in China (12 months i.e. Sept. 2016-Aug. 2017). Subsequently, the total duration is 48 months.

As pursuing traceability in any manufacturing sector is a multimodal concept which combines the technical approaches to capture, store and communicate appropriate information, and the organizational/managerial aspects to implement such system in the supply chain. Subsequently, the methodological framework opted as a combination of abductive and inductive approach. The understanding the relevant literature to the traceability, its positioning in the textile sector and the concept were built following the abductive process. The part of research work dealing with the technical developments follows an inductive process, which develops the understanding and generates the data by inducing appropriate lab-based experimentation.

The first mobility of the Ph.D. started from ENSAIT France, which was more aligned towards engineering aspects. Therefore, the work was carried out during the first mobility was concept development of traceability with more focus on the technical development of the traceability tags and laying out a path for research at University of Borås. Subsequently, the supply chain and managerial aspects of traceability were explored in-depth with relation to traceability tag at University of Borås and Soochow University.

The research thesis is based on five research publications resulted from different studies carried out during the span of Ph.D. at different universities. The research chronology of the full Ph.D. duration is shown in Figure 3.1. Paper I deals with the understanding of the traceability needs in the textile sector, and studies the textile product the recalls trend in European counties, which are managed by RAPEX. Paper II and Paper III deal with the technical developments of traceability tags, which describe the manufacturing strategy of yarn coding and yarn coding-based traceability tag. Earlier versions of Paper II and Paper III were presented in the 14th world textile conference at Bursa Turkey in the year 2014 and 15th world textile conference at Bucharest Romania in the year 2015, respectively. Further Paper IV deals with the supply chain perspectives and proposes a framework to implement traceability in the textile supply chain. An earlier version of this paper was presented at NOFOMA (logistics conference) in the year 2016 as work-in-progress. Finally, the last paper appended in this thesis i.e. Paper V deals with the understanding the supplier-buyer supply chain having traceability as a quality inspection technique using game theoretical approach. A shorter and slightly different version of this paper was presented at the The 12th International Flins Conference (conference on uncertainty modelling in knowledge engineering and decision making) in France in the year 2016.

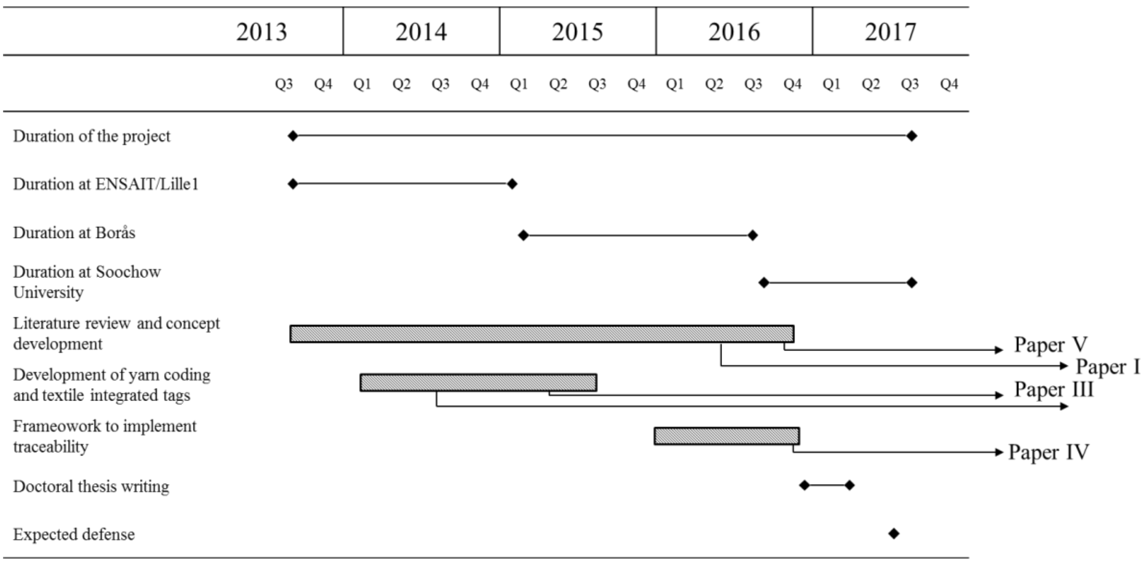


Figure 3.1 Research chronology

3.3. Scope and objectives of appended papers

Scope, purpose and main method followed each appended paper are listed in Table 3-2. Broadly, the first paper deals with one important application of traceability i.e. product recalls. Although the data analysed in this paper may not directly contribute to the other appended publications but it provides a strong foundation pragmatically for the requirement of traceability in the textile sector, which is the area of focus aim of this thesis. Moreover, it hints some issues with the current traceability practice and how it can be improved further, which can be considered as indirect contact with other appended papers.

Table 3-2 Scope, purpose and methods used in different appended papers

Paper #	Scope	Purpose	Main method
I	Product recalls	Studies textile product recalls in the EU and provides underpinning for the requirement of traceability	Empirical research/multiple regression analysis
II	Manufacturing, yarn coding	Introduces integrated tagging and yarn coding.	Image processing, Decision support systems
III	Manufacturing, integrated textile tag	Development of fully textile integrated yarn-based tags	Image processing, pattern recognition
IV	Supply chain management	Implementation of traceability in the textile supply chain.	Conceptual
V	Supply chain management	Exploring the scope of traceability as ex-post quality control	Game theory

Paper II and Paper III describes the implementation of traceability from manufacturing aspect and introduces integrating tagging for textiles using yarn-based features. The idea of integrated tags are supported the experimental investigations which uses different informational extraction and decision tools as enlisted in Table 3-2. Further, Paper IV and Paper addresses traceability from management lens proposes the possible ways to manage information in the supply chain network and discusses the effect on supply chain management. While Paper IV utilizes the conceptual approach to holistically understand the traceability information management and implementation, Paper V uses game theoretic approach to understand the impact on supplier-retailer welfare. Therefore, this thesis follows a techno-managerial approach to understand the implementation of traceability while introducing the feasibility of a new kind of yarn based traceability tag.

3.4. The research gap

In this Ph.D. research work, the research gap was identified through a literature review. Traceability has been addressed in literature in many aspects which differ to a varying degree from each other. Some supply chain stakeholders interpret traceability from the lens of organizational policies to create transparency in the supply chain (for example, case of Nudie Jeans (Egels-Zandén et al. 2015)) and utilize it as a competitive element (such as, examples highlighted by Goswami (2014) and Guercini and Runfola (2009), while many others regard it as a tool for controlling operations and supply chains. Furthermore, the extent of traceability information and features of a traceability system vary from actor to actor depending upon the expected output and the context of traceability. On the other hand, Johansson and Månsson (2013) postulate that textile industry does not have a long history of promoting traceability. Within this setting, understanding the potential of traceability by a supply chain actor is another key reason which confines the implementation or practicing traceability in a supply chain. Therefore, concluding or generalization of literature gap in a context or specific case would require sufficient number of comparable cases; however, as textile industry does not have a long history of traceability, the literature is rather limited to for a good case-specific comparison. To avoid this, the focus of the work is kept broad and instead of targeting context, the emphasis is given to analyse the core concepts which built traceability so that learning can be made from wide-ranging traceability literature, even from the studies targeting other manufacturing sectors. As the core notion of traceability can be regarded as traceable by means recorded information, which is interweaved by technology and management (such as supply chain management, organizational policies). As stated previously, technology drives the traceability by capturing the relevant traceability information and exchanges it with other supply chain actors; as a result, traceability heavily relies on IT and traceability tagging for uniquely identifying the products in supply chain. In this direction, the implementation is mostly investigated using existing tags such as barcodes and RFIDs (Al-Kassab et al. 2011; Kwok and Wu 2009), whereas some researchers have identified the issues and limitations in using these tags for traceability including privacy concerns, easy cloning, and disposal issues (Blankenburg et al. 2013; Köhler et al. 2011). Since most of the tags are externally attached to the product or packaging, therefore the traceability is generally limited to the point the traceability tags remains with the product. Concerning this the expert panel proposes by the European Commission (Informal Product Traceability Expert Group - Final Report 2013) suggests using these tags on the physical product to enhance a level of security and traceability. In this direction, attempts have been made to redefine the traceability markers (such as Xin et al. (2011), Blankenburg et al. (2013)) in some sort of integrated way. As traceability tag acts as a compulsory element for traceability therefore more research is required for explore tags which can be integrated into the textiles while respecting the existing manufacturing process. Further, there are a number of research papers and white papers focusing on the implementation of traceability. This cover the role of supply chain actors, information sharing techniques for specific sectors (such as (Thakur and Hurburgh (2009) for bulk grain supply chain, Hu et al. (2013) for vegetable sector) – which obviously cover the particular dimensions of the studied sectors, however none of the articles provides a deep understanding of the traceability framework to the complete textile sector.

This thesis majorly covers two gaps, i.e. development of integrated traceability tag and framework to implement traceability in the textile sector. Further, it will suggest a number of research questions which need to be addressed when considering the real implementation of the traceability in the specific industrial context of the textile sector. Therefore, the work in this can be regarded as a 'stepping stone' for future researches, and it covers some of the core foundation of traceability implementation in the textile sector.

3.5. Data sources

Data sources can be in general divided into two categories – primary and secondary. Primary data source includes the results from experiments, statistical data or any observations related to specific subject made by a researcher. It is also known as first-hand original data, and since it is collected for the relevant topic, therefore the degree of accuracy is considered high. On the other hand, secondary data source – also known as second-hand data – obtained from the primary source and then analyzed and interpreted to make conclusions. Secondary data (Rabinovich and Cheon 2011) is generally used to gain the initial insight and overview of the problem. Further, it is termed as internal and external, where former implies the data collected within an organization while latter implies the data obtained from the outside the organization. Working with secondary data provides an opportunity to use the best possible data source available. Nonetheless, the selection of a particular data source depends upon the expected outcome and suitability of the data collection.

This thesis is based on primary as well secondary data sources. Since the research topic concerns a wider perspective traceability in textile supply chain, understanding of the relevance and supply chain complexities were analyzed by the investigation of secondary data sources. It includes the information from the literature review and publicly available databases from international organizations including the EC managed Eurostat and RAPEX, Transparency International and the World Bank. The statistical data is kept in the best possible original form.

The primary data is collected through the laboratory experimentation. This mainly concerns the development of the integrated traceability tag for textiles. These experiments were designed to use yarns to implement traceability marking and then checking the feasibility in certain simulated use conditions. As the experimental setup have a limitation regarding studied factors as compared to real use or implementation scenario. Since this thesis investigated the yarn-based integrated tagging from scratch, therefore the experiments were particularly focused on investigating the feasibility perspective, which would provide the opportunity for future research investigations in this area.

Table 3-3 summarizes the data source for appended papers in the thesis.

Table 3-3 Data sources in the appended papers

		Data source		
		Statistics from public database	Laboratory-based experimentation	Literature/ conceptual
Paper #	**I**	X		
	II		X	
	III		X	
	IV			X
	V			X

4. Summary of appended papers

The aim of this chapter is to presents the summary of the paper appended in this thesis. It provides an overview of the research contribution of the thesis author and presents the way the appended papers address the research questions formulated in Chapter 1.

This thesis is based on five publications to address the different research questions. To briefly describe, Table 4-1 shows the relation between appended papers and the proposed research questions.

Table 4-1Relation between the appended research papers and the proposed research questions

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

As this research is conducted in three different institutes in the supervision and with the help of multiple authors. shows briefly the contribution of various authors in each of the appended publications.

Table 4-2 Authors' contribution in the appended papers

Paper #	First author	Second author – last author	Responsibility
I	Vijay Kumar	Daniel Ekwall	VK designed the study with the help of DE. VK collected the data, analyzed the results and wrote the manuscript. DE helped in result analysis and manuscript refinement.
II	Vijay Kumar	Ludovic Koehl, Xianyi Zeng	VK is the first and corresponding author of the manuscript. VK conceptualized the study with the help of LK and XZ. All authors contributed to finalized the methodology. VK carried out the experimental part, analyzed the results, wrote the manuscript. LK and XZ contributed in analyzing the results and refinement of the manuscript.
III	Vijay Kumar	Ludovic Koehl, Xianyi Zeng, Daniel Ekwall	VK is the first and corresponding author of the manuscript. VK conceptualized the study with the help of LK and XZ. All authors contributed to finalized the methodology. VK carried out the experimental part, analyzed the results, wrote the manuscript. LK, XZ and DE contributed in analyzing the results and refinement of the manuscript.
IV	Vijay Kumar	Carina Hallqvist, Daniel Ekwall	VK is the first and corresponding author of the manuscript. VK conceptualized the study with the help of CH from (IT aspect) and DE (from supply chain aspect). VK formulated the traceability framework and wrote the manuscript. CH and DE contributed to the refinement of the framework and manuscript.

IV	Vijay Kumar	Daniel Ekwall, Lichuan Wang	VK is the first and corresponding author of the manuscript. VK conceptualized the study with the help of DE. VK formulated the game theoretical models, carried out computational part, analyzed results and wrote the manuscript. DE and LW contributed to the result analysis and refinement of the manuscript.

4.1. Paper I: Macro-Scale Indicators Based Analysis of Textile Product Recalls in the EU

4.1.1. Purpose and Overview

One of the important applications of traceability from social and industrial perspectives is in managing efficient product recalls. A product recall is a reverse logistic activity of withdrawing a product from the customer and market due to noncompliance of product specifications or services with the government regulations. While a well-organized product recall minimizes the harmful impact of the defective product on the end users, organizations can not only minimize the financial or reputation manage with an organized recall, but may also find opportunities to gain unforeseen paybacks including enhanced consumer trust. Further, the EU member states have seen a substantial increase in total recall cases with a considerable portion of textile and fashion products. While textile, clothing and fashion product category is among top three product categories recalled by RAPEX, its distribution is much skewed in some countries as shown in Figure 4.1.

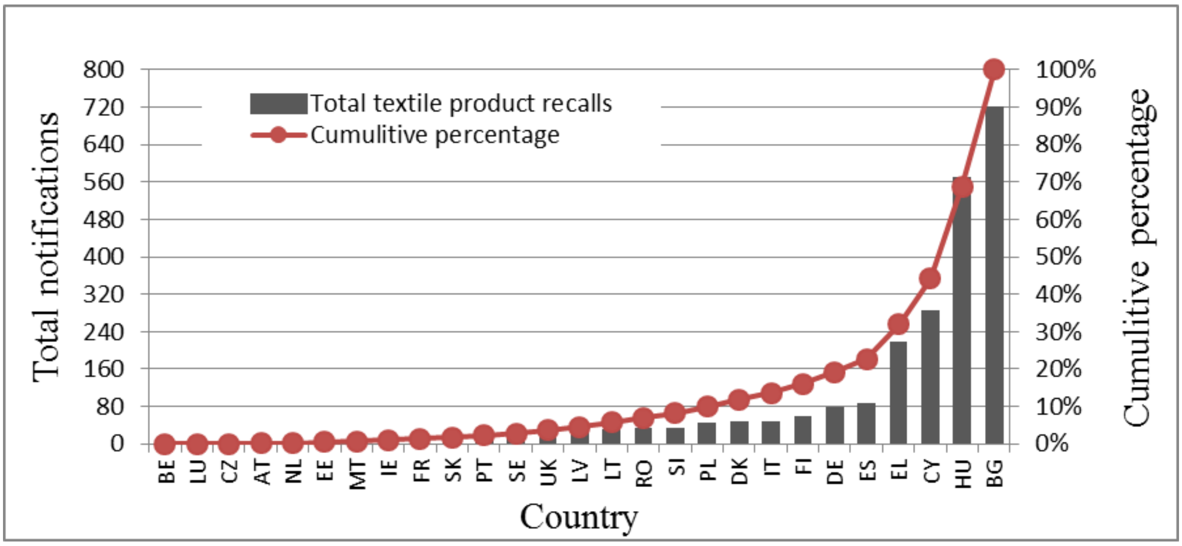


Figure 4.1 Distribution of total textile recall notifications reported by RAPEX for the EU 27 during the years 2008-2013. (Paper I)

More than 50% of recalls related to textile and clothing product have been originated from Bulgaria and Hungary alone and, while 10 European countries account for >90% of the recalls in EU 27 for the period of 2008-2013. To holistically understand the relation of different component affecting the textile recalls, this study takes various macro-scale indicators (namely economic, social and governance) of different EU member states and relate with respective textile recalls. Further, the findings of this study would give an abstract understanding of the textile recalls. The abstract understanding is particularly relevant for designing the traceability system as which component would need particular attention while considering various components in traceability implementation.

4.1.2. Research Questions (RQs)

1. Which macroscale parameters affect the textile product recalls significantly in the EU?

2. Is there any pattern in affecting parameters by which the textile product recall cases can be characterized as a problem originating from a wider issue i.e. economic, governance or social?

As earlier stated, the above research question aims in developing an abstract understating of product recalls in the textile sector, which will insinuate on which particular aspect should be considered for implementing traceability in the textile sector. It also aims in answering RQ1 by investigating the product recall of textiles from a holistic perspective as traceability is of particular importance to the sectors, which have high recalls.

4.1.3. Research Method

The research is based on logical deductive hypothesis reasoning developed based upon relevant literature and then empirically tested with the secondary data. The data has been obtained from well-known publically available databases belonging to government and non-government organizations. Since the study involved multiple EU countries, each of the data variables for all the countries was obtained strictly from only one source; therefore, the accuracy of every variable can be considered the same for all the countries. The data related to textile product recalls is collected from official non-food product recalling agency RAPEX, which updates the recalls notifications on EC official website[3] every week. The inferences were drawn using multiple regression analysis between the independent variables i.e. macroscale indicators and dependent variable i.e. number of recall cases. Further statistical significance at 99% and 95% levels were taken as reference for concluding if the corresponding independent variable is statistically important for the textile product recalls in the EU. This analysis was carried out by formulating two cases i.e. EU27 and EU10, where former case studies all EU member states while latter considers only top 10 EU member states which have contributed towards ~90% of the total textile recall cases during 2008-2013. As the findings of this study are based on secondary data collected from publically available databases, therefore it provides both high internal validity and a good opportunity to replicate the study (Rabinovich and Cheon 2011).

4.1.4. Main findings

Product recall is an activity associated with the non-compliance of regulations or product defect which can endanger the end-user directly or indirectly. While one can apprehend recall as mismanagement of local surveillance authorities in monitoring the product inflow, it can also be related to the opportunistic belief of the distributor or manufacturer who intentionally introduces or sells non-compliant products to maximize the profit due to his faith of escaping without penalty or any other major consequences.

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[3] https://ec.europa.eu/consumers/consumers_safety/safety_products/rapex/alerts/?event=main.search

Furthermore, the price is a competitive factor and recall can be expected for a less expensive product where the product cost is minimized by using substandard raw material or processes. Further, the less expensive products would be expected in more demand by the restricted financial state of the end-users. The other initiators for the recall include governance and demographic factors. For instance, a country with high population has more number of users, thus can lead to high recalls. Similarly, better governance can restrict the non-compliant products to enter in the market; therefore this can lead to lesser number of recalls.

The results of this paper provide holistic insights of textile recalls relating with 18 economic, social and governance indicators. As it can be anticipated that product recalls are more expected from less developed economic developed countries where the customer would expect inexpensive products. In the endeavor of providing such products, one might expect the producer to use inferior raw materials or substandard quality checks to minimize the product cost. However, there are no such trends observed in this study i.e. null hypothesis stating the relation of number of textile recall cases with economic indicators of EU member state was found to be true. Although another argument can also be made that the quality or specification regulations for product recalls vary from the country-to-country. However, the countries included in this analysis were those which were regulated by single agency and the regulatory compliance standards were same for all of them, therefore the variation of regulatory standards should not exist. Nonetheless, the effective implementation of policies for safety standards is influenced by the individual member state because it involves various departments regulated by respective member state. In this context, hypothesis stating the influence of governance on recalls were found to be true and in general better governance lead to lesser product recalls. Furthermore, hypothesis supporting the influence of social indicators on recalls also found partially true, i.e. some of the social indicators were significant at 95% and 99% statistical significance. Therefore implementation of traceability can be considered as an important tool for countries where higher recalls are expected as product recalling is directly related to the public safety. Brand owners can take this opportunity to project themselves as responsible organizations and use traceability as a marketing tool. Moreover, retailers generally outsource their production to upstream suppliers. Therefore implementing traceability retailers can make the upstream suppliers accountable for their actions.

4.2. Paper II: A fully yarn integrated tag for tracking the international textile supply chain

4.2.1. Purpose and Overview

The main goal of this paper was to conduct a swot analysis (strengths, weaknesses, opportunities, and threats) of the existing traceability tags used in the textile industry to identify their shortcomings and thus pave the way for integrated traceability in the textiles. Traceability stands for introducing traces in or on a product which can be used for tracking purpose in the supply chain. A traceability tag acts a unique identifier to the attached product. Thus it not only helps in recording product's footprints by scanning the tags in the supply chain but also acts as authentication mediator and information recalling token to the attached product. Subsequently, tags play a vital role in implementing traceability, and experts suggest using integrated form of tags to ensure that traceability tag remains connected to the product for a robust traceability (Informal Product Traceability Expert Group - Final Report 2013). In this context, this study reviews the existing traceability tags and aligns the characteristics required for an ideal traceability tag. Subsequently, the paper presents the idea of fully integrated tags to use in the textile supply chain and introduces the yarn coding technique to code the yarn which would act as a component of traceability markers in the textile integrated tagging. This study also demonstrates how yarn tagging-based traceability tag can conform to the requirements posed by an ideal traceability tag.

4.2.2. *Research Questions (RQs)*

1. What are the characteristics required for a traceability tag?
2. How can integrated tags overcome the shortcomings possessed by externally attached tags such as barcodes, printed labels and RFIDs?
3. How can the structure a yarn be modified to utilize it as a component for traceability in textiles?

The above stated RQs in this paper relate to all research questions of the thesis and further the results of this paper make a foundation for realizing the integrated tagging in the textile structures discussed in Paper III. RQ 1 and RQ 2 of the Paper II related to RQ 1 of the thesis mentioned in Chapter 1.7 by organizing the concerns of textile sectors which can be directly addressed using specific features of the traceability tags. Further, RQ 3 of the Paper II relates to first step one of RQ2 of the thesis by introducing yarn as a potential candidate to use as traceability component. Further, RQ2 of the paper II investigates on how yarn based tag can be used for traceability implementation in the textile supply chain therefore it contributes to RQ3 of the thesis.

4.2.3. *Method*

A part of the paper is literature-based, which investigates the features required for an ideal traceability tag and conceptualizes the implementation of traceability in the supply chain. Further, this paper uses a lab-based experimental approach for proposing the potential of yarn as a component of traceability. Here a wrapped yarn assembly has been prepared using a white core yarn and black wrapping yarn as shown in Figure 4.2(b). The wrapped yarns were manufactured on hollow spindle spinning frame with five levels of machine set twists (200 twists per meter/TPM, 400TPM, 600TPM, 800TPM and 1000TPM). Further, the yarn features for traceability were extracted using image analysis techniques and a decision support system is proposed for support system for the identification of the yarns based on their optical features. The support system is formulated and optimized using fuzzy system and fractional factorial experimental design.

4.2.4. *Main findings*

One of the primary conditions for implementing traceability in any supply chain is the ability to uniquely tag the products. As traceability tags are used to tag the products, the traceability of a product is limited to the point the corresponding tag is removed. Furthermore, the tag has the encoded information which acts as product identifier for authentication. In this direction, it is important this encoded information should not be easily reproducible, clonable or a tag should not reusable with other products to protect again counterfeiting, which is a common problem in the clothing sector. A tag integrated into the product thus minimizes the possibility to detach it from the product.

In order to create a yarn based tagging for textiles, this paper introduces the yarn coding technique to introduce the optical features in yarns in a controllable manner. Yarns act as an integral part of textiles. In order to make a textile fabric, yarns are woven or knitted to make a two-dimensional sheet-like assembly and the optical or visual features of constituent yarns make a visual impression on resultant textile. Therefore, in this paper, the concept of yarn coding is introduced which can be used for to produce optical features in the yarns and the features would be later used as traceability markers. A yarn-based tag can offer multiple advantages over the conventional tags such as barcodes and RFIDs. For instance, the yarns used for traceability would also act as a textile component which is fully integrated into the textile structure. Therefore, firstly it cannot be simply removed because removing the yarns will result in disintegration of the textile structure itself. Similarly, the cloning of the yarn tags would a lengthy process and far complicated than cloning the barcodes by simple printing. To clone the tag, one would need to prepare the yarns first, followed by manufacturing of the fabrics and then use the manufactured fabrics to make the final product. Moreover, as a yarn-based tag needs only textile fibres, it can be processed in regular textile recycling processes.

Here, a composite yarn structure is used to introduce three twist-based optical features, including wrapping area, wrapping helix angle and twist distance (twist per meter/TPM). Figure 4.2 shows schematic and actual produced coded yarns as components for integrated traceability tags. Further, a methodology for yarn coding recognition system is introduced, which combines different optical features and make the decision based upon the capability of capacity of individual feature to classify the yarn. As yarn coding introduces different optical features in the resultant yarns, the recognition system is designed to calculate the membership of different yarn features to the known yarn classes using the following formulation,

$$d(x,\mu_1,\mu_2,\sigma') = \frac{1}{\sigma'\sqrt{2\pi}} \int_{-\infty}^{x} e^{-\frac{(x-\mu_1)^2}{2\sigma'^2}} dx \times \left(1 - \int_{x}^{+\infty} e^{-\frac{(x-\mu_2)^2}{2\sigma'^2}} dx\right)$$

$$\mu_1 = \mu - 2.25\sigma$$
$$\mu_2 = \mu + 2.25\sigma$$
$$\sigma' = \frac{2.5\sigma}{3.129}$$

where d is the membership of a feature cluster having mean μ and standard deviation σ, and x is the feature magnitude.

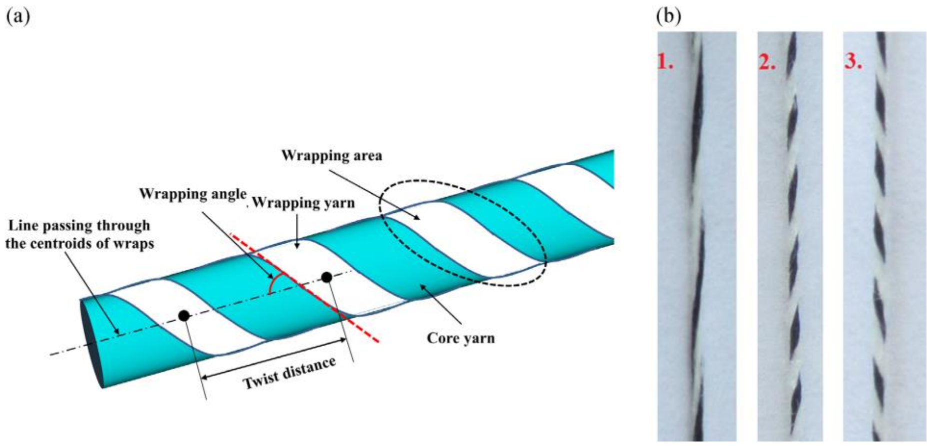


Figure 4.2 Yarn coding features in a wrapped yarn assembly. (a) schematic is representing the yarn assembly (b) actual yarns with different twists and twist directions. (Ref. Paper II)

Since there are multiple yarn features, therefore the aggregated membership for a yarn class is calculated as,

$$D_i = \left[\prod_{j=1}^{n} d_{ij}^{w_j} \right]^{\frac{1}{\sum_{j=1}^{n} w_j}}, \; i \in \{1, C\}, 0 < w_j \leq 1$$

Where D_i is the aggregated membership to yarn class i, d_{ij} is the membership value calculated for j^{th} optical feature of i^{th} yarn class, C is the total number of yarn classes, and w_j is the weight assigned to j^{th} optical feature.

The yarn coding was experimentally applied using a white core yarn (50 Tex polyester) and a black multifilament wrapping yarn (16.6 Tex multifilament polyamide) with five different machine-set twists i.e. 200TPM, 400TPM, 600TPM, 800TPM and 1000TPM. In this analysis, twist distance was found to be most robust features to identify the above-mentioned yarn classes. The yarn coding was tested using one-leave-out cross-validation method. Despite the overlapping of the features clusters, 100% success rate was obtained with the designed recognition system. This confirms that the yarn coding with above-mentioned yarn specifications can be used for implementing traceability in textiles.

4.3. Paper III: Coded yarn based tracking tag for textile supply chain

4.3.1. Purpose and Overview

A physically integrated form of the tag not only reduces the possibility of detachment of the tag from the product for robust traceability but also serves for potential traceability applications after the point-of-sale (POS). This includes product segregation during the recall and post-POS product authentication and information-based intelligent applications. The conventional tags including RFIDs and barcodes are generally removed at POS which limits their scope to use in the use phase. Moreover, use of RFIDs integrated products creates the privacy concerns as RFIDs respond to almost every nearby RFID reader (Garfinkel et al. 2005). Thus they can be easily used for tracking the end-users. Köhler et al. (2011) stated the recycling concerns of RFID integrated textiles where RFIDs cannot be easily separated in automatic shredding processes and acts as a contamination in recycled fibres if not removed during the recycling process. On the other hand, barcode printing on the product itself is a good alternative to extend traceability beyond POS, but the ease of cloning restricts them to use for anti-counterfeit. Hence, the industry would need an alternate approach which can bypass the privacy concerns while securing the product with integrated from of the tag.

In this context, this main purpose of this article is to introduce the strategy to implement coding-based yarns to produce integrated tags in woven and knitted structures, while keeping the focus on shortcomings offered by existing tagging techniques. It further demonstrates the image processing algorithm to decode the information coded by means of optical features-based coded yarn. The study is validated with the experimentally fabricated tags and then testing under different conditions.

4.3.2. Research Questions (RQs)

1. How can a yarn coding-based technique be used for creating traceability in the textiles?

2. How can a pattern recognition technique be employed to read the yarn-based integrated traceability tag in textiles?

The RQs of this paper directly relate to RQ1, RQ2 and RQ3 of the thesis. The yarn coding introduced in Paper II is utilized in this paper to create integrated traceability tag in the textiles, which also consists of a discussion from textile manufacturing perspective. Therefore, this contributes towards the RQ2 of the thesis. Further, the implementation is conceptualized in supply chain on how traceability implementation during the manufacturing can be used in later stages including product security and authentication, which contribute to RQ 1 and RQ 3 of the thesis.

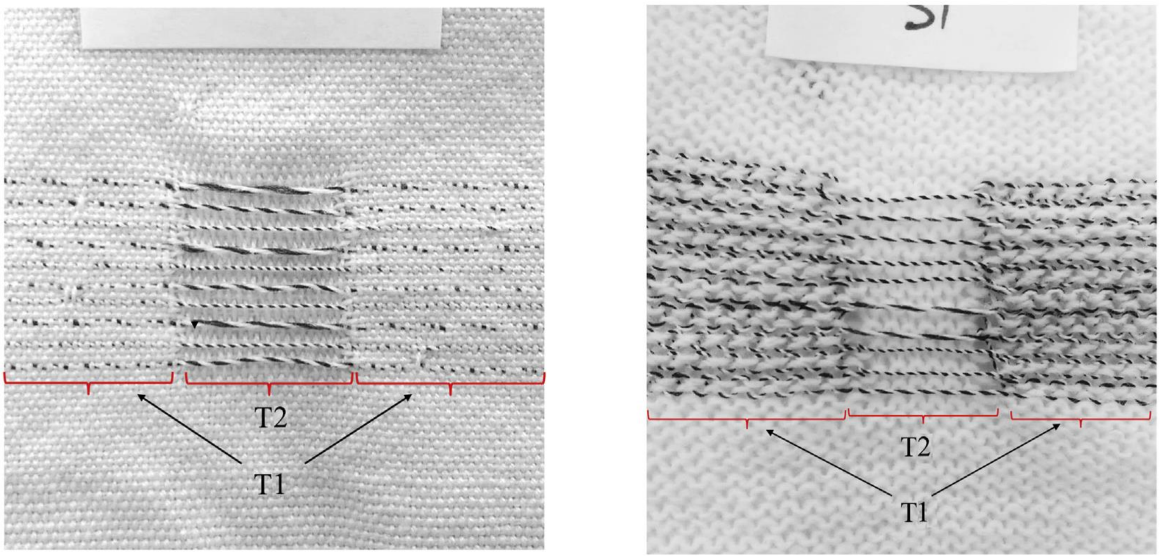
4.3.3. Methods

This paper is mainly based upon the lab-based experimental work, where the samples containing coded yarns were manufactured into plain woven and weft knitted structures. Five classes of yarns coded yarns i.e. five different twists (machine set twists were 200TPM, 400TPM, 600TPM, 800TPM, 1000TPM) were manufactured on hollow spindle spinning frame with the same process parameter as used in Paper II. The woven samples were developed on lab-scale sample shuttle loom using all coded yarns while knitted samples were prepared on automatic knitting machine using all yarns except 1000TPM. Nonetheless, in the recognition system, the accountability of all classes was taken into account by comparing the optical features against all yarn classes irrespective of a tag having all classes or not. Further, image processing was used to detect the specific pattern that the yarn features have resulted on the fabric surface and then these features were combined to using decision support system developed in Paper II to generate the output or the tag code. Since the materials and process parameters were same as that of Paper II, the parameters of the decision support system were also considered same as mentioned in Paper II.

4.3.4. Main findings

The yarn coding is the technique of introducing some specific features on the yarn as described in Paper II. Therefore, the resultant of such component-based tagging will be a visual feature based labeling. As compared to RFID, the benefit is that the privacy concerns can be avoided by simply hiding the tag in the product, where it is not directly visible. However, unlike RFID which can be read without direct contact or visibility, it yarn-coding based tags need to be scanned individually, which inevitably needs more manual handling. Nonetheless, as yarn-based tags are simple textile components, it can be anticipated that they need no extra care or special operation during the recycling process. *Figure 4.3* shows the experimentally fabricated tags in the woven and knitted textile structures.

As the integration of the coded yarns in the textile structure creates distinctly visible



(a) (b)

Figure 4.3 Coded yarn-based integrated tags in (a) woven and (b) knitted textile structures (Paper III)

textures (as shown by T1 and T2 in Figure 4.3) from the rest of the fabric, they act as tag identifiers. In this context, this article establishes an algorithm for identifying the tag location and decoding the individual yarn features. From the information decoding perspective, the tags were tested by introducing the electronic image noises and washing treatments. From the analysis perspective, the analysis was divided into three steps, namely preprocessing, membership threshold and code generation. Preprocessing deals with the identification of the tag location and decomposition of the tag into individual code yarn. Membership threshold defines the minimum identification membership in the recognition system (designed in the Paper III); therefore, the membership threshold success rate defines the percentage of tags able to cross the defined identification threshold (which is described in detail in Paper III). The decoding success rate implies the tags whose yarn features have successfully achieved the identification threshold and correctly identified. As the main purpose of the tag is to reflect the information encoded in it, in this study the decoding success rate is particularly relevant, which shows a rate of accurate information retrieval. The results indicate ~80% of the initial decoding success rates (i.e. for freshly prepared tags), whereas the overall success rates (multiplication of all above-mentioned success rates) of 59% and 67% for knitted and woven tags as shown in Figure 4.4.

Five washes with each wash followed by tumble drying, has reduced the overall success

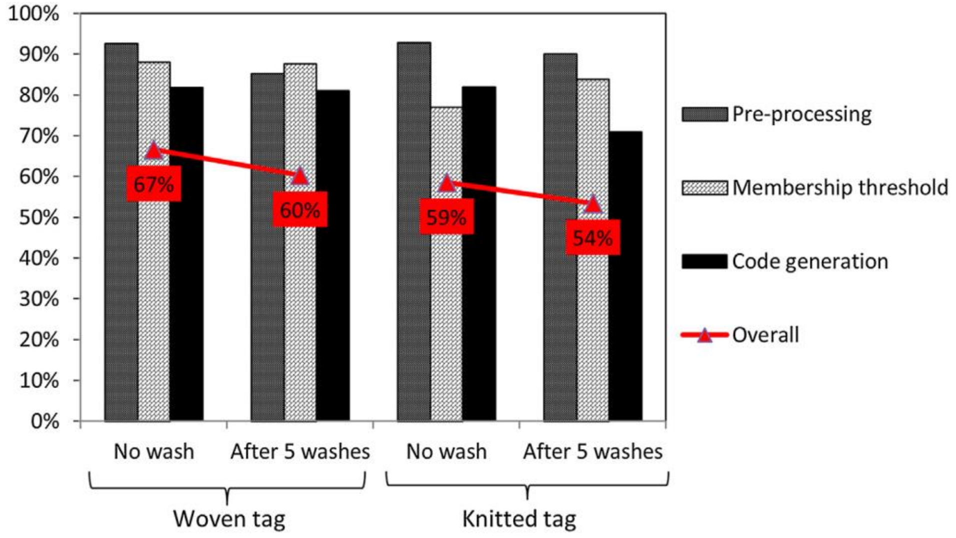


Figure 4.4 Tag decoding analysis (Paper III)

rates. Furthermore, the introduced image noises show their impact, particularly on preprocessing success rate which follows a decreasing trend with an increase in noise (in Paper III). Although the success rates may be still low for real industrial implementation as compared with existing tags such as RFIDs and barcodes, nonetheless the results show that yarn based tagging can be potentially implemented with certain improvements in yarn features. Moreover, the idea behind the article was to look at the feasibility of a new way to tag the fabric. In this direction the results indicate that to use product's components for traceability can be a new way to visualize traceability, which reduces the reliability on external tags. Therefore, it provides a new direction for research to visualize traceability relying on product's inharent property.

4.4. Paper IV: A framework to implement traceability in the textile supply chain

4.4.1. Purpose and scope

Traceability is a concept of informationally extending the scope of supply chain stakeholders (including customers) beyond their organizational or personal boundaries. Furthermore, the individual actor needs to capture, systematically manage, and communicate the traceability information other actors in the supply chain. Subsequently, implementation of traceability becomes a technological as well as organizational concern and where every supply chain management actor not only contributes to the traceability but also complies with the traceability requirement agreed with other involved actors. Furthermore, as reported by Lam and Postle (2006), not using the common semantics create a problem in communication among the supply chain actors, which results in the selection of multiple semantics for different supplier buyers suppliers. This inevitably increases the complexity and cost to implement any information sharing system. In this context, the purpose of this article is to develop a framework for the traceability implementation in the textile supply chain.

Information is a crucial component for the success of any business, and according to Štorga et al. (2011), organizations would like to take the leverage of information irrespective of its source which can help them to innovate or compete. Conversely, organizations would like to restrict the sharing of the traceability information to the extent it does not give an undue advantage. This is particularly a concern when there is no mandatory requirement, unlike the food sector, for traceability implementation. Thus, this study proposes a conceptual framework incorporating the technical concept of the information management and managerial context of the supply chain to implement traceability in the textile supply chain. Here a system base-based approach is followed for the framework which combines business process integration tools including system requirements planning, enterprise modeling, and integration.

4.4.2. Research Questions (RQs)

1. How can traceability be conceptualized as information network in the supply chain?
2. What are the important considerations from supply chain perspective that are required for traceability information exchange in the textile supply chain?

RQs of this paper directly contribute to RQ1 and RQ3 of the thesis. Firstly it describe on how traceability can act as a component contributing towards the supply chain management and then a framework is described which takes into the account the roles of various supply chain actors to implement a supply chain-wide traceability.

4.4.3. Methods

This is a concept based paper which is based on a systematic approach to implement traceability by using business integration tools including requirement planning, enterprise modeling, and integration. It incorporates the dynamics of textile supply chain from literature to conceptualize the implementation. Further, it uses Integrated Computer-Aided Manufacturing (ICAM) Definition Part 0 (IDEF-0) and Unified

Modeling Language (UML) use case and sequential diagrammes to visualize the implementation in the supply chain. XML datasheets have been used to illustrate the example of traceability data exchange between the supply chain actors.

4.4.4. Main findings

Traceability, in general, can be divided into internal traceability and external traceability. Internal traceability is the primary link to the supply chain-wide or external traceability. Internal traceability, also known as intra-actor traceability, implies the ability to recall the history of a product or traceability unit within an organization. External traceability implies that the traceability information is recallable beyond the scope of one organization. Therefore implementing traceability in a supply chain can be considered as a two-step process, where internal traceability of various individual actors is connected through external traceability to form a supply chain-wide traceability. Within the same context, the article follows a process to propose the traceability implementation framework considering the supply chain dynamics at two levels i.e. within an organization and between the organizations. Moreover, before the implementation of internal traceability, it is important that each supply chain actors clearly identify the internal objectives as well as the objective of other supply chain actors associated with the implementation traceability. In most of the textile supply chain, the main function of retailers is to predict the market demands and accordingly place production order to upstream suppliers. Therefore, the proposed framework considers the textile supply chain as a network of B2B (business-to-business) actors which carry out the main manufacturing operations and B2C (business-to-customer) actors which include the retailers or distributors who deal with end-users and create a demand for B2B actors. Therefore, the main traceability information in textile supply chain originates from these B2B actors who source different materials and apply processes to produce the final product. Therefore they are considered as the main contributor of traceability. On the other hand, from the operational aspect, a retailer acts as a reseller and does not contribute from alteration of the material. Nonetheless, a retailer is considered as the main actor in the textile supply who serves as an interface between the textile supply chain and customers for exchanging the products and traceability information.

The internal traceability in the proposed framework has accounted for a four-step process, which systematically aligns different traceability activities and requirements at an organizational level. The initial step includes the identification of traceability information to capture which complies with various requirements such as regulatory compliance, internal needs, and requirements from the next supply chain actor. Further, in the subsequent steps, the identified data is segregated into private and shareable data to ensure that during the exchange of traceability information, no private data is shared. By following this, each supply chain actor is responsible for the security of data. The proposed traceability framework further follows the notion of network traceability in data sharing for external traceability. In network traceability, supply chain actors manage their traceability information and share the traceability number with a third party. Subsequently, the traceability information is recalled through the third party. Nonetheless, it requires a third party for functioning. To avoid the dependency on third party, the framework proposes to exchange the traceability number between the actors. Moreover, the actors not only share the traceability numbers but also exchange the required or agreed traceability data. Therefore the receiving actor stores the incoming information along with traceability number in his database. The inbound material information is linked to the outbound lot so that traceability information can be recalled even after different materials are aggregated together to form a new lot. For implementing external traceability, the proposed framework divides the supply chain into two sections. As the retailer act as the dominant actor in the supply chain, therefore supply chain division is made based upon the retailer position. The retailer manages the first section or part of the supply chain. It consists of the actors who are critical to the retailer regarding innovation and value creation. Therefore, retailer ensures a full control over them by making a direct contact. On the other hand, the second section is not that critical therefore the retailer either occasionally monitors them or does not monitor at all. In such scenario, the framework proposes to implement a central data exchanging for first section of the supply chain, where the retailer would manage a central server and all retailer-managed links exchange the traceability data through it. In this way, the retailer ensures that the supply chain actors are exchanging the required traceability information. Moreover, the retailer would also have full control on data flow as it is exchanged through the retailer-own server or database. On the other hand, the second section of the supply chain is not controlled by the retailer so no single actor can control the flow of information. In such scenario, the responsibility should be given to relevant supply chain actors to ensure that their immediate suppliers comply with required traceability. In this case, one-up one-down traceability can be implemented which implies that there is no central unit to monitor the traceability data, and actors make direct contact with each other for data exchange. Nonetheless, it would require standardization of data exchange semantics at a global level so that the supply chain actors by default have an alignment in terms of technology.

4.5. Paper V: Supply chain strategies for quality inspection under a customer return policy: a game theoretical approach

4.5.1. Purpose and scope

The relation the supplier and buyer is an important aspect for the success of supply chain. This is particularly important when the success of one actor in the supply chain is highly dependent on the other. For instance, brand owners outsource the production activities to the upstream suppliers. Therefore the quality of the product is decided by the efforts of these suppliers. As the textile manufacturing industry has seen a shift towards some Asian countries which has resulted in increase of manufacturer/supplier–retailer distance, the retailer cannot observe the production activities at a distantly located supplier. As supplier and retailer may have divergent priorities regarding investment in production quality, this gives an advantage as well as the malicious opportunity to the suppliers to provide defective or inferior products to the retailer. In this context, the responsibility of the retailer is to implement an optimal quality inspection strategy to minimize or avoid the risks associated with defective products. Quality inspection helps in identifying the defective or non-conforming items or supplies provided by a supplier. However, as all the product characteristics are difficult to inspect due to technological and financial constraints, there is always a possibility of defective products reaching the end-user customer (Cheng et al. 2013). In such events, it is important for the retailer to provide a fair compensation on product returns (such as product repair, replacement, discount, etc.) to ensure the confidence of customers. Furthermore, the financial liabilities associated with the above-mentioned product return-based compensations have prompted practitioners and researchers to reassess the quality inspection policies and share the defective product borne liabilities with the supplier who is the originator of the defect. In this context, traceability plays an important role for the retailer, which acts for the identification of the suppliers from where the quality issue arose. Therefore, the purpose of this article is to model the textile manufacturer – retailer relation, where the retailer uses the traceability information to penalize the textile manufacturer for the quality related concerns arises on the customers' end.

To provide the understanding of the textile manufacturer – retailer (or the supplier -- buyer) relation, this paper uses the game theory framework where retailer uses quality inspection and traceability to punish the textile manufacturer for defective items. It uses a deductive and explicit approach, which is based upon different game models and the input parameters used are assumed to be known. It demonstrates four cases based upon the different dominance of the supply chain actors in the supply chain. Further, this article provides the perspective of bargaining in the supply chain.

4.5.2. Research Questions (RQs)

1. How traceability is can be used as ex-post quality control tool in a supplier-buyer network?
2. What is the impact of traceability in a manufacturer-retailer relationship in the textile supply chain?

Both RQs of this paper contribute to RQ1 and RQ3 of the thesis. As traceability allows the recalling of products therefore it makes supply chain actors accountable to their claims. Within this context, this paper conceptualizes the importance of traceability for manufacturer and buyer when the buyer uses traceability as ex-post traceability tool and holds the manufacturer accountable for any defect in the product. Furthermore, it numerically demonstrates the suitability of leading the supply chain with varying market scenario. Here, the scenario is controlled by independently varying the return rate for defected products from the customers.

4.5.3. Methods

This paper follows a game theoretic approach for conceptualizing the supply chain arrangement. It assumes four cases for with different power asymmetries of the manufacturer and retailer in the supply chain and solves those using well-known Stackelberg and Nash game models.

4.5.4. Main results

Traceability is an important tool for *ex-post* quality control. While for the regulatory authorities traceability acts as vital component particularly in the recall and compliance enforcement, supply chain actors can use it for quality control along with many other objectives such as supply chain security, visibility, and control (Cheng et al. 2013; Hobbs 1996). Wang and Roush (2000) further argue that supply chain actors transfer their risk as a common strategy to control risk, which can be seen in textile supply chain as the outsourcing of production activities by the retailer to the upstream suppliers, thus reducing their risk by not owning the manufacturing facilities and related issues such as technology obsolesce/up gradation. Further, it helps them to focus on core activities they are specialized in. However, the supplier gains the chance to manipulate the system if it increases the supplier's welfare without getting noticed (Cheng et al. 2013). As traceability extend the informational boundaries of a supply chain stakeholder, therefore, it can restrict the opportunities to the supplier as the buyer can trace the supplier even if the buyer has sold the product to the downstream actor (or customer).

In this context, four game models were formulated, two of which were dominated by the either by the textile manufacturer or by the retailer, thus account for their own welfare. On the other hand, the remaining models account for their independent or linked contribution to the supply chain welfare. As the two latter models concentrate towards the supply chain welfare, the formulated model shows that the traceability retains its minimum level in the supply chain. This can be related to the fact that any opportunistic action from the textile manufacturer would lead to the decrease in supply chain profit, hence indirectly affecting his profit. Moreover, in the absence of opportunistic action, keeping the minimum traceability insures that maximum supply chain profit is obtained by making a minimum investment on traceability. On the other hand, when one of the actors in the formulated game has an independent profit (i.e. not related with the supply chain profit), this results in the opportunistic behavior, thus the formulated models show that the optimum traceability can result a non-zero value. Thus traceability can be used for *ex-post* quality control in the supply chain.

4.6. Results of appended papers concerning research questions

This section presents a combined overview of the appended paper with reference to the RQs of the thesis presented in Chapter 1.7. Table 4-3 shows the main contexts of appended papers with respect to the RQs to provide a general overview of traceability and its implementation in supply chain. Further Chapter 5 uses the combined results of Table 4-3 to make a detailed discussion.

Table 4-3 The result of the appended papers and the research questions

		RQ #		
		1	2	3
Paper #	I	- Product recalls		
	II	- Authentication	- Required features - Yarn coding/ component preparation - Concept of fully integrated tag	-Planning for tagging
	III	- Product security - Product authentication - Supply chain security	- Coded yarn-based tagging - Fabric structure modification	- Planning for tagging
	IV	- Extending informational boundaries		- Intra-actor traceability - Inter-actor traceability - Data management
	V	- Supply chain management		- Role of supply chain actors
Combined results		- Product recalls - Product Authentication - Extending informational boundaries of organizations - Supply chain management	- Yarn coding/ component preparation - Coded yarn based fully integrated textile tags	- Planning for intra-actor traceability - Planning for inter-actor traceability and role of supply chain actors

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 to each other. Table 4-4 briefly describes the interconnection between different appended papers.

Table 4-4 Interconnection between the papers

	Paper II (Yarn coding)	**Paper III** (Coding based tags)	**Paper IV** (Traceability framework)	**Paper V** (Game theory)
Paper I (Product recall)	Product recall management requires a traceability system which can help in substantiating the recalled items.	–	Retailer needs to have full traceability information for immediate recall	–
Paper II (Yarn coding)		Wrapped yarn assembly can be used in textile integrated traceability	Supply chain actors should use the information encoded on traceability tags as a link to connect the inter-organizational information systems.	–
Paper III (Coding based tags)			The retailer needs to take the initiative and act as supply chain captain to implement traceability	–
Paper IV (Traceability framework)				Traceability can be used as ex-post quality control in supplier or retailer dominated supply chain for profit maximization

5. Analysis

The purpose of this chapter is to provide an analysis of the results in the frame of reference presented in Chapter 2 and to answer the formulated research questions. The discussion in this Chapter follows the points aggregated in combined results of Table 4-3.

The proposed research questions (RQs) described in Chapter 1 are analyzed based upon the results obtained in the appended papers, as presented in Chapter 4.1– Chapter 4.5 and summarized in Chapter 4.6.

5.1. RQ1: How is traceability relevant to the textile sector?

Traceability has been a concern in almost every industrial sector. RQ1 seeks to determine how or from which perspectives traceability can be relevant to the textile sector. The following explains the findings from the appended papers which relate to above-mentioned question.

- *Product recalls*

Product recall is a reverse logistics activity of taking back the products from the market or consumer due to lately identified non-compliance of the product w.r.t. end-user safety, security or standardization. As mentioned in Chapter 4.1, Textile and clothing product category was identified as one of the highest product recalling categories by number of cases in the EU member states and a large proportion of the recalled product was characterized as dangerous, therefore it is of utmost importance that these identified products for recalling are recovered from the market or end-users. To efficiently organize a recall, traceability acts a prerequisite. As aforementioned in Chapter 2.2, traceability combines the facets of track and trace which ensures that product's history such as used raw materials, suppliers as well as distributor information. Since the textile sector spans from conversion of individual of fibres into a finished garment, the shortcomings or inadequacies related to material quality or design to comply with regulatory permitted standards may result in the recall of the final product from the market. Product recalls are particularly relevant to the textile sector as textile, clothing and fashion products category are one of top product recalling categories by a total number of cases in the EU. During the execution of a product recall, traceability information plays a critical role for the recalling agencies for tracing the recalled products in the market and distributor information. Furthermore, it is difficult to convey the identity of recalled textile products to the end-users using color, design or specifications as most of these parameters are fuzzy which are difficult to convey. Traceability implies the recalling of product history and it is implemented using product tags with some sort of encoded information, therefore the encoded information can be used in place of descriptive parameters for product identification during the product identification and recall. Moreover, customers can use this information to verify if their products are safe.

- *Product authentication*

Textile sector is a very prone as well as an ill-affect sector for counterfeit products and accounts for a significant proportion of counterfeit or pirated by volume as well as value confiscated by border customs of various countries. Some of the major reasons behind such a huge counterfeit business are ease to replicate textile product and inability or the limited ability of the end users to distinguish between original and counterfeit products. Textile products are mostly authenticated by the end user by the brand names, brand logos or any other tag attached to or printed on the item (as discussed in Paper II). The ease to replicate these identification markers acts as an easy break-in to integrate counterfeit products in the market and unavailability to authenticate the product make it difficult to recognize the counterfeit items. In this direction, traceability can play a vital role in product authentication. For implementing traceability, products are mapped with traceability tags. Each traceability tag carries a unique number (encoded information) which acts as a unique identifier for the product in the supply chain. Thus every product can be traced in the supply chain using the above-mentioned unique number. In this context, Paper II demonstrates how the randomizing of the traceability number can be potentially used for product authentication. Randomizing means assigning the traceability number in a random way which is generated using a secret function that is controlled by the brand owner or authorized person. Therefore, if there are n products, each product would have a unique number on its tag and there would be no apparent pattern in assigning the numbering as the unique numbers have been randomzinsed before encoding on the tags. Therefore, no one can guess the number which would be assigned to next product. To authenticate the product, the buyer/customer would need to validate the traceability number (i.e. the unique number printed on the tag) with the brand owner in order to ensure that the brand owner has assigned that particular number to a product. In case the traceability number has been assigned by the brand owner to a product, the corresponding product specifications (such as product type, color, size etc.) can be provided to the user. Therefore, the buyer/customer can verify the product specification with that of provided by the brand owner to authenticate the product. Nonetheless, in this case, one primary requirement is that traceability tags should possess certain level of anti-cloning or anti-replication so that no one easily copies the tags. In this context, simple printed barcodes may not be a suitable choice as they are very easy to replicate and can be easily detached or clonned and re-used with another product, as described in Paper II and Paper III.

- *Product security*

Product security, here, implies securing the product from unauthorized alteration in the supply chain. A textile supply chain consists of supply chain actors located worldwide, and the supplies are displaced by third party logistics companies. The supplies can be replaced during the transit of supplies; therefore product security is an important aspect. The basis of traceability is to use traceability tags which act as product identifiers. In this direction, the integrated traceability tag – which cannot be removed from the product – can be potentially used for securing the product in the supply chain. In this way, the product security is linked to the tag security, which implies that, first tag should not be detachable from the product and second it should possess no easy and quick cloning, as discusses in Paper II and Paper III. As Blankenburg et al. (2013) discussed, simple RFIDs and QR-codes based traceability tags are easy and quick to replicate. Therefore they may not be a better choice for a robust security. Nonetheless, Paper III describes an example of product security between a weaver and downstream supply chain using a yarn-based integrated tag, which is integrated by in the cloth role during the weaving process. Yarn based integrated tags consist of yarns, having special optical/visual features, arranged in a predefined sequence in the fabric during the weaving process. Subsequently, besides acting as a traceability marker, these yarns act as product components. Therefore, replication is hindered by the lengthy process as it would need manufacturing of yarns with same or similar optical features followed by weaving them in a defined sequence in the fabric to replicate another cloth role with integrated tagging. Furthermore, these special yarns act as a cloth-role component. Therefore they cannot be removed without destroying the cloth role itself, and hence they provide enhanced security.

- *Extending informational boundaries of organizations*

Information is an important component for the functioning of a supply chain. A textile supply chain consists of actors who rely heavily on each other for the raw material supplies and the synchronous functioning. According to Štorga et al. (2011), organizations would like to take the leverage of information originating from any source, which can help them to innovate or decision making. However, as the involved actors act as independent entities, each has its organizational boundaries and sharing information would need to make a linkage. Paper III shows an example of how implementing traceability in a real-time can extend the informational boundaries of a supply chain actor. Traceability implementation implies assigning a traceability code to the product or traceable resource unit (TRU), which act as an identifier. Therefore, if a buyer can monitor its offshore suppliers while assigning the traceability codes to the TRUs, virtually the firm monitors the offshore suppliers for the production. For example, the yarn-based tags need be integrated into the cloth-roll during the weaving process. The process, in which these coded yarns are introduced in the cloth-roll, can be resourcefully used by the buyer to monitor the production at a distant buyer. Nevertheless, it would need an agreement from the offshore supplier to share this information with the buyer in a real-time. Further, Paper IV describes a framework to manage and share the traceability information in a linked manner such that product history can be recalled at any point in the supply chain. Moreover, the traceability provides a framework to systematically store information, which retains the link even if the related product or raw material is physically or chemically transformed. Using these traceability links, the information can be recalled from the upstream suppliers in the supply chain, as shown in Paper IV, which helps in informationally extending the boundary of a supply chain actor.

- *Supply chain management*

Supply chain management is by defination referes to various aspects of management related to the management of the flow of goods and services as described in Chapter 2.1. Since the textile supply chain consists of multiple stages of operations from fibre sourcing to final products, therefore one important chellange is maintianing the product quality as the different stages of production are handled by individual supply chain actors. Accordingly, the quality of the final product is often decided by the effort of the suppliers (Chapter 4.5). However, in order to ensure the quality, it is important that supplies are thoroughly inspected at each stage of production. While the random inspection methods are always not relaiable to identify all quality issues, the inspection of all quality characteristics cannot be carried out due to technological limitations and financial concerns. Therefore, in supply chain management, traceability can be used as a tool for keeping the track of supplies so that any quality related – which was not identified during the transiction of suppliers – can be traced back to its origin and preventive measure at source can be taken. Furthermore, supply chain actors can be held responsible for their actions as traceability keeps the track of supply chain stakeholders. Within this context, Paper V studies the traceability as an *ex-post* quality control to the buyer with a constant demand supply chain. Finding suggests that if there is a single supply chain “captain” who controls the profits of the other actor, while the other actor acts as a follower, traceability as ex-post quality control can play a role in supply chain management for profit maximization. On the other hand, if supplier and buyer both act simultaneously in the supply chain, traceability remains at possible minimum level. Furthermore, there are many other aspects of traceability which has been highlighted in Paper IV and related to the supply chain management. Since traceability allows sharing of the critical information about the products, operations and distribution, it is particularly relevant for supply chain activities such as claim verification, regulatory compliance and product recalls.

- *conclusions*

The RQ1 targets in investigating the importance of traceability in textile supply chain. Traceability is basically an ability to recall the information therefore its implementation has numerous applications which can be common as well as specific to the supply chain actors. In this analysis, some relevant aspects were investigated which are common in general to the textile sector. Since every individual product can be separately identified in the supply chain, the communication can be more discrete for information exchange about individual products. Subsequently, it can provide enhanced control and visibility in the supply chain. Moreover it reduces the information asymmetry between the supply chain actors which directly or indirectly assists in other organizational objectives. In this direction, Bechini et al. (2008) describe traceability as a required strategic element for any kind of supply chain.

5.2. RQ2: How can traceability be implemented without using external tags?

Traceability is a concept of tracing the product and linking the related information throughout the supply chain. In this direction, traceability tags assist in coding the product with relevant information which helps in uniquely (or individually) identifying the corresponding product or material. If visualized from its functionality dimension, a tag’s only worth is the information encoded on it, which connects the product with product information. However, from a broader perspective, tag should also ensure that it links only the original product with relevant information, not with any replaced or counterfeit product. Hence a tag should be capable enough to deter easy replication and need to accompany a product as long as traceability is required (as discussed in Paper II). Within this context, as a tag is crucial element in traceability which not only act as basic foundation for traceability but also supports other traceability based assertions. Hence selecting an appropriate tag is very first requirement for a secure traceability. In this direction, one way to improve the traceability is to encode the information on product itself so that it is not removable from the product; therefore, it reduces the possibility to use it with replaced or counterfeit product. However, the encoded information should have certain level of security against copying to ensure that that encoded information cannot be cloned or reproduced straightforwardly to use with counterfeit products. In order to improve the security of integrating tagging for traceability, Paper II firstly identifies the characteristics of an ideal traceability tags. This includes the features like tag integration into the product to avoid detaching, robustness to retain the encoded information, irreproducible to avoid cloning, cheap (or inexpensive), easy to manufacture and environmentally friendly. Further, traceability in the integrated form can be established via two routes – first, using foreign material integrated into the product and second, designing the product components in such a way that they produce inherent traceability marker when assembling into the product (as discusses in Paper III). In the former route, the foreign material acts as an additional component used only for traceability. Printing of barcodes or integrating RFIDs inside the fabrics are the example of foreign material-based integrated traceability, which cannot be removed from the fabrics but act as additional materials. The inherent properties of the components act as identification marker in the latter scenario. For instance, Blankenburg and co-authors (2013) proposed the use of clothing texture, smell and other features for generating a traceability signature for counterfeit detection.

In order to address the traceability without external tagging, this thesis follows the latter approach i.e. product component-based traceability and targets textile fabrics to show the potential of product component (i.e. yarns) modification and structural changes to implement integrated traceability. Here, the yarn components were firstly modified to encode them with certain visual features which were used as the traceability components in the woven and knitted fabrics. The appended Paper II and Paper III describe yarn-based traceability for textiles describing the designing of appropriate components (called as *yarn coding* in Paper II) and assembling the components in the textiles to generate traceability markers (called as coded yarn-based traceability markers in Paper III) as described below,

- *Yarn coding/ component preparation*

Yarn coding is the concept introduced in Paper II describes the introduction of a twist- or wrapping-based yarn features – namely twist density, wrap area and wrap helix angle – in a two-colour based yarn assembly, which consists of a core yarn and wrapping yarn. Yarn coding here implies preparing the yarns with special optical/visual features which will act as components for traceability. As the twist or wrap density in a yarn assembly changes, the magnitude of above-mentioned yarn feature changes, as shown in Figure 4.2; subsequently the twist or wrap density acts as feature controlling parameter. The coded yarns with distinct twist density as terms as yarn classes as each class of coded yarn would have features different from other coded yarn classes based upon the twist density dissimilarity.

As yarn acts as an integral component of fabric, therefore introducing these coded yarns with special optical features during the weaving or knitting process produces an optical stamp on the resultant fabric. Nonetheless, the optical stamp resulting from the coded yarns needs to be related with the coded yarns to use it as traceability marker; therefore, the different coded yarn classes should be prepared such that each has a distinct optical features existing in clusters. In order to identify a coded yarn from fabric integrated yarns, the optical features of coded yarns (those woven or knitted into the fabric) need to be correlated to the different feature clusters to match the closest resembling yarn class. Paper II describes the matching of yarn features with different feature clusters using a decision support system, which calculates the membership values to all feature clusters and the highest membership among all cluster signifies the actual class of a coded yarn. Therefore, in yarn coding step, the appropriate yarn components can be prepared to be used as traceability component for the fabrics and a relation showing how these component can be identified by their optical feature (as decision support system was used in the case of coded yarns)

- *Coded yarn based fully integrated textile tags*

As the coded yarn components described above act as a fundamental unit of integrated traceability in the fabrics. However, for implementing traceability, the important part is their integration into the textile and resultant visual impression on fabric surface which can be used as encoded stamp for traceability application. Therefore, the coded yarn components are required to strategically assembled such that the optical stamp created on the resultant fabric is interpretable to use as a traceability tag. Paper III describes a methodology in which yarns are systematically inserted into the fabrics (knitted and woven) and with a particular area where optical stamp generated from the coded yarns can be potentially used as a traceability marker. The formation of a textile takes place by the intermeshing (i.e. knitting) or interlacement (i.e. weaving) of the yarns. However, due to the interlacement or intermeshing, a yarns is not continuously visible hence it is difficult to identify the yarn features. Nonetheless, in order to make the coded yarns visible or able to make their optical features identifiable, they require the formation of floats (for woven structures) and mis-stitches (for knitted structures) for a certain length. As a result, the coded yarns do not interlace or intermesh with other yarns and appear continuous on one face of fabric. By doing so, the combination of coded yarns and the sequence in which they are inserted into the region where floats or mis-stitches are made, decide the resultant optical or visible stamp generated on the fabric surface.

Therefore, by controlling the use of coded yarns and their sequence, a unique predefined visible impression can be generated on every single cloth roll, which can be used for later tracking them in the supply chain. Besides traceability component, the coded yarns act as a fabric component. Hence, they cannot be removed and any attempt to remove them would lead to the destruction of fabric itself. Therefore, this kind of tagging can be called as fully integrated tagging which is made up of nothing but product components itself. Since the yarns cannot be altered for their position after weaving or knitting to make any change, therefore implementation of specific traceability information inside the fabric would require a well-planned approach for sequence of the coded yarns to insert into the fabric and the location where they are required to appear inside the fabric.

- *Conclusions*

RQ2 investigates on how traceability can be implemented without using the external tags. It targets a very basic limitation of the regular externally attached tags (such as RFIDs and QR-codes) of being able to be easily cloned to use with counterfeit products or get separated during product movement or on POS, which limit the traceability. Therefore, implementing traceability without external tags mean transferring the encoded information into the product itself, so that the reliability on the tag can be reduced or minimized. Traceability in the integrated form requires the systematic integration of trace-generating provisions inside the product. If the product components carry the marking capabilities, then the components are the probably best alternatives for introducing the features required for traceability. Nonetheless, it would require a systematically designed components and assembly of these components into the product during the manufacturing process with advance planning, since post-integration adjustments may not be possible. For example, yarns act as elementary units of a fabric, therefore integrated traceability can be implemented using cannot be removed, replaced or changed post-weaving, therefore advance planning needs implement such integrated traceability. Furthermore, encoded information needs to comply with a standard format such that subsequently supply chain actor can decode it to use are traceability reference.

5.3. RQ 3: How can traceability information be managed and exchanged in a multi-actor textile supply chain?

Textile supply chains are unique in the sense that it includes various actors, dealing with specialized raw materials and located in specific locations where they can be more efficient and provide supplies at a competitive cost. A typical textile supply chain consists of fibre producing industries, yarn manufacturers, weaving mills, chemical processors, apparel developing companies and retailers or distributors besides the logistic partners. At each stage, inbound materials are often mixed to form new outbound lots with changed physical or chemical characteristics. Therefore, the effective supply chain traceability can be achieved through making the link between inbound and outbound materials at different levels in the supply chain and subsequently the information needs to be mapped with respective outbound materials. As traceability works on the linkage of supply chain actors for information exchange, therefore the traceability information should not only be managed as the linkage of inbound–outbound material, but it should also be managed and communicated in the supply chain.

- *Planning for intra-actor traceability*

Traceability can be visualized as a chain of information connection throughout the supply chain, intra-actor traceability acts as first step for complete supply chain traceability. This step aims in identifying the expected targets of traceability implementation by a supply chain actor, accordingly identifying the internal policies for traceability information identification, its documentation, and managerial and technical alignment with other supply chain actors for streamline exchange of the information. At each stage of the supply chain, different industrial operations (such as transforming fibres into the yarns and yarn into the fabrics) are applied on the inbound materials which lead to the addition of traceability information from various perspectives such as materials properties, process information, quality characteristics, etc. The added traceability information may be further useful for other supply chain stakeholders or regulatory compliance. Therefore, the intra-actor traceability implies the management of inbound raw material information and added traceability information by the supply chain actor which is relevant from expected traceability outcome and complies with the requirements of other supply chain stakeholders and regulatory requirements. Furthermore, the suppliers of textile supply chain are often specialized and often deal with processes which are not disclosed or only revealed to selected buyers (such as information related to the suppliers). Therefore, while managing and communicating the traceability information one needs to segregate the information private or protected information from shareable information. Sharable information is passed to the next supply chain actor while the private information is kept in the database only accessible to the database owner and used in case of urgency (such as product recall) and shared with regulatory authorities. Moreover, mapping of inbound and outbound materials information should be done in a systematic way such that information about the inbound material suppliers can be recalled from outbound material, including in those situations when the physical characteristics of outbound material greatly or entirely differ from inbound materials. Since traceability works on assigning unique numbering to the merchandises or commodities (i.e. encoded information on tags) which acts as referencing in the database entries where the corresponding traceability data is stored. Therefore, the outbound material traceability data should retain the traceability IDs of all inbound materials' information to make a chain linking all traceability information residing or originating from supply chain actors. Paper II and Paper IV show the framework to link the inbound and outbound materials such that traceability ID is generated either from inbound material ID (Paper II) or from the current Lot ID (Paper IV) which act as a reference to the database entries.

- *Planning for inter-actor traceability and role of supply chain actors*

Inter-actor traceability builds on intra-actor traceability. While intra-actor traceability is a fundamental requirement for traceability implementation, inter-actor traceability completes the notion of traceability implementation by connecting the links i.e. intra-actor traceability together to make a chain. The basis of inter-actor traceability is to be able to link, request, communicate and apprehend the traceability information from/with other supply chain actors. Therefore, it involves the recognizing the role of various supply chain actors and how they can play a role in driving other actors to technologically align other actors to implement traceability. Without technical alignment for information apprehension and exchange techniques, firms end up on choosing different technology and systems for exchanging the information according to their suppliers and buyers, which inevitably increase the system complexity and implementation cost, as Lam and Postle (2006) highlighted. Within this context, government regulations and dominant supply chain actors can an important role by regulating the technology and related parameters in the supply chain. For instance, in a retailer-driven textile supply chain, retailer has upper hand to enforce his strategies on the upstream supplier therefore retailer can play an important role enforcing the upstream suppliers to collaborate for a required level of traceability and implement it using a standardize or unified technology for exchanging the traceability information. Other important consideration in inter-actor traceability is configuration for traceability data storage and exchange. As mentioned before, traceability data for a product originates from each stage in the supply chain. Since the supply chain is managed by multiple actors, the traceability data is owned by respective supply chain actors. In this context, how supply chain actors collaborate to share the data is a practical concern. If all supply chain actors retains their individual databases and communicate data with each other, it requires a strong integration for information exchange and increases the reliability on each individual actor. On the other hand, handling all traceability data by a single supply chain actor has other practical concerns including data security and privacy. Moreover, it is also a question as who would be this lead actor to manage the whole data. In this direction, Paper II describe a framework to store the information in a such a way that it links to the traceability codes of previous actors by taking them input in a function and results into a new code. In this way, traceability codes of all materials can be retained and can be recalled by using inverse functions (as given in Paper IV). Paper IV describes a framework a hybrid data configuration for traceability data management. In this proposed framework, each supply chain actor maintains his database therefore each actor is responsible for data security and privacy. Further, since retailer (brand owner) acts as supply chain captain in the textile supply chain, it can play a key role in inter-actor data management by forcing the other directly managed actor to share to communicate the data via retailer server. Therefore, while retailer acting as a link between the other actors, it can also ensure that the supply chain actors communicate the required traceability information. The proposed framework presents the data management and communication configuration as a combination of two systems – one-up one-down traceability and central traceability. One-up one-down traceability system is favourable where two supply chain actors communicate directly is proposed for the supply chain which are not directly managed by the supply chain captain. On the other hand, central traceability is favourable for the region of supply chain the supply chain captain can directly control and manage the actors. Here the central database does not imply that the supply chain captain will manage the data of its directly managed actors. Rather, it means that the communication between the directly actors would take place through the supply chain captain and each actor would be responsible for maintining their own databases. Nonethless, the supply chain captain can chose to capture the data which is communicated among the managed links.

- *Conclusions*

RQ3 aims on investigating the means to implement traceability in the textile supply chain which is managed multiple supply chain actors. Implementing traceability in a supply chain is a joint action of supply chain actors which maintains and collaborates for a desired level of traceability, traceability information management and exchange. Subsequently, supply chain actors act as link in the traceability chain, and shortcomings from any actor could hinder the traceability implement. Therefore, one of the primary requirements for implementing traceability is to familiarize each supply chain actor for the traceability information and develop a traceability system which can recall the information within an organization at each level in the supply chain. It includes the data capturing, management and ensuring that it complies with the requirements or fulfils the objectives that are expected from implementation of traceability. Further, the second step in traceability involves the communication of traceability data within the supply chain for recalling the desired information. In order to implement traceability, the role of government agencies and supply chain captains can play an important role by mandating the minimum required traceability level for the suppliers within the supply chain. In the textile sector, most of the manufacturing activities are carried internationally; therefore, beyond the organizational efforts, global regulations would be required to solve the problem of traceability. Therefore, traceability implementation requires a techno-managerial apprehension of the textile supply chain.

6. Conclusions: summary and contribution

The purpose of this chapter is to conclude the thesis and present the theoretical and practical contribution. While discussion in Chapter 5 was made particularly in context of research questions proposed in Chapter 1.7, present chapter discusses the contribution in a general perspective.

6.1. Summary

Traceability is an inter-organizational concept, which relies on organizational policies to share the data but also on technical competencies to capture, store and communicate data in a systematic way. According to 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 labour) to improve noneconomic chain performance and reduce risks." For sectors including food and medicine, traceability has been prioritized because of the products' impact on end-users (which could be even fatal) in case of any shortcoming related to the quality of the products. Furthermore, these sectors have received strict scrutiny, and several nations have come forward to implement traceability as a compulsory prerequisite for businesses to function (Goswami 2014). Subsequently, one of the driving forces for traceability is regulatory compliance, which forces the multiple supply chain stakeholders to maintain a required level of traceability. On the other hand, the fashion industry has not a long history promote traceability with their supplier (Johansson and Månsson 2013). Nonetheless, traceability in the textile sector is fuelled by the consumer demand for transparent products and increasing awareness of organizations about the benefits of traceability implementation. Increasing consumer interest in knowing the product history and product's social and environmental impacts have aligned the actors in textile supply chain to pursue traceability practice. Therefore, in order to implement traceability in textile sector, the work in this thesis explores the implementation of traceability from supply chain, information exchange and yarn-based traceability tag perspectives.

Traceability, in general sense, refers to recalling of the history using some kind of traceability markers/tags, which substantiate the product among same or similar products. The information systems keep the record of these tags and use them as a reference in information storage and exchange. As a result, traceability tags act as an important linkage between physical product and information systems. Moreover, the textile supply chain in general consists of multiple actors, therefore traceability tags acts as information exchange element between the supply chain actors. Therefore in order to implement a robust traceability, while a robust traceability tag can be regarded as a prerequisite, the capability of relevant traceability data collection and its exchange among the supply chain actors is a requirement for streamline functioning. In this direction, the work in thesis has explored on how the dependency of an external tag, such as RFIDs or barcodes, can be reduced by directly encoding the traceability information on the product. It has been explored for the textile fabrics where the yarn components have been used to implement the traces on in the textile structures which can be directly used for traceability application as shown in Figure 6.1. The second important component of traceability is traceability information. Since textile product is an outcome of transformation and aggregation of different materials at various levels of the supply chain, therefore a supply chain wide traceability is the outcome of linking the information systems of actors in the supply chain to share the relevant traceability information.

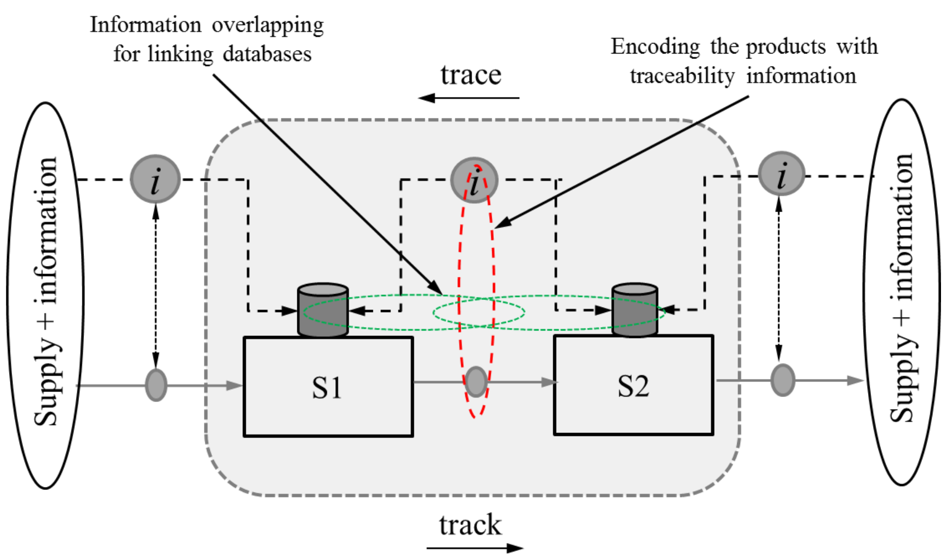


Figure 6.1 Traceability in the supply chain

Regardless of the technology implemented the capability and credibility of each supply chain actor to store and maintain relevant information and alliance with other supply chain actors to exchange it act as important prerequisite for traceability. Therefore traceability becomes a multi-facet concept, combining the technical as well as organization aspect. In this direction, the work in this thesis has explored the possible ways for implementation of traceability information systems in the textile supply chain and how the possible overlapping of information into two inter-organizational information systems can help in recalling of complete traceability information. Further, the work in this thesis provides a comprehensive overview on various aspects where traceability is particularly relevant in the textile supply chain.

6.1.1. Theoretical contribution

The theoretical contribution of this thesis aims to explore the implementation of traceability in the textile supply chain and introduces yarn based integrated tags. Most of the previous researches have focused on the traceability using general tags, such as RFIDs, printed labels and barcodes, which are externally attached to the product to simply identify and track them in the supply chain. A tag associates the traceability information with the product, and unintended detachment of the tag from the product can lead to a traceability cut-off. From the practice context, the abovementioned tags are mostly removed at point-of-sale (POS) which limits the traceability to POS. However, traceability has multiple applications even beyond POS (such as product recall as discussed in Chapter 5), which needs traceability tags to be associated with the product. Furthermore, traceability information needs to be managed by the supply chain actors and communicated to recall the whole traceability information about a product.

As aforementioned, theoretical contribution of this thesis explore the implementation of traceability in the textile supply chain using integrated tags. As yarn act as a basic material for a large portion of clothing, textile clothing Paper II appended in the thesis explored how the yarn structure can be potentially used as a trace for traceability implementation. Furthermore, Paper III uses this concept to implement in woven and weft knitted structures. Besides, the traceability is tested in woven and knitted tags using a wrapped yarn structure, it opens the possibility to explore other yarn structures with same or different optical features to use as trace in fabrics. Although, the abovementioned technique may not be application on other intermediate products, such as fibre processing or manufacturing, yarn manufacturing. Nevertheless, it provides a direction to think from the perspective of component-based traceability.

From information perspective, supply chain actors need to systematically capture and communicate the traceability information at each level. According to Bechini et al. (2008, p. 358), "*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*". In this context, Paper IV discussed a generic framework to implement traceability, which can be used in future researches as a reference model for modifying according to actual needs.

To summarize, the work presented in the thesis is like an initial point for integrated tag based traceability.

6.1.2. Practical contribution

The practical contribution of this thesis is to introduce a new kind of traceability marker for textiles which is entirely made of textile components and integrated into the textile structure. For existing traceability markers such as RFIDs, firstly – the actors in textile supply chain are dependent on other industries which fabricate and then deliver them in the form of tags. Furthermore, RFIDs integrated in the clothing creates issues during the recycling process (Köhler et al. 2011). During the recycling process, the disposed clothing is mechanically shredded to form fibres which can be re-used. Therefore, if the RFID integrated clothing is processed in the recycling process, RFID shreddings contaminate the resultant fibres. On the other hand, removing of clothing integrated electronic component is an expensive process (Köhler et al. 2011). The concept introduced in this thesis is a pure textile material solution, which is firstly as environment-friendly as normal textiles are. Secondly, textile with yarn integrated tag can be processes in normal recycling process without any concern of electronic component. Furthermore, yarn structure used for traceability making can be made using existing manufacturing technologies by the textile manufacturers, which not only opens the possibilities for textile actors (such as spinner and weavers) to use their knowledge of material structure and properties to use in traceability marking, but also reduces their dependency on other industries (as it exists for other traceability markers). The main practical contribution of the thesis can be accounted as introduction of textile integrated tag from the scratch, which were never explored before from the perspective of yarn structure. Nonetheless, to see the real practical contribution, system would be required to develop and use them at an industrial scale (or realistic scenario), which were not possible in the PhD duration and may require more time and resources.

6.2. Research validity, reliability and generalization

Thanasegaran (2009) describes reliability as "*degree to which measures are free from error and therefore yield consistent results (i.e. the consistency of a measurement procedure)*". For instance, an instrument is reliable if it is producing repeatedly the same output for the given same set of inputs. Similarly, reliability of research means the extent to which results can be reproduced using a same methodology. A research is considered as highly reliable if the results reproducible with high consistency. As the consistency of the results not only depends upon the methodology, but also on other factors such as test conditions and test instrument to name a few, therefore the reliability of the research is a function of multiple factors which need to controlled for replicating the results. According to Kirk and Miller (1986, p. 41), reliability in the quantitative research can be described in three types – degree to repeatability, stability of measurements over time and similarity of measurements within a given time. Research validity, on the other hand, determines if the measurement process, assessment, or project actually measures what it was intended for. According to Gregory (2004, p. 117), research validity is *"the extent to which [a test or experiment] measures what it claims to measure".*

This thesis presents the analysis from some data obtained from primary as well as secondary sources. The use of secondary data provides both high internal validity and a good opportunity to replicate the study (Rabinovich and Cheon 2011). Data from secondary sources – mainly used in Paper I – is kept in best possible original form so that the results can be replicated by the other researchers. The primary data source used is lab-based experimentation, as described in Paper II and Paper III. Lab-based experiments are usually carried-out in close environment. Further, there are many factors which affect the exact replication of the results. Example of factors are, the state of the instrument on which the samples are fabricated, testing conditions, researcher's biasness, quality or characteristics of the raw materials used, and other uncontrollable variables. These variables affect the exact replication of the lab-based research. Therefore, in order to improve the reliability of the research work, it has been carries out using multiple test samples, made into two different textile structures, and analyzed under different conditions. As the findings are not based upon single-test sample, this provides certain degree of reliability. Furthermore, as a limited work has been done in the past in the direction of traceability in textile sector, the main intension of the work in this was to build a stepping stone for integrated traceability which could be helpful for the future researches. In this context, Paper IV and Paper V are conceptual papers, which is not using as such any data from the sources rather concepts have been proposed (as in Paper IV) and mathematically explored (as in Paper V) based upon the literature, which would need further work to prove the validity in practical scenario.

7. Future research recommendations

In this chapter, future research directions have been described which can not only cover the limitations of the present work but also the research perspectives where this thesis can contribute and/or act as a starting point.

This thesis investigates the traceability in textile supply chain context and introduces the yarn-based textile integrated tags as a component for tracing textile fabrics in the supply chain. Traceability is a broad subject, which is an outcome of multiple strides from comprehension, application as well as implementation perspectives and they are often crosslinked with each other. From the industrial standpoint, traceability can be regarded as an outcome from aspects such as technology, regulatory compliance, organizational policies, need from operational, marketing and buyer point-of-view, and the direct (such as traceability tags, IT, system maintenance, etc.) and indirect (such as training of employees, change in existing processes) investments. Moreover, traceability is a chain concept, which means that the combined efforts of all supply chain actors to implement appropriate means to capture required information and share with other stakeholders decide the success of traceability. From the implementation perspective, as highlighted by Bechini et al. (2008), traceability implementation in any field first requires an abstract understanding of the field. Moreover, an expert panel on traceability (Informal Product Traceability Expert Group - Final Report 2013) reports that the lack of understanding of the organizations regarding the needs and benefits of traceability acts as a major hindrance in the implementation of traceability. In addressing traceability in textile supply chain, this thesis has explored traceability as information management on how it can be managed in the supply chain and how it can affect the supply chain actors. Further, a yarn coding-based traceability marking has been introduced to use as integrated traceability marking. As traceability has emerged relatively recent in the textile supply chain, it is not explored as deeply as compared with other sectors like food and pharmaceutical. Therefore, the work presented in this thesis can be regarded as an attempt to develop an abstract understanding of the field towards implementing traceability while providing yarn-based tagging as an example for integrated tagging-based traceability. The content of this thesis while contributing to the existing understanding for traceability particularly in the textile domain, it can be regarded as a starting point for future discussion in multiple directions, as discussed next.

The author has specifically advocated on how integrated tagging can enhance the breadth of traceability in textile supply chain. Traceability tag encodes the information which is required not only for recalling the traceability information but also to segregate or uniquely identify the products so that they can be tracked inside the supply chain. Therefore, the association of the tag with the product is a prime requirement for implementation of traceability. In this direction, a tag integrated into the product ensures that tag remains with the product. Textile supply chain consists of multiple actors who deal with different materials and operations. Therefore the yarn tagging proposed in this work is a starting point towards integrated tag-based traceability. It is proposed for one stage in the textile supply chain where materials exist in woven or knitted form. Within this context, the future research can be directed towards accommodating the proposed yarn-based tagging with current manufacturing and design practices, which were not explored in this thesis. For instance, the yarn coding-based tagging relies on the twist in the yarn assembly. For its successful implementation, twist in the coded yarn should not vary or only vary in a very limited range. However, on certain weaving looms such as airjet and waterjet loom, the weft yarn is guided using fluidic motion and one end of the weft yarn remains free during its insertion into the warp yarns. Therefore, it is difficult to control the untwisting of yarn's free end (Dhamija and Chopra 2007; Mohamed et al. 1987). In this direction, the future research can be directed on implementing yarn coding with the optical features which are not twist dependent and can be implemented on weaving looms where the weft is guided by fluidic motion.

Furthermore, the yarn based tagging uses yarns having special optical features and these yarns are integrated into textiles. As the sequence of these yarns (i.e. yarns with optical features) decides the code of traceability tag, therefore automation in selecting appropriate yarn sequence during the weaving or knitting process to implement a specific code needs to be explored in future research. In addition to this, as integration of coded yarns in the fabric results in a visual impression on fabric surface, as shown in Chapter 4.3.4, there is a need to explore on how the coded yarns-based visual impression affects the apparel design and manufacturing process when a fabric with integrated tagging is used.

Considering the basic feature of traceability, it is the outcome of information linking throughout the supply chain. In this prospect, one direction for future research – where this thesis can act as a starting point – is towards devising integrated tagging for fibre and yarn stages, which are the upstream stages of fabric manufacturing. In order to cover the whole supply chain using integrated tagging it is important to cover all upstream stages with required integrated tagging. In general, a tag, in any form, should possess certain features, as discussed in Paper II. Therefore, learnings from this work can act as guide to research which focuses on different stages of textile supply chain on how material components can be utilized as traceability markers which comply with the required traceability tag features. It might also not be possible to have materials with components-based traceability. Therefore, future research can also focus on how materials can be tagged with external material but in integrated form. In this direction, one of the plausible research possibilities is to enhance the security of existing tags from cloning and detaching from the corresponding traceable unit (or product). For example, Agrawal et al. (2016) propose the inclusion of micro-sized particle on QR codes where the randomness of the particle can act as a key for QR code authentication.

One broad area of research concerning traceability is supply chain management. While the above-mentioned traceability tags link products with traceability information, the traceability implementation is largely connected to relationship between the supply chain actors for their cooperation (Guercini and Runfola 2009). In this direction the present research draws a boundary in terms of assuming the supply chain as collection of actors which contribute to the traceability information and visualizes the traceability information exchange directly between them. However, the textile supply chain consists of agents who act as mediators and do not (necessarily) apply any physical or chemical operations. The key role of these agents is to search appropriate suppliers for the buyers thus act as mediator for the transaction of supplies. In this context, the key competitiveness for the agents is name of their suppliers and buyers and therefore revealing the names of suppliers to buyers or vice versa means potentially losing the role as mediators for future (Egels-Zandén and Hansson 2015). As traceability allows tracking back the history, therefore, by a large it reduces the information asymmetry in the supply chain. This alternately implies that agents have to provide the information about their suppliers to the buyers, which is of course not favourable for the agents. In this direction, research is required from organizational and supply chain relation perspectives in order to maintain necessary confidentiality while implementing traceability. Bechini et al. (2008) proposes the role of a third party which handles the traceability information requests and retrieve the information from respective suppliers in food supply chain. Following the same research direction, research on exploring the role of third party could be one possible future research direction for implementing traceability while keeping necessary confidentiality for information in the supply chain.

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

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Appendix A – Additional publications by the author

(* denotes the work was directly related to the topic of thesis)

Journal Publications

2017

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

*[††]**Kumar, V.,** [††]Agrawal T. K., Wang, L., & Chen, Y. (2017) Contribution of traceability towards attaining sustainability in the textile sector. *Textile and Clothing Sustainability*. Accepted for publication

Kumar, V., & Rawal, A. (2017) Elastic Moduli of Electrospun Mats: Importance of Fiber Curvature And Specimen Dimensions. *Journal of the Mechanical Behavior of Biomedical Materials*. Accepted, In press

***Kumar, V.**, Hallqvist, C. and Ekwall, D. (2017), A framework to implement traceability in the textile supply chain. *Systems*, 5 (2), 33.

Kumar, V., Rao, P. K., & Rawal, A. (2017). Amplification of electrolyte uptake in the absorptive glass mat (AGM) separator for valve regulated lead acid (VRLA) batteries. *Journal of Power Sources*, 341, 19-26.

Rawal, A., **Kumar, V.**, Hietel, D., & Dauner, M. (2017). Modulating the Poisson's Ratio of Articular Cartilage via Collagen Fibril Alignment, *Materials Letters*, 194, 45-48.

***Kumar, V.**, Koehl, L., Zeng, X., & Ekwall, D. (2017). Coded yarn based tag for tracking textile supply chain. *Journal of Manufacturing Systems*, 42, 124-139

Rawal, A., **Kumar, V.**, Saraswat, H., Weerasinghe, D., Wild, K., Hietel, D., & Dauner, M. (2017). Creating three-dimensional (3D) fiber networks with out-of-plane auxetic behavior over large deformations. *Journal of Materials Science*, 52(5), 2534-2548.

2016

[††] Authors with equal contribution

*Kumar, V.**, Ekwall, D., & Wang, L. (2016). Supply Chain Strategies for Quality Inspection under a Customer Return Policy: A Game Theoretical Approach. *Entropy*, 18(12), 440.

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*Kumar, V**., Koehl, L., & Zeng, X. (2016) A Fully Yarn Integrated Tag for Tracking the International Textile Supply Chain. *Journal of Manufacturing Systems*, 40, 76-86

Kumar, V., & Rawal, A. (2016). Tuning the electrical percolation threshold of polymer nanocomposites with rod-like nanofillers. *Polymer*, *97*, 295-299.

Kumar, V., & Rawal, A. (2016). Compression induced electrical response of entangled network of carbon nanomaterials. *Polymer*, *84*, 117-120.

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Rawal, A., Sibal, A., Saraswat, H., & **Kumar, V**. (2015). Geometrically controlled tensile response of braided sutures. *Materials Science and Engineering: C*, *48*, 453-456.

2014

Kumar, V., & Rawal, A. (2014). A model for predicting uniaxial compression behavior of fused fibrous networks. *Mechanics of Materials*, *78*, 66-73.

2013

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Rawal, A., & **Kumar, V.** (2013). Compressibility of highly porous network of carbon nanotubes. *Applied Physics Letters*, *103*(15), 153103.

Conference Presentation/Publications

(* denotes the work was directly related to the topic of thesis)

2016

Sibal. A., **Kumar, V.**, Rawal. A., Theoretical modelling of 'smart' nanogenerators grown on nonwoven materials, SIWAN conference, Szeged, Hungary, 12-14 October, 2016.

Kumar. V., Haspel, H., Nagy, K., Rawal. A., Kukovecz, A., Compression induced electrical response of entangled network of buckypaper, SIWAN conference, Szeged, Hungary, 12-14 October, 2016.

***Kumar, V**., A Game-Theoretic Approach for Textile Manufacturer-Buyer Relation under Quality Inspection and Traceability Regime, Uncertainty Modelling in Knowledge Engineering and Decision Making: Proceedings of the 12th International FLINS Conference (FLINS 2016), Roubaix, France, 24-26 August 2016.

***Kumar, V.,** Textile integrated tags**,** Textil spårbarhet genom supply chains, Seminar presentation, Textile Fashion Center, lokal Garfveriet, University of Borås, 22 August, 2016

***Kumar, V**., Ekwall, D., Hallqvist, C., Development of Traceability Framework for Textile Supply Chain, The 28th NOFOMA Conference, Turku, Finland, 9-10 June, 2016. (work-in-progress)

***Kumar, V**., Ekwall, D., Macro-Scale Indicators Based Analysis of Textile Product Recalls in the EU, The 28th NOFOMA Conference, Turku, Finland, 9-10 June, 2016.

Rawal, A., **Kumar, V.**, Saraswat, H., Weerasinghe, D., Wild, K., Dauner, M., Hietel, M., Can Nonwovens Avoid the Shrink?, International Nonwovens Symposium 2016, Warsaw. Poland, 1-2 June, 2016.

2015

Kumar, V., Rawal, A., Modelling of Compression Induced Electrical Response of Carbon Nanofibre Nonwovens , Nonwovens Innovation Academy, Leeds. U.K., 5-6 November, 2015.

Sibal, A., **Kumar, V.**, Rawal, A., Modelling of Self-Powered Nanogenerators Grown on Nonwoven Materials, Nonwovens Innovation Academy, Leeds. U.K., 5-6 November, 2015.

Sibal, A., **Kumar, V.**, Rawal, A., Designing Bio-Inspired Superhydrophobic Nonwoven Mats, Nonwovens Innovation Academy, 6th International Technical Textiles Congress, Izmir, Turkey, 14-16 October, 2015.

***Kumar, V**., Koehl, L., Zeng, X. Encoding and Decoding Methodology for Yarn Based Tracking Tags, 15th World Textile Conference (AUTEX), Bucharest, Romania, 10-12 June, 2015.

Rawal, A., **Kumar, V.**, Furkó, M, Lakatos-Varsányi, Modeling of Self-Powered Piezoelectric Energy Harvesters grown on Nonwoven Materials, NANOSMAT Asia, Kayseri, Turkey, 24-27 March, 2015.

2014

Rawal, A, **Kumar, V.**, Modelling of Compression Properties of Nonwoven Materials and Related Systems, Future Technical Textiles 2014, Istanbul, Turkey, 15-17 October, 2014.

***Kumar, V**., Koehl, L., Zeng, X. A Yarn Coding Based Tracking Tag for Textiles, 14th World Textile Conference (AUTEX), Bursa, Turkey, 26 - 28 May, 2014.

Rawal, A., **Kumar, V.**, Furkó, M., Lakatos-Varsányi, Modeling of Piezoelectric Energy Harvesters grown on Nonwoven Materials, MRE 2014, Hong Kong, 8-10 August, 2014.

Rawal, A., **Kumar, V.** Modeling of Uniaxial Compression Behavior of Nonwoven Materials and Related Systems, TBIS-APCC 2014, Hong Kong, 6-8 August, 2014.

Rawal, A., **Kumar, V.**, Furkó, M., Lakatos-Varsányi, M. Modelling of Self-Powered Nanogenerators Grown on Nonwoven Materials, Indo-Czech Conference on “Advancements in Specialty Textiles and their Applications in Material Engineering and Medical Sciences”, Coimbatore, India 29-30 April, 2014

2013

Kumar, V., Rawal, A., Tailoring the Compressibility of Highly Porous Network of Carbon Nanotubes, Nonwovens Innovation Academy, Lille, France, 27-28 November, 2013. (Poster)

Rawal, A., **Kumar, V.**, A Two-step Model for Uniaxial Compression Behavior of Thermally Bonded Nonwoven Materials, Nonwovens Innovation Academy, Lille, France, 27-28 November, 2013.

Appended Papers

Paper I

Kumar, V. and Ekwall, D. (2016), "Macro-Scale Indicators Based Analysis of Textile Product Recalls in the EU". *In proceedings of Nofoma*, Turku, Finland

Macro-Scale Indicators Based Analysis of Textile Product Recalls in the EU

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Macro-Scale Indicators Based Analysis of Textile Product Recalls in the EU

ABSTRACT

Purpose

The purpose of this article is to study the relationship between macro-scale indicators (social, economic and governance) with textile product recalls in the EU. Here the main focus is given to a systemic approach to understand the problem from a holistic perspective, focusing on the interactions among components rather than focusing only on causes.

Design/methodology/approach

The EU's recalled textile product data and macroscale indicators used in the study were obtained from multiple sources, namely RAPEX, Transparency International, Eurostat, and The World Bank. The data have been used for the years 2008-2013. Multiple linear regression analysis and *p*-value statistics were used to scale the impact and statistical significance respectively, of the indicators on the textile product recalls.

Findings

Findings from the study suggest that the textile recall is influenced by governance and social aspects of the EU member states while the economic aspect has negligible statistical significance. Results further suggest that better governance and higher social inequality lead to lesser textile product recalls.

Original/value

This study is first to quantitatively identify of the role of social, governance and economic aspects of the EU member states on their textile-product recalls. The previous qualitative research works have been focused on a particular brand or recall which limit the generalization of their conclusions. Whereas, this paper uses a systemic approach to understand the problem from a holistic perspective, focusing on the interactions among components rather than focusing only on causes.

Keywords: Textile product recalls, macro-scale indicators, governance, social, economic

1. INTRODUCTION

Nowadays, with strict government regulation and consumer interests, product recall has become prevalent. In spite of state-of-the-art operations, philosophies, tools and techniques, products may still be flawed. Product cost has always been a competitive aspect therefore to optimize a product cost; manufacturers sometimes knowing/unknowingly use inferior or restricted materials, chemicals, or design. This poses direct threats to the consumers, and results in recall whenever identified (Ahsan and Gunawan, 2014; Etayankara and Bapuji, 2009; Kumar and Schmitz, 2011). In 2014, the European Commission's rapid alert system for dangerous non-food products (RAPEX) reported unprecedented 2435 product recall notifications and only 14% of the total notified products were found to be originated from Europe (EU28 and EEA countries) whereas among remaining 86%, 79% were originated from non-European countries and 7% were unidentifiable. (*European Rapid Alert System for Dangerous Non-Food Products: 2014 Complete Statistics*, 2014). Further exploring the statistics, Textiles and clothing (hereafter called *textile products*), one the regular products used by all classes of the society, is one of the frequently recalled products accounting for more than 25% of the cases for the years 2010-2014 (*European Rapid Alert System for Dangerous Non-Food Products: 2014 Complete Statistics*, 2014).

Providing a safe product comes under the corporate social responsibility (CSR) for manufacturer, however, the government and society play an important role in the implementation of an effective CSR and sometimes act as watchdogs (Porter and Kramer, 2006). Studies have suggested that the product quality or standard set by a manufacturer is influenced not only by the place/country of manufacture, but also by the targeted destination or country-of-sale (Bastos and Silva, 2010; Fajgelbaum et al., 2009). Effect of country-of-sale is obvious because the product has to meet the expectations of the end user. Further, every government has its product safety regulations, and product not complying with such regulations has sale restriction. Product safety regulations and their implementation are often influenced by living standard, consumers' safety awareness, and social and environmental concerns (Ene, 2012; Nadvi, 2008; Ponte and Gibbon, 2005). Studies have evaluated the impact of product recalls on brand equity/reputation (Eilert, 2013; Grunwald and Hempelmann, 2010; Korkofingas and Ang, 2011; Magno et al., 2010), financial losses (Davidson III and Worrell, 1992; Govindaraj et al., 2004; Zhao et al., 2013), firm's competitiveness (Chen et al., 2009; Eilert, 2013; Korkofingas and Ang, 2011) and retails' brand value (Ni et al., 2014), whereas the effects of social, economic and governance aspects of a country on its recalls have remained elusive. To the best of our knowledge, there is no published quantitative analysis correlating the occurrence of product recalls with a country-of-sale's economic, social and governance aspects, even though, according to recent incidents and previous studies (such as, Ene, 2012; Luo, 2008; Magno, 2013), they incite or act as underlying reasons for the product recalls. In this context, this paper studies the effect of macroscale indicators including economic, social and governance aspects of various EU member states on their textile product recalls.

2. FRAME OF REFERENCE

Product recall is a reverse logistic activity of withdrawing a product from the customer and market due to noncompliance of product specifications or services with the government regulations. These products may harm the users directly or indirectly. According to Ahsan and Gunawan (2014), manufacturer-initiated recall is considered voluntary, and Hora et al. (2011) argued that these recalls are influenced by many factors, including the type of product defect, recall strategy and supply chain issues. Chen et al. (2009) showed that the 'preventive recall' or manufacturer-initiated recall strategy has higher negative impact on stock value as compared with that of 'reactive recall' or government-initiated recalls. Moreover, consumers may consider a manufacturer-initiated recall as confession of guilt and file lawsuits against the company (Spier, 2011). Therefore, the manufacturer may want to avoid or delay to initiate a recall. Government-initiated recalls follow a series of investigation stages before notifying the manufacturer/supplier for the recalls. Luo (2008) argues that weak legislation, lax enforcement, lack of government supervision and rampant corruption play important roles in recalls, and stated that only poor management and weak organizational control of manufacturers resulting in a harmful product in the market cannot wear the whole blame.

Magno (2013) stated the complexity of products and markets, consumer protection activities, product safety legislation and intervention of government agencies as the major factors behind product recalls. Ene (2012) argued in the Bulgarian context that insufficient consumer protection was negatively correlated with the purchasing power of citizens. Therefore, beside government regulations, consumers' social and economic aspects become underlying reasons for product recalls.

The government-initiated recalls of the EU member states are initiated by a single organization, RAPEX, and the criteria for determining the government regulation-wise non-complying product are same for all the EU member states. RAPEX notifications are notified in two categories to the enterprises/distributors regarding the product recalls i.e. obligatory or mandatory, and voluntary. In obligatory recall, member state authorities oblige the producer/distributor to take preventive or restrictive action to the recalled product, whereas in voluntary recall, the preventive measures adopted by the producer/distributor are independent from the intervention of the authorities of member state. Previous studies (for example (Korkofingas and Ang, 2011; Kumar and Schmitz, 2011; Tennert, 2014)) have attempted to understand recalls and their consequences from an organization or set of organizations or specific recall perspective, and the conclusions were generalized. Whereas, this paper attempts to understand the recalls from a holistic perspective, without going into the company or product details so that a generalized understanding can be made accounting all the recalls. Hence, in this study, recalled textile products were not differentiated based on recall type or involved company/organization or total recalled units, rather total unique textile related notifications by RAPEX were taken into account. Furthermore, the problem is attempted to understand from multiple aspects. Based upon the above analysis the following hypotheses are formulated for the present study,

- H1: Economic aspects of an EU member state have an impact on its textile product recalls.
- H2: Social aspects of an EU member state have an impact on its textile product recalls.
- H3: Governance aspects of an EU member state have an effect on its textile product recalls.

Social, economic and governance aspects of a country can be explained by a large number of indices, calculated by local as well as international, government, non-government and/or private organizations. Economic aspect is an important to understand the basic questions, such as does low consumer buying power implies more recalls? or is it simply that poorer countries import cheaper products that are more prone to errors? To calculate the economic cost of IPR infringement cost in 'clothing, footwear and accessories sector', various EU member states were analysed on social, economic and governance indices ("The Economic Cost of IPR Infringement in Clothing, Footwear and Accessories Sector", 2015). Since the present study also analyses the EU member states in a similar way, therefore we chose some of descriptor variables from above-mentioned report, which were relevant to this study (shown in Table 1). Among all the selected variables, final consumption expenditure of household for clothing per capita (rCLE/C) and the percentage of household spending on clothing (HSC(%)) were the variables directly related to textile products, whereas other indicators represent general social, economic and governance aspects. Furthermore, aforementioned RAPEX recalled products were found to be majorly originated from outside the EU; hence, border customs can play a role in the preliminary filtering of the harmful/non-complying products. To account for the border customs role, 'Logistics Performance Index' (LPI) which is calculated by the World Bank, was included in this study. For short descriptions of variables see Table 1. These variables can be grouped into three categories, namely, economic, social and governance. As the name specifies, *economic* consists of variables related to the economic aspect, such as rCLE/C, GDI/C, nGDP/C, rGDP/C and PT. Whereas, social category consists of variables representing the social aspect, such as POP, POPuP, POPuP (%), II and HSC (%). Governance category comprises the variables or indicators which are influenced by local governance and politics. This includes CPI, RG, GE, V&A, PS&AV, RoL, CoC and LPI.

Table 1. Description of the selected independent variables

Sr.	Parameter	Acronym	Units	Description/definition
1.	Total Population	POP	--	The number of persons having their usual residence in a country on 1st January of the respective year. Countries may report legal or registered resident
2.	Final consumption expenditure of household for clothing	rCLE/C	€	Final consumption expenditure of household income on clothing per capita.
3.	Gross disposable income per capita	GDI/C	€	Real gross disposable income per capita
4.	Percentage of household spending on clothing	HSC (%)	%	Percentage of total household spending on clothing
5.	Nominal gross domestic product	nGDP/C	€	Nominal gross domestic product per capita
6.	Real gross domestic product	rGDP/C	€	Real gross domestic product per capita
7.	Income Inequality	II	--	The ratio of total income received by the 20 % of the population with the highest income (top quintile) to that received by the 20 % of the population with the lowest income (lowest quintile). Income must be understood as equivalised disposable income. II also known as 'social exclusion'.
8.	Poverty threshold	PT	€	Poverty threshold is the income level below which one is considered to be poor. Poverty threshold in general calculated as 60% of the national median income.
9.	Population under poverty	POPuP		Number of people (in thousand) in a country having income below poverty threshold.
10.	Percentage of total population under poverty	POPuP (%)	%	Percentage of the total population. which have income below the selected poverty threshold
11.	Corruption Perceptions Index	CPI	--	Corruption perception index measures the extend of corruption in a country perceived its public.
12.	Control of corruption	CoC	--	Control of corruption captures perceptions of the extent to which public power is exercised for private gain, including both petty and grand forms of corruption, as well as "capture" of the state by elites and

				private interests.
13.	Rule of law	RoL	--	Rule of law captures perceptions of the extent to which agents have confidence in and abide by the rules of society, and in particular the quality of contract enforcement, property rights, the police, and the courts, as well as the likelihood of crime and violence.
14.	Political stability and absence of violence	PS&AV	--	Political Stability and Absence of Violence/Terrorism measures perceptions of the likelihood of political instability and/or politically-motivated violence, including terrorism.
15.	Voice and accountability	V&A	--	Voice and accountability captures perceptions of the extent to which a country's citizens are able to participate in selecting their government, as well as freedom of expression, freedom of association, and a free media.
16.	Government effectiveness	GE	--	Government effectiveness captures perceptions of the quality of public services. the quality of the civil service and the degree of its independence from political pressures, the quality of policy formulation and implementation, and the credibility of the government's commitment to such policies.
17.	Regulatory quality	RG	--	Regulatory quality captures perceptions of the ability of the government to formulate and implement sound policies and regulations that permit and promote private sector development.
18.	Logistic performance index	LPI	--	Logistics Performance Index overall score reflects perceptions of a country's logistics based on efficiency of customs clearance process, quality of trade- and transport-related infrastructure, ease of arranging competitively priced shipments, quality of logistics services, ability to track and trace consignments, and frequency with which shipments reach the consignee within the scheduled time.

3. RESEARCH DESIGN AND PROCEDURES

All data utilized in this paper are secondary and from publicly available statistics sources. The use of secondary data provides both high internal validity and a good opportunity to replicate the study (Rabinovich and Cheon, 2011). The research presented here uses a systemic approach to understand the problem from a holistic perspective, focusing on the interactions among components rather than focusing only on causes (Aastrup and Halldórsson, 2008).

3.1. Data Collection

The RAPEX notification database has been used for the textile product recall notifications made in EU for the years 2008-2013. RAPEX relies on the close cooperation between the European Commission and the participating national authorities of EU member states, Norway, Iceland, and Liechtenstein. We focused on the official EU member states in the years 2008-2013. Croatia has joined the EU as well as RAPEX in the year 2013 therefore it has been excluded from the present study and we focused on remaining EU member states (as shown in Table 2).

*Table 2: Country- and year- wise textile recalls notifications reported by RAPEX. * denotes the country participating in 10 countries having uppermost total notifications for the years 2008-2013.*

		2008	2009	2010	2011	2012	2013	Total
Austria	AT	2	0	0	0	0	0	**2**
Belgium	BE	0	0	0	0	0	0	**0**
Bulgaria*	BG	36	86	154	118	202	121	**717**
Cyprus*	CY	0	39	100	37	22	81	**279**
Czech Republic	CZ	0	1	0	0	0	0	**1**
Denmark*	DK	0	5	2	21	14	0	**42**
Estonia	EE	0	0	0	0	1	4	**5**
Finland*	FI	4	24	13	8	3	1	**53**
France	FR	2	0	0	3	1	2	**8**
Germany*	DE	8	15	24	19	3	4	**73**
Greece*	EL	20	53	69	11	19	40	**212**
Hungary*	HU	32	11	100	75	224	124	**566**
Ireland	IE	3	0	0	1	3	0	**7**
Italy*	IT	1	4	37	1	0	0	**43**
Latvia	LV	0	0	0	20	1	0	**21**
Lithuania	LT	4	4	8	3	3	3	**25**
Luxembourg	LU	0	0	0	0	0	0	**0**
Malta	MT	0	0	0	0	2	4	**6**
Netherlands	NL	0	0	1	1	0	0	**2**
Poland*	PL	1	5	4	18	8	3	**39**
Portugal	PT	0	7	2	3	0	0	**12**
Romania	RO	0	0	1	10	15	3	**29**
Slovakia	SK	0	0	0	1	1	6	**8**
Slovenia	SI	0	0	5	1	19	5	**30**
Spain*	ES	2	7	7	27	20	18	**81**
Sweden	SE	2	1	6	0	2	4	**15**
United Kingdom	UK	8	4	1	3	2	1	**19**
Total		**125**	**266**	**534**	**381**	**565**	**428**	

Each RAPEX participating nation has a national contact point which notifies the European Commission (EC) for any observed harmful or non-complying product or incident. Then the EC circulates this information to all other RAPEX members' national contact points and simultaneously publishes a report on the notified products on the website on a weekly basis. Further, the national contact points communicate the notified dangerous products to responsible authorities to monitor and take appropriate measures in their respective countries. The RAPEX database shows the recalled products in total 30 categories. Textiles and clothing items are included in the category entitled 'Textiles, clothing and fashion items', which also includes non-textile fashion items such as belts, slippers, leather items, etc. Therefore, the non-textile item notifications were manually excluded by analysing the product description in the secondary data obtained from the RAPEX database.
The 18 independent variables (macro-scale indicators) selected were obtained from primarily three sources: Eurostat, Transparency International, and the World Bank. Each of the variables for all the countries was obtained strictly from only one source; therefore, the accuracy of every variable can be considered the same for all the countries. The list of all variables with a short description is given in Table 1. Eurostat is the official statistics department for the EU that maintains the official figures about the EU member states. In some cases, where data for a member state were not available for a particular year, the missing values were replaced with the immediate previous year's data. GDI/C for Luxembourg and Malta were not reported by Eurostat for any of the years between 2008-2013, therefore the missing values were replaced by the mean manipulation method (Acuna and Rodriguez, 2004) of that particular year of the remaining countries. Similarly, data were interpolated for LPI values that were officially published in 2007, 2010, 2012 and 2014.

3.2. Research Method

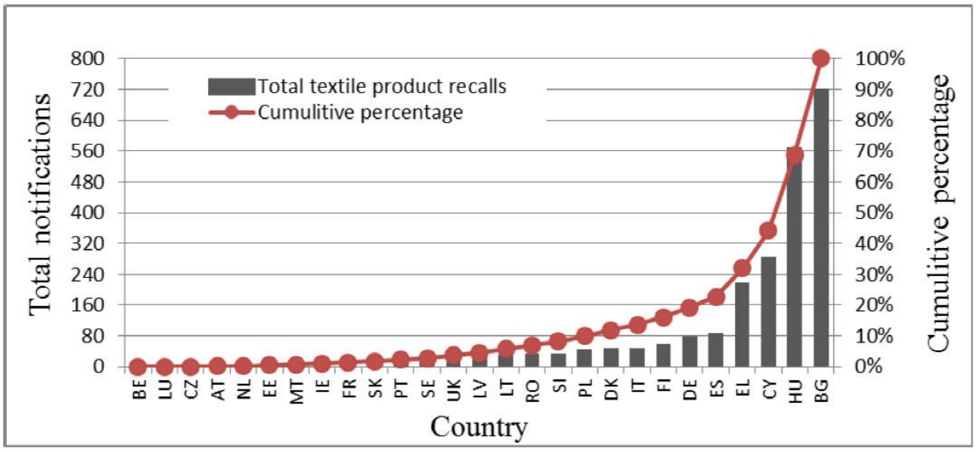

Figure 1 Distribution of total textile recall notifications reported by RAPEX for the EU 27 during the years 2008-2013.

It has been observed from the RAPEX notification data that, 10 EU member states accounted for more than 90% of total recall notifications in the years 2008-2013 (as shown in Fig. 1). Therefore, to analyse the effects of input variables and study the differences between all EU member states and top 10 EU member states (EU10), the analysis was done in two stages i.e. stage one: analysis of EU27; stage two: analysis of EU10.

Multiple linear regression analysis was used to study the interrelationship between various independent variables with the textile recalls, and the *p*-values were used to substantiate the statistical significance of the input variables. Pairwise correlations among the input variables were used to group the highly correlated variables, and one variable was selected from a group of variables that showed correlation magnitude 0.9 or higher (hereafter called 'correlation threshold') with other variables present in the same group. The linear regression model used for the analysis is as follows,

$$y_{ij} = \alpha_0 + \sum_{k=1}^{n} \alpha_i x_{ijk} + \varepsilon_{ij} \qquad \ldots(1)$$

where y_{ij} is the total textile recalls for *i*th country during *j*th year. n is the number of un-correlated independent variables, α_0 is the intercept, $\alpha_1, \alpha_2, \ldots, \alpha_n$ are the coefficients to be estimated, x_{ijk} is the value of *k*th variable for *i*th country during *j*th year. ε_{ij} is the residual or error term.

4. RESULTS

Table 3 shows an overview of independent variables. Between EU27 and EU10, major changes were observed for POP and POPuP (with an increase in the mean values for EU10 from EU27), which means that comparatively big countries by population participate in EU 10. The same is evident from the skewness value which changed for POP from 1.48 for EU27 to 0.85 EU 10. The same is true for POPuP where it changes from 1.23 to 0.85. Therefore, these variables may be different impacts while studying in both of the cases separately. Some changes can be seen in the skewness values for the variables nGDP/C, rGDP/C and GE although major changes in their means or ranges were not observed.

Table 3. Overview of variable distributions for EU 27 and EU 10.

	EU 27			EU 10		
	Mean	**Skewness**	**Range**	**Mean**	**Skewness**	**Range**
POP[1]	18479954.27	1.48	407832 – 82217837	26540853.32	0.85	776333 – 82217837
CLE[1]	528.40	0.16	100 – 1200	533.33	-0.33	100 – 1000
GDI/C[1]	17381.48	-0.32	7153 – 25897	17473.77	-0.54	7153 – 25897
HSC (%)[1]	4.79	-0.11	2.7 – 6.8	4.51	0.20	2.7 – 6.7
nGDP/C[1]	24141.98	1.53	4600 – 83400	22118.33	0.19	4600 – 44400
rGDP/C[1]	21408.64	1.01	3500 – 68700	19756.67	0.09	3500 – 39300
II[1]	4.77	0.57	3.2 – 7.4	4.97	0.17	3.4 – 6.6
PT[1]	5494.26	0.28	781 – 13320	5408.22	0.00	869 – 10759
POPuP[1]	4395.35	1.23	72 – 18194	6684.67	0.54	181 – 18194
POPuP(%)[1]	24.54	1.20	14 – 49.3	27.02	1.19	16 – 49.3
CPI[2]	6.36	0.09	3.33 – 9.40	6.11	0.35	3.33 – 9.40
CoC[3]	1.02	0.10	-0.30 – 2.52	0.90	0.41	-0.30 –2.52
RoL[3]	1.16	-0.37	-0.16 – 1.98	0.99	0.04	-0.16 – 1.98
PS&AV[3]	0.75	-0.58	-0.47 – 1.51	0.59	-0.28	-0.47 – 1.45
V&A[3]	1.13	-0.33	0.29 – 1.71	1.07	0.04	0.32 – 1.69
GE[3]	1.15	-0.32	-0.36 – 2.26	1.06	0.38	-0.05 – 2.26
RQ[3]	1.24	0.00	0.49 – 1.92	1.16	0.34	0.49 – 1.91
LPI[3]	3.47	-0.05	2.78 – 4.18	3.468	-0.01	2.83 – 4.11

[1]Source: Eurostat. [2]Source: Transparency International. [3]Source: The World bank.

Table 4: Pairwise correlation of input variables for EU 27 member states for the period 2008-2013. Highlighted numbers in bold show correlation magnitude ≥ 0.9

	POP	CLE	GDI/C	HSC (%)	nGDP/C	rGDP/C	II	PT	POPuP	POPuP (%)	CPI	CoC	RoL	PS&AV	V&A	GE	RQ	LPI
POP	**1**																	
CLE	0.23	**1**																
GDI/C	0.39	0.82	**1**															
HSC (%)	0.08	0.51	0.37	**1**														
nGDP/C	0.05	0.84	0.65	0.18	**1**													
rGDP/C	0.11	0.87	0.71	0.20	**0.99**	**1**												
II	0.15	-0.28	-0.46	0.09	-0.40	-0.41	**1**											
PT	0.14	**0.90**	0.82	0.24	**0.94**	**0.96**	-0.46	**1**										
POPuP	**0.96**	0.15	0.23	0.03	-0.06	0.00	0.29	0.01	**1**									
POPuP (%)	-0.06	-0.55	-0.69	-0.30	-0.57	-0.59	0.77	-0.64	0.13	**1**								
CPI	0.05	0.69	0.72	0.28	0.74	0.78	-0.51	0.82	-0.11	-0.69	**1**							
CoC	0.06	0.72	0.75	0.27	0.78	0.82	-0.52	0.86	-0.10	-0.70	**0.98**	**1**						
RoL	0.03	0.70	0.78	0.31	0.74	0.78	-0.55	0.83	-0.15	-0.77	**0.93**	**0.95**	**1**					
PS&AV	-0.32	0.30	0.32	0.09	0.48	0.45	-0.71	0.45	-0.43	-0.61	0.55	0.56	0.58	**1**				
V&A	0.06	0.76	0.80	0.33	0.80	0.83	-0.60	0.87	-0.11	-0.82	**0.92**	**0.94**	**0.95**	0.62	**1**			
GE	-0.03	0.69	0.77	0.30	0.71	0.74	-0.60	0.82	-0.22	-0.78	**0.93**	**0.94**	**0.95**	0.60	**0.93**	**1**		
RQ	0.00	0.63	0.64	0.24	0.71	0.74	-0.52	0.76	-0.15	-0.67	0.88	0.88	**0.90**	0.57	0.89	0.87	**1**	
LPI	0.40	0.74	0.83	0.19	0.71	0.77	-0.39	0.81	0.27	-0.58	0.79	0.81	0.77	0.37	0.81	0.74	0.70	**1**

Table 5: Pairwise correlation of input variables for EU10 member states for the period 2008-2013. Highlighted numbers in bold show correlation magnitude ≥0.9

	POP	**CLE**	**GDI/C**	**HSC (%)**	**nGDP/C**	**rGDP/C**	**II**	**PT**	**POPuP**	**POPuP (%)**	**CPI**	**CoC**	**RoL**	**PS&AV**	**V&A**	**GE**	**RQ**	**LPI**
POP	**1**																	
CLE	0.23	**1**																
GDI/C	0.40	0.89	**1**															
HSC (%)	0.41	0.86	0.73	**1**														
nGDP/C	0.13	0.84	0.87	0.51	**1**													
rGDP/C	0.18	0.84	0.88	0.53	**1.00**	**1**												
II	0.18	-0.21	-0.32	-0.08	-0.39	-0.40	**1**											
PT	0.09	0.88	0.88	0.59	**0.98**	**0.97**	-0.40	**1**										
POPuP	**0.97**	0.16	0.27	0.39	0.01	0.05	0.31	-0.04	**1**									
POPuP (%)	-0.21	-0.69	-0.83	-0.55	-0.82	-0.84	0.63	-0.81	-0.07	**1**								
CPI	-0.01	0.50	0.64	0.23	0.80	0.81	-0.63	0.80	-0.18	-0.80	**1**							
CoC	-0.01	0.54	0.67	0.26	0.84	0.84	-0.61	0.84	-0.18	-0.81	**0.99**	**1**						
RoL	0.02	0.56	0.73	0.29	0.84	0.85	-0.64	0.83	-0.15	-0.89	**0.96**	**0.97**	**1**					
PS&AV	-0.08	0.18	0.25	0.05	0.39	0.39	-0.78	0.38	-0.17	-0.51	0.66	0.62	0.57	**1**				
V&A	0.12	0.64	0.76	0.39	0.89	0.89	-0.63	0.87	-0.03	**-0.93**	**0.92**	**0.94**	**0.95**	0.61	**1**			
GE	-0.13	0.57	0.68	0.29	0.83	0.82	-0.65	0.85	-0.29	-0.82	**0.96**	**0.97**	**0.97**	0.61	**0.91**	**1**		
RQ	-0.03	0.53	0.65	0.28	0.81	0.81	-0.72	0.81	-0.20	-0.83	**0.96**	**0.96**	**0.95**	0.67	**0.94**	**0.95**	**1**	
LPI	0.48	0.63	0.77	0.41	0.81	0.83	-0.35	0.77	0.36	-0.74	0.77	0.76	0.75	0.49	0.81	0.69	0.73	**1**

As reported in Table 4, nGDP/C, rGDP/C and CLE/C are highly correlated to each other. PT, which is a relative measure to median income, found to be correlated with nGDP/C, rGDP/C, CLE/C and GDI/C. However, the correlation between PT and GDI/C is below 0.9 therefore they cannot be considered the same as per selected *correlation threshold.* CPI and CoC represent the perception of general public towards corruption control but calculated by two different organizations. A very high correlation with each other (0.98 for EU27 and 0.99 for EU10) confirms their accuracy. Except PS&AV, all remaining governance indicators (i.e. CoC, RoL,V&A, GE, RQ) show high correlation with each other, while many of them show a good correlation with variables such as, nGDP/C, rGDP/C, PT and GDI/C. PS&AV does not show a high correlation with other governance indicators as it shows with II and POPuP (%). LPI for all EU 27 fall in the upper half quantile and show a good correlation with many of the economic indicators nGDP/C and rGDP/C, which is similar to the observation made by (Arvis et al., 2014). The similar observations for correlation among various indicators can be made with some changes in correlation magnitude for EU 10, as shown in Table 5.

Table 6. Grouping of highly correlated variables. Underlined variable represents the selected variable from the corresponding group.

EU 27		**EU10**	
Group 1	POP, POPuP	**Group 1**	POP, POPuP
Group 2	GDI/C	**Group 2**	CLE
Group 3	HSC (%)	**Group 3**	GDI/C
Group 4	II	**Group 4**	HSC (%)
Group 5	PT, CLE, nGDP/C, rGDP/C	**Group 5**	nGDP/C, rGDP/C, PT
Group 6	POPuP(%)	**Group 6**	II
Group 7	RoL, CPI, CoC, V&A, GE, RQ	**Group 7**	V&A, POPuP(%), CPI, CoC, RoL,GE, RQ
Group 8	PS&AV	**Group 8**	PS&AV
Group 9	LPI	**Group 9**	LPI

Table 6 shows the variable groups selected based upon the correlation, as discussed earlier. In each group one variable (indicated by underline in EU27 and EU10 columns) is selected which qualifies the selection criterion i.e. correlation threshold. In both cases (EU27 and EU10), there are 9 groups; however, the members of each group are not the same due to the differences in correlation for EU 27 and EU 10.

Table 7 and Table 8 show the statistics obtained by fitting the multiple linear regression for EU 27 and EU 10 respectively. For EU 27, II and POPuP (%) show $p < 0.001$, while for PS&AV $p = 0.023$. For the remaining independent variables, $p > 0.2$, which indicates a comparatively a very small statistical significance as compared with II, POPuP (%) and PS&AV. II and PS&AV having negative sign with their regression coefficients indicate that increase in these quantities results in lower recalls. This may be attributed to the fact that the EU states with more stable political and peaceful status (indicated by high PS&AV) may result the authorities to regulate the product well and therefore result in better monitoring of the products before introducing in the markets. Whereas, increased II implies increased social gap or income difference between the richest and poorest classes. Therefore, negative sign of the II coefficient indicates that the increased gap results in the lesser product recalls. POPuP (%) with a positive sign points to countries where a higher fraction population living under poverty are more susceptible to textile product recalls. This model could explain 44.2% of the total variance.

Table 7: Multiple linear regression model for EU27

	Estimate	SE	tStat	*p* Value
Intercept	14.32	35.24	0.41	0.68
POP	-1.43×10^{-7}	1.35×10^{-7}	-1.05	0.29
GDI/C	8.62×10^{-4}	1.15×10^{-3}	0.74	0.46
HSC (%)	-3.09	2.94	-1.05	0.29
II	-21.27	4.60	-4.63	<<0.01*
PT	6.45×10^{4}	1.44×10^{-3}	0.45	0.66
POPuP(%)	3.96	0.62	6.36	<<0.01*
RoL	-4.99	8.63	-0.58	0.56
PS&AV	-20.24	8.82	-2.30	0.02**
LPI	6.88	11.28	0.61	0.54
	Number of observations: 162, Error degrees of freedom: 152 Root Mean Squared Error: 26.4 R-squared: 0.44, F-statistic vs. constant model:13.4, p-value: <<0.001			

*Significant at 95%, ** Significant at 99%

Table 8: Multiple linear regression model for EU10

	Estimate	SE	tStat	*p* Value
Intercept	158.75	108.85	1.46	0.15
POP	-7.51×10^{-7}	3.34×10^{-7}	-2.25	0.03**
CLE	-0.07	0.11	-0.61	0.54
GDI/C	1.74×10^{-3}	3.02×10^{-3}	0.58	0.57
HSC (%)	-2.28	18.31	-0.12	0.90
nGDP/C	2.26×10^{-3}	2.62×10^{-3}	0.86	0.39
II	-26.78	9.01	-2.97	<0.01*
PS&AV	-12.71	17.32	-0.73	0.47
V&A	-233.24	57.90	-4.03	<0.001*
LPI	73.12	30.28	2.41	0.02**
	Number of observations: 60, Error degrees of freedom: 50 Root Mean Squared Error: 32.20 R-squared: 0.65, F-statistic vs. constant model: 10.2. p-value: <<0.001			

*Significant at 95%, ** Significant at 99%

For EU10, II and V&A have p <0.001, while POP and LPI have p = 0.02 and 0.03 respectively (as shown in Table 8). Although, RoL and V&A represent the groups having almost same indicators in EU27 and EU10, respectively (as shown in Table 6a and 6b), V&A

shows a much higher significance in EU10 as compared with RoL in EU27. Similarly, PS&AV, which is common in both cases (EU27 and EU10), shows $p = 0.46$ for EU 10 as compared with $p = 0.02$ in EU 27. Therefore, it can be concluded that PS&AV is an important factor in general, however, when countries with the most recalls are concerned, these are the remaining governance indicators (i.e. CoC, RoL,V&A, GE, RQ) represented by RoL are more significance while PS&AV becomes insignificant. The negative sign with the regression coefficients of V&A, ROL and PS&AV points that the countries with better governance indicators (represented in terms of V&A, ROL and PS&AV and other correlated indicators) are likely to have lesser recall notifications. It is worth noting that, POP has a negative coefficient, which means that the country with higher population tends to have less recalls. The positive sign of the regression coefficient with LPI clearly indicates that higher LPI leads to higher recalls. Current model (EU10) explains ~65% of the total variance.

5. DISCUSSION

From the presented data (in Table 1) it is clear that some of the EU member states have high recalls as compared to other, for instance BG and HU accounted for more than 50% of the total recalls in the years 2008-2013. The underlying reasons could be the weak legislation, lax enforcement and/or lack of government supervision which let the harmful products to enter in the market. The same is verified by the negative regression sign with governance indicators (PS&AV, RoL for EU 27 and PS&AV, V&A for EU10) in the multiple regression coefficients, which show that weaker governmental control will increase the number of recalls. This supports the argument made by Luo (2008) that the strict and transparent government legislation impacts the recalls negatively and forces the organizations to closely monitor their products for safety aspects. LPI is the measure of the border customs efficiency and efficient logistic distribution and in general, positively influenced by the better governance (Arvis et al., 2014). Inspite of having a positive correlation, there are different signs of regression coefficients with LPI and as that with other governance indicators (such as PS&AV, V&A and RoL). This means when good governance (indicated by higher value of governance indicators such as PS&AV, V&A and RoL) would result in lesser recall, better LPI, which is positively correlated with governance indicators, would lead to higher recalls. In reality, most of the textile products recalled in the EU were reported to made-in-China and other non-EU countries, therefore they must have confronted EU border customs in a legitimate trade transaction. Country with better customs performance (or LPI) indicates that its border customs can capture the non-complying products more efficiently and allows relatively safer textiles in the market. This, in turn, would generate less recalls. But LPI having a positive sign with the coefficients in both cases (EU10 and EU27) shows that higher LPI tends to increase textile recall notifications, in contrast to the expected outcome. Moreover, LPI is highly significant for EU10 ($p < 0.01$), it cannot be neglected. Therefore, it clearly indicates that the textile recalls cannot be handled by mere good governance, but different indicators need to be considered separately. Further, it is worth noting that, none of the economic indicators (nGDP/C, PT and GDI/C) shows good statistical significance, which confirms that the textile recall is not an issue related with economic aspects of a country, rather it is a social and governance issue as social indicators (such as II, POPuP(%) and PS&AS for EU27 and V&A, LPI, II and POP for EU10) show a high statistical significance (as shown in Table 7 and Table 8). In a specific context to Bulgaria, Ene (2012) also made the similar conclusion that product recalls can be controlled by effective implementation of consumer protection policies where the government and society have a primary role.

Furthermore, following the above analysis and revisiting the formulated research hypotheses, H2 and H3 are supported because many social and governance indicators showed a high statistical significance ($p \leq 0.05$) for both of the cases. However, all the economic indicators that showed a low statistical significance ($p \geq 0.45$), therefore H1 stands false and confirms that the economic aspects of the EU member states do not affect the corresponding textile product recalls and this is true for both cases (EU10 and EU27). This clearly indicates that low consumer buying power and/or poorer countries (which may import cheaper products) have no relation with product recalls.

6. CONCLUSIONS

Product recall has recently become a very common phenomenon and an inevitable action for manufacturers. The present paper studied the impact of macro-scale indicators on textile product recalls in the EU. Textile product recalls pertaining to this study represent the unique recall notification made in the EU during the years 2008-2013, which were obtained from the RAPEX database, the EU's official database for non-food dangerous products notified for recall by the European Commission. The analysis was done by formulating two cases. In the first case, all EU member states were studied and the impact of various indicators on the EU member states was scaled using multiple regression analysis. Whereas, in the second case, top 10 EU member states, which account for more than 90% recalls were studied using the same regression analysis technique. Both analyses revealed that textile product recall is influenced by social and governance indicators, while economic indicators show little statistical significance. In general, with no surprise, better governance (specified by various governance indicators, except LPI) negatively correlated to the textile product recalls. However, there is an exception with LPI, which shows a positive regression coefficient. Better LPI indicates an efficient border customs, transportation, and other related parameters, which may help in preliminary filtering of the harmful products. Considering the contradicting results from the current study, the role of border customs may need further analysis. Further, a large difference in significance levels of some indicators was observed as a major difference in two cases. Particularly, POP and LPI show a high significance for EU10 as compared to EU 27. This certainly indicates that population and border customs forces play an important role for current high product recalling EU states, which may not be true when all EU states taken all together. Recalling is an issue pertaining to non-complying products in the market. Since, both cases reveal that importance of governance and social aspects on textile product recalls, handling of this issue can be done by facilitating the government and society with more information about the product. It is also important for the customers to be notified for recalled products. These both purposes are served by the traceability system, which identifies and trace the products by product attached traceability tags; hence, the recalled products can be located and identified efficiently. Externally attached RFIDs and barcodes are generally removed at the point-of-sale; as a result, it becomes difficult trace products afterwards. The expert group setup by EU for involuntary traceability recommends integrating tracking tag to the physical product so that it remains with the product (*Research Support for an Informal Expert Group on Product Traceability*, 2013). Therefore, future research can be focused on designing of traceability system with integrated tracking tags to textiles for better textile product traceability in the markets and their withdrawal during the recall crisis.

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Paper II

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A fully yarn integrated tag for tracking the international textile supply chain

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ABSTRACT

Textile and clothing industry is one of the classical manufacturing industries which have recently undergone major transformations due to delocalization and high market volatility. In this context, one solution to guarantee the control and optimization of globalized supply chain is the implementation of a traceability system to follow-up the activities of different actors of the supply chain, improve brand value by countering pirate and enhance value creation in reverse supply chain. Therefore, in this paper, we first introduce the idea of fully integrated tracking tags for casting traceability in the textile. Then, as one stage of the traceability system development, we describe a yarn coding scheme to transform a textile structure into a tracking tag. Here, a number of special yarns were coded according to various combinations of optical characteristics. Further, a recognition system was developed for identifying the unique identification yarn code by using different image analysis techniques.

1. Introduction

Globalization has opened possible ways for enterprises to manufacture products, especially textiles, in developing countries due to cheap labor and relaxed environment policies/working regulations, and ship all around the World [1–3]. However, with this spectacular increase in distance between manufacturers and customers, distribution systems have become more complex and keeping track of every product has placed a great demand for right and on-time delivery [4–6]. In today's global competitive and volatile market, offshore suppliers are also required to respond faster to the manufacturers' demands in order to be competitive in the market and reduce the possible production lead-time. Therefore, globalization has led to an open market to undercut the competition with optimized global supply chain and maintaining a rapid communication between suppliers and buyers. Development of various manufacturing processes has realized a fast production with reduced liability on labor for increasing textile and fashion products' demand but at the same time opened possible ways for easy cloning by opponents and counterfeiters. On the other side, exposition of counterfeit products and various unethical practices in production, poor labor conditions in manufacturing countries and consciousness for the environment, consumers are demanding transparency and sustainable products [7–9]. Therefore, the conventional business models standing on the pillars of product cost or quality are not sufficient to compete in today's globally changing business environment. New ways are being explored to satisfy the customers' needs and technologies are being developed for optimizing supply chain, bringing transparency to customers and protection against counterfeits [10].

The adoption of traceability system is a good proposition to handle above-mentioned issues. A good traceability has a significant importance for manufacturers, distributors and consumers in terms of quality control, supply chain organization, warehouse management, market forecast, and product security. It reinforces the communication between different industrial partners, especially when the communication is hindered by geographical separation. Therefore, it can bring more transparency and control over production and distribution systems. The traceability works on tracking unique identifiers assigned to each traceable resource unit [11,12]. Universal product code (UPC), 2-D barcodes and radio frequency identification (RFID) tags are the common unique identifiers. This system relies on enterprise's credibility which ensures the authentic information management, maintenance and delivery of an authentic product to its counterpart or the buyer. Easy replication of above-mentioned identifiers, however, makes an easy break-in to integrate counterfeit products in the supply chain or

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directly in the market [13,14]. Therefore, identifying counterfeit textile products has become increasingly difficult. Detachability of identification tags is another issue which opens possible ways for losing the product in supply chain and a breach in well-managed traceability system. The covert identifiers integrated into textiles such as integrated RFID tags minimize the separation possibility from the textiles but their disposal cause severe impacts on the environment [15]. Therefore, development of cost-effective, easy to manufacture, reliable, electronic chip less and secure marking or tag in the integrated form for textiles has become the interest of many researchers.

Securing product based upon product's inherent features is a good proposition to fight against counterfeit and other earlier-mentioned threats since it does not add extra cost and accessories to the product [13]. In the similar way, the structure of woven fabrics has been utilized by many researchers to transform them into traceable label [16–18]. A textile consists of yarns as a basic building block; therefore, optical features based yarn in a textile structure opens possible ways for generating yarn based integrated tags [19]. Further it opens the scope for casting traceability in the product itself, which is a common practice in many fields (for example [20]). Yarns in woven textiles appear in two sets of perpendicularly interlaced yarns, known as warp and weft. Yarns in a set appear nearly parallel to each other. Whereas, (weft) knitted textile structures are made by interlooping of yarns with each other, and the loops for a yarn appears linearly along the wales or fabric width. The use of yarns with foreknown optical features can be used as a traceable marking, where the optical/visual stamp generated by optical-featured yarns can be used as traceability code for the textile. Therefore, in this paper, we propose a methodology for yarn coding based fully integrated tracking tag for textiles. Here, yarns are coded based on multiple optical features and it is anticipated that weaving or knitting in a particular sequence can create a numeric token for traceability system which can be used as an original product identifier and information recalling signature in the supply chain and on the consumer end.

2. Literature review

GS1 global traceability system [21] 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.*" In sectors like agri-food, government regulations have pushed various organizations to adopt traceability system for providing guaranteed healthy product. Whereas, sectors such as textile and fashion, implementation of traceability is motivated by customers' expectations and economic incentives associated with lower cost distribution systems, reduced recall expenses and brand protection [22,23]. A traceability system is a management system permitting to identify and track the unique identification code assigned to each product. The unique identification code acts as a token for storing or retrieving data from a product data management system which is accessible to manufacturers/distributors and consumers. The widely used tags for traceability applications are as follows.

2.1. Barcodes

Barcodes are the printed machine-readable patterns used for the data representation. Due to the low manufacturing cost, and easy and robust readability, they are widely used in many commercial applications including in-house production management, supply chain management and in supermarkets. Since the unearth of first barcode developed by IBM named 'Universal Product Code' (UPC) which is, in general, capable of encoding 95 bits [24] with unidirectional data representation, bidirectional or 2D high data encoding capacity barcodes [25] have been developed and widely used in many commercial applications. However, owing the possibility of easy cloning and implementation [14], these codes are problematic in counterfeit detection and brand protection for textile products [13]. Nevertheless, barcodes have been proven very useful in production management, warehousing and logistic applications.

2.2. Radio frequency identification tags (RFIDs)

An RFID tag contains electronic microchip and antenna coil. Electronic chip holds the memory of the tag and the antenna coil powers the chip by electromagnetic mutual induction coupled with the receiver or decoder and transmits back the identity encoded in the memory. Delivering non-contact and covert read and write capability with large data capacity, RFID tags find applications in textile production and supply chain. Recently, integrated RFIDs have been explored with the direct encapsulation on fabric surface [26]. Similarly, RFIDs have been incorporated inside the seam so that they could stay with fabric for post selling 'intelligent' applications [27,28]. However, the requirement of dedicated devices for decoding hinders its reach to the wider public. Cloning and easy implementation make them questionable to use in anti-counterfeit and brand protection. Data encryption techniques have improved the RFID protection at the cost of increased size and implementation cost [29,30].

2.3. Magnetic barcodes

Magnetic barcodes are similar to the printed barcodes (or UPC) except the variant width printed lines are replaced with spaced magnetic elements. For decoding, the position of each magnetic element is identified remotely for precise location and response using magnetic sensing technology [31,32]. Thin size and resistance to heat and pressure make magnetic barcodes suitable to use with products and packaging during manufacturing [32].

2.4. Miscellaneous techniques

Microtaggant® developed by 3M is another tagging technique, initially designed for explosive testing, finds popularity in counterfeit medicine detection (www.microtaggant.com). In this technique, the arrangement of highly cross-linked melamine plastic particles with multiple stratified layers of different colors are translated into a numeric code for counterfeit detection. Cloning is deterred by highly complex replication manufacturing process. More recently, anisotropic optical characteristics of highly oriented polymers have also been explored to form a tracer fiber or pattern under polarized light [33,34]. Organic chemical marking of fibers is another proposition for anti-counterfeiting at the cost of sophisticated testing instruments. Covert and invisible taggants or inks responsive in a specific wavelength of light or heat or other conditions are another class of signature developed to fight counterfeit [35].

3. The proposed textile fully integrated tracking system

Textile and clothing industry is organized by a number of worldwide spread supply-chains, each comprising diverse partners such as fiber as raw material manufactures, yarn spinning mills, weaving and knitting mills, dyeing and finishing factories, apparel manufacturers and retailers. For a meaningful information exchange between different partners, a unified information sharing scheme is required which is hindered by lack of explicit semantics and contexts in knowledge sharing through product data management

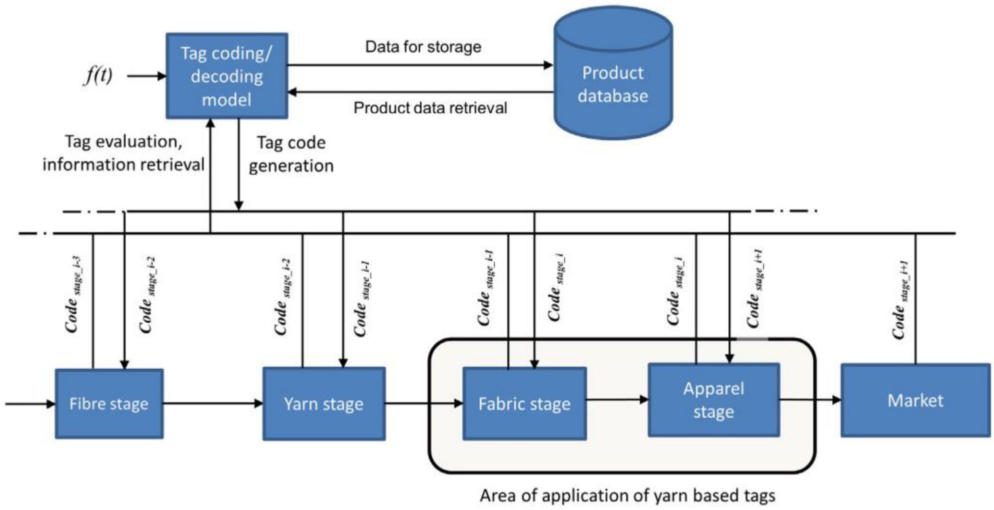

Fig. 1. The proposed tracking system for the textile supply chain.

(PDM). However, the above-mentioned challenges are considered in traceability implementation which provides semantics and structural guidelines in the context of knowledge integration and sharing [36,37]. Traceability, in general, refers to the ability to trace the history, application or location of an entity by means of recorded identifications. For a complete traceability system, every partner or stage has to be the part information building. For the protection of tracking codes, the code generation can be coupled with a confidential time-varying function $f(t)$ controlled by the brand manager or supply-chain manager, such that no unauthorized organization or person can predict it. An example of this traceability scheme is shown in Fig. 1, where stage i in the production-chain amalgamate its information with the one received from the previous stage $i-1$ and generate new marker or tag for the current stage. Therefore, the code generating function can be written as, $\text{code}_{\text{stage}\_i} = f(\text{code}_{\text{stage}\_i-1}, t)$. Further, the product information can be stored in product database server with the reference to each generated code and tag can be attached or integrated into the product.

Tags used for traceability in integrated form offer more transparency and control in production. More transparency in the sense that, integrated markers cannot be removed from product therefore firstly provide security to the product and secondly, any partner in production chain can recall the product history at any level. Currently, RFID and barcodes are mostly used traceable markers. As far as textile is concerned, there are shortcomings associated with these markers, for instance, RFIDs are relatively expensive and cannot withstand the wet treatments carried out in the textile industry. Further, they are made-up of non-textile material, therefore, cannot be fully integrated into textiles. In addition to this, in general RFID and barcodes have almost no security against cloning and are easy for unauthorized re-implementation. Yarn-based fully integrated tracking tag can have its application in fabric and apparel (shown in Fig. 1), where yarns can be integrated into the textiles or yarn-based tags can be used as an apparel component. Further, the coded yarns can be inserted in a realtime so that production can be monitored by the distant buyers. This can bring more transparency in production and product security. The information coded in fabric by means of appropriately selected yarns can be processed with textiles for various wet treatments since there is no electronic component. Further, yarns are an integral part of a textile therefore cannot be removed and used elsewhere.

4. Requirements for an ideal tracking tag

A tag with traceability data is the only link between a physical product and product database system; therefore a good traceability system can fail to trace a product due to poor tag scheme [38]. A better tracking tag is important because it goes to the customer or other company's domain and its security and proper handling cannot be controlled/assured. Furthermore, tags are an integral part of a product when it comes to brand authentication and protection, therefore easy cloning of tags can help in counterfeiting [13]. Decoding device dependence is one the driving factors for acceptance of the tag. This is why smartphone decodable QR codes and barcodes are widely used in pre- as well as post-selling applications, while RFIDs, which require a dedicated device, remained mostly limited to pre-selling applications [28]. The integrated form of tag has minimum risk of detachment of the tag from product and the tag cannot be reused with other (counterfeit) product. In general, harmful chemical free products which possess minimum threats to humans and environment is another requirement from government regulations and customers. Therefore the same applies to tags also. Economic and technological spending in manufacturing of a tag could be a big hindrance no matter how near it conforms to above-mentioned requirements. Therefore, to summarize an ideal tag for traceability system can be described as,

- *Robustness* in the sense that it retains readable information even after undergoing through different mechanical agitations in transportation and use.
- *Integrated into the product* for reducing the chance of detaching from associated product.
- *Irreproducible* to fight against counterfeit.
- *No dedicated device requirement for decoding* such as barcodes which could be read by smartphones.
- *Cheap and technically facile* to produce with minimum investment in technology and manpower.
- *Environmental friendly* so that the tag has minimum impact on environment and user.

Further, tag flexibility is another requirement in the case of application in textiles and it should not change the feel of textiles.

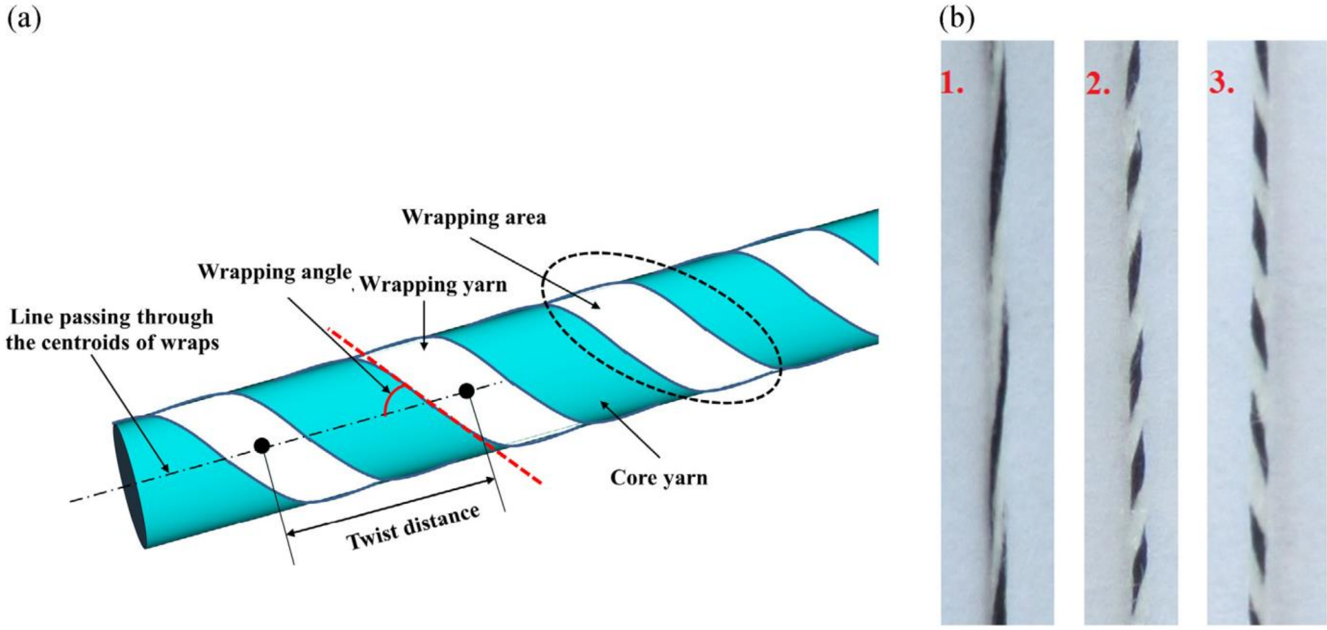

Fig. 2. (a) A typical wrapped yarn geometry. (b) Actual wrapped yarns where (1) and (2) are the *Z*-direction twisted yarns with different twist densities and (3) is *S*-twisted yarn.

5. The proposed yarn coding with variation of optical features

A yarn consists of multiple optical features which can be used for its characterization [39]. Yarn characteristics such as twist and linear density can be approximated using digital image processing by analyzing the associated optical features. Twist can be approximated by the helical angle of fibers [40] and linear density can be approximated by the yarn's diameter [39,41,42]. A plied or wrapped yarn assembly made up of yarns having different color contrasts (or colors) and/or linear densities has possibilities of yarn identification based upon optical features, such as yarn surface occupied by one contrast, the distance between the same contrast, etc. In this paper, a twist-dependent color contrast-based yarn identification method has been discussed, where a composite yarn assembly has been used which contains two yarns having different colors. The identification method of the information coded in the yarn will be similar to that of the UPC. In the UPC, the information is generated by the analysis of sequence of variant width of printed lines, whereas in the yarn-based tag, the information can be generated by analyzing the sequence of yarns having variant optical features. Further, a yarn-based integrated tag offers the attributes required for an ideal tag. Firstly, yarns used for tag coding are 100% textile hence they do not require additional cost or material and are environmentally clean as normal textiles are. Secondly, a yarn tag is an integral part of the textile, meaning no additional instrument or process required for its manufacturing. Further, the yarn-based tag cannot be removed from fabric because doing so will lead to the destruction of the textile itself. For the unauthorized reproduction/replication, a long process has to be followed from the spinning of yarns to weaving and finishing of textiles. In addition, the yarns should meet the same technical specifications as that of original tag's yarns. Moreover, it is commonly understood that counterfeit works on minimum investment in the R&D and production, therefore a long reproduction time and technical specification would hinder from replication.

For the purpose of code identification, repeatability and robustness are two primary requirements. Repeatability is an important aspect for extracting the assigned identity code of the tag for a given lifetime of the product. Since, the identification system is based on the analysis of certain optical features which in turn depends on the image capturing conditions such as lighting, external noise, and capturing instrument variables. Therefore, robustness against above-mentioned factors is the second important criterion for an effective identification methodology. So, in the following text, the potential yarns' features are first defined and then the extraction algorithm is presented. Next, without losing the generality regarding the robustness of the methodology, an aggregated group decision support system (DSS) has been proposed for yarn code identification by combining multiple optical features to minimize the effect of variability associated with the yarns.

5.1. Yarn nomenclature and definition of optical features

Our idea of traceability is based on optical features of a yarn, therefore we selected a yarn assembly made-up of two yarns with different colors to generate robust optical features. This kind of yarns can be produced on a hollow-spindle spinning-frame, where a core yarn is wrapped with a sheath yarn. A typical wrapped yarn is shown in Fig. 2.

In this paper, we have used nomenclature as *wrapping yarn* for sheath yarn, *core yarn* for the core yarn and *wrapped yarn* for the yarn made of the core yarn and sheath yarn. The wrapped yarns used for tags are referred as *coded yarn* in the following parts of the paper. Assuming the different colors of these yarn components, yarn optical features can be defined as follows,

5.1.1. Wrapping angle or wrapping helix angle

Wrapping angle or wrapping helix angle is the angle made by wrapping yarn around the surface of core yarn with the core yarn axis, as shown in Fig. 2a.

5.1.2. Wrapping area

Wrapping area is the area occupied by wrapping yarn in a single wrapping in the 2D longitudinal view of the wrapped yarn.

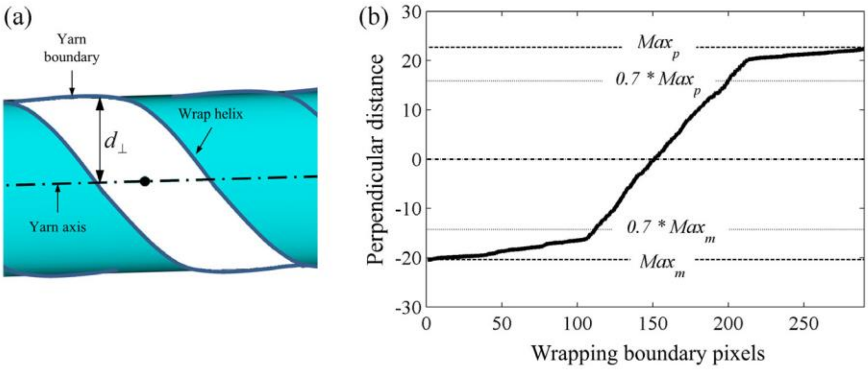

Fig. 3. (a) A typical parallelogram shape boundary of the wrapping made wrapping helix and wrapped yarn boundary. (b) Perpendicular distance ($d_\perp$) of the wrapping boundary pixels from the yarn axis arranged in ascending order.

5.1.3. *Interwrap distance or twist distance*

Interwrap distance or twist distance refers to the distance between the centroids of consecutive wraps in the 2D longitudinal view of wrapped yarn. Alternately, this is a measure of twist density (or twist per meter) of the wrapped yarn. It should be noted that results for twist distance are presented in this paper as twist per meter.

Fig. 2(b) shows the yarns having different twist densities. It can be clearly inferred that as the twist density changes there exist changes in the optical features. The twist in a coded yarn can be easily controlled during the manufacturing on a hollow-spindle spinning-frame, which alternately provides better control over the above-mentioned twist-based optical features. This control is important when the coded yarns need to be produced in different batches with same or different optical features. Further, the use of coded yarns having different twists (or yarn classes) during weaving or knitting of textile creates an optical feature-based stamp on the resulting textile surface, which can be used as a tracking code. The number of coded yarns in optical stamp decides the length of code. Let n_c be the number of classes of coded yarns and n_l the number of coded yarns used in each tracking tag. This results $(n_c)^{n_l}$ number of possible unique combination codes for the resulting tracking tag.

6. Image analysis algorithm for optical features extraction

As mentioned previously, the wrapped yarn comprises of two base yarns having different colors, can create a pattern by repeating the elementary geometric structure (wrapping), as shown in Fig. 2(a) and (b). In this situation, the original image of a coded yarn can be converted into a binary image such that core yarn acquires the background status (i.e. pixel value 0) and wraps acquire foreground status (i.e. pixel value 1). As wrappings appear periodically over the core yarn surface, each wrapping appears as connected pixels mass with value 1 repeated periodically along the length of yarn. Therefore, the area of each wrapping can measured by calculating the number of pixels in each connected pixels mass. Further, inter-wrapping distance or twist distance can be calculated by the Euclidean distance (y_{ij}) between the centroids of consecutive wrappings. The centroid coordinates (C_{xi}, C_{yi}) of the ith wrapping is calculated as $C_{xi} = \sum_{a=0}^{m}(a \times n_a)/\sum_{a=0}^{m} n_a$, $C_{yi} = \sum_{a=0}^{n}(a \times n_a)/\sum_{a=0}^{n} n_a$, where m is the image size in the horizontal direction, n the image size in the vertical direction, n_a is number of pixels in the ath row or column in the ith wrapping. The inter-wrapping distance can be converted into twist per meter ($D_{ij[\mathrm{TPM}]}$), i.e.

$$D_{ij[\mathrm{TPM}]} = \frac{1000}{y_{ij[\mathrm{mm}]}} \quad (1)$$

where $y_{ij[\mathrm{mm}]}$ is the inter-wrapping distance y_{ij} represented in mm.

The wrapping angle can be measured by following the wrapping yarn path over the yarn surface. As shown in Fig. 3(a), the shape of a wrapping resembles with parallelogram with no sharp corners which could differentiate the pixels forming helix or wrapping yarn and yarn boundary.

In order to separate wrapping helix pixels from total boundary pixels, the following methodology has been adopted. Firstly, the perpendicular distances of all the boundary pixels from the wrapped yarn axis passing through the centroid of each wrapping were calculated (as shown in Fig. 3(a)) and the boundary were arranged in ascending order of their perpendicular distance (as shown in Fig. 3(b)). Here the boundary pixels below the yarn axis have been assigned a −ve sign and pixels above the yarn axis have been assigned a +ve sign (shown in Fig. 3(b)). From the wrapping geometry, we know that the pixels along the diameter are approximately at the same distance from yarn axis and have more distance as compared with the helix pixels. Therefore, the pixels having distance less than 70% of maximum distance (i.e. Max_p and Max_m) on either side of yarn axis were identified to be the wrapping helix pixels as shown in Fig. 3(b). Further, the slope of wrapping helix was calculated by fitting the equation of the first order on the identified wrapping helix pixels. The wrapping helix angle was calculated by normalizing the slope obtained from equation fitting with respect to the yarn axis.

The data obtained for various features of each class of yarn from analyzing the yarn images have been further normalized with the length scale.

7. DSS for coded yarn recognition

Textile yarns are flexible and non-uniform and the magnitude of an optical feature for a yarn possesses a range depending upon its sensitivity to deformation and unevenness. Therefore, for assigning an unknown yarn to a known class of yarn, it becomes imperative to incorporate some tolerance for input variables in the classification system. For handling such imprecise information, Zadeh [43] introduced the fuzzy sets where the parameters are defined in terms of fuzzy classes and are characterized by the degrees of membership. In other words, fuzzy membership represents the similarity of input variable to a class instead of providing crisp value therefore this technique is very helpful especially to handle imprecise data. Degree of membership is derived using membership function which in turn is a generalization from classical set or statistical data [44,45]. Therefore, in case of yarn classification, when a feature of an unknown yarn is compared with the membership functions of various yarn classes, the highest membership value to a yarn class signifies the highest possibility of unknown

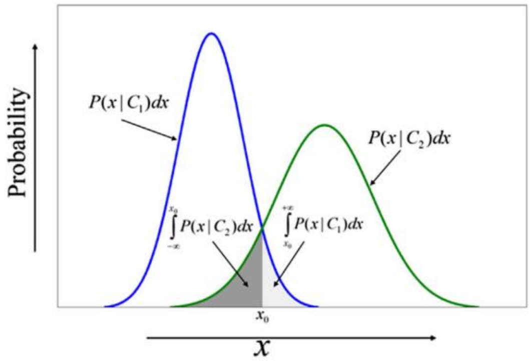

Fig. 4. Overlapping of the distributions of two classes for the same feature.

yarn belonging to that particular yarn class. However, a decision with the highest possibility may not be always relevant, especially when the measured feature of the yarn belongs to the overlapped region of the features of two or more yarn classes. For example, in two overlapped distributions C_1 and C_2 as shown in Fig. 4, the uncertain region is represented by the shaded region. Therefore, the yarn belonging to yarn class C_2 having optical feature magnitude below x_0 will always classified as C_1 and vice versa is true beyond x_0.

In order to avoid such ambiguities, a robust DSS is required. Further, to reduce the uncertainty, Forman and Paniwati [46] discussed the methodology of the aggregation of individual judgment (AIJ) for an aggregated decision making where multiple individual inputs are aggregated to a robust output. As we have multiple yarn optical features, the ambiguity can be minimized by aggregating membership values of all features. Therefore, to design a DSS for yarn classification, there are two important steps, i.e. selection of membership functions and aggregation of membership values, and are explained below.

7.1. Design of the membership functions

The use of an appropriate membership function is an important step in designing a good DSS [44,45]. The membership functions are the generalized indicator of classical data, so, in general, a membership function should represent the distribution of data or cluster in Euclidean space. In our case, various optical features are distributed around their means with certain variances and such distributions can be represented by Gaussian distribution functions. Therefore, membership functions resembling to Gaussian distribution would be an appropriate choice for DSS. However, in order to increase the error handling capacity of the DSS, broad bell-shaped membership functions were constructed, which have a broader bell space as compared to simple Gaussian membership function. The membership functions were constructed by the multiplication of increasing and decreasing Cumulative Gaussian Distribution (CGD) functions and formulated as,

$$d(x,\mu_1,\mu_2,\sigma') = \underbrace{\frac{1}{\sigma'\sqrt{2\pi}}\int_{-\infty}^{x} e^{(-(x-\mu_1)^2/2\sigma')}dx}_{A} \times \underbrace{\left(1-\frac{1}{\sigma'\sqrt{2\pi}}\int_{x}^{+\infty} e^{(-(x-\mu_2)^2/2\sigma')}dx\right)}_{B} \quad (2)$$

$$\mu_1 = \mu - 2.25\sigma, \quad \mu_2 = \mu + 2.25\sigma, \quad \sigma' = \frac{2.5\sigma}{3.129}$$

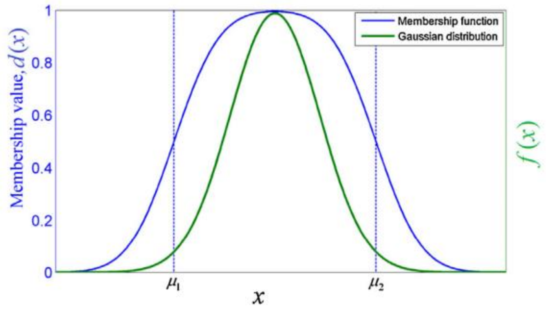

Fig. 5. Membership function extrapolated from a Gaussian distribution function.

where μ is the mean and σ is the standard deviation of optical feature distribution. In Eq. (2), term A represents the increasing CGD function and term B represents decreasing CGD function.

An example of membership function is shown in Fig. 5.

Further, it should be noted that there are several cases where unidirectional overlapping exists. For instance, in case of highest twisted yarn, the twist distributions may overlap only from comparatively lower twist yarns. In such cases, the membership function was defined by placing term B as unity in Eq. (2). Similarly, for lowest twisted yarn, twist distribution overlapping exists from yarn having comparatively higher twist only. Therefore the membership function was calculated by placing term A as unity.

7.2. Membership values aggregation in DSS

The membership aggregation is an important step to minimize the misclassifying possibility [45]. Misclassification is associated with the overlapping feature clusters, therefore during aggregation, it is important to provide different weights to the membership values based upon the classification capability. Hence, for the aggregation of membership values, geometric mean with different weights for optical features has been employed as given below.

$$D_i = \left[\prod_{j=1}^{n} d_{ij}^{\,w_j}\right]^{(1/\sum_{j=1}^{n} w_j)}, \quad i \in \{1, C\}, 0 < w_j \le 1 \quad (3)$$

where d_{ij} is the membership value of ith yarn class for jth optical feature, n is the total number of optical features, C is the total number of yarn classes, w_j is the weight associated with the optical feature j (discussed in the following section).

The final decision of the belongingness of an unknown yarn to a given yarn class c is obtained from the maximal value of all D_i's i.e.

$$D_c = \max\{D_i | i = 1, 2, \ldots, C\} \quad (4)$$

7.3. Optimization of the weight factors (w)

The weight assigned to each optical feature is an influencing parameter and needs to be substantiated by the associated degree of uncertainty. In the Bayesian theory, the measure of uncertainty degree can be substantiated by the overlapping of the distributions of each optical feature for various classes of yarns. For example, in two probability distributions shown in Fig. 4, the probability of uncertainty (P_u) can be calculated as,

$$P_u = \left(\int_{x_0}^{+\infty} P(x|C_1)dx + \int_{-\infty}^{x_0} P(x|C_2)dx\right) \quad (5)$$

Alternately, it characterizes the overlapped area O, as shown in Fig. 4. Formally, it can be expressed by

$$O = A_1 \cap A_2 \quad (6)$$

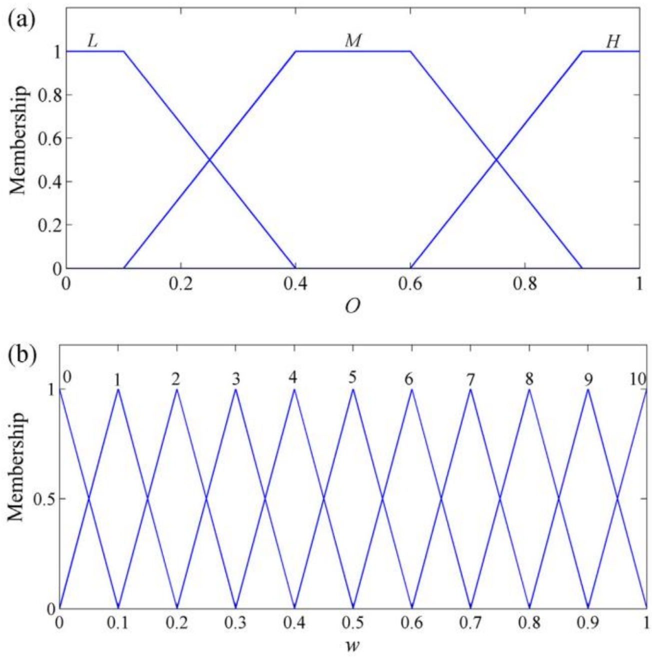

Fig. 6. (a) Trapezoid shape membership functions for classification of overlapping for a class of yarn. Here horizontal-axis represents the extent of overlapping (O). (b) Triangular membership functions for output "w" or weight assigned to a feature. Here horizontal-axis represents the weight $w \in [0 \ \ 1]$.

where A_1 and A_2 are the areas under the curves of $P(x|C_1)$ and $P(x|C_2)$ respectively, and each one is equal to unity. Therefore, $O \le 1$.

Further, if there exist more than two distribution functions, the probability of error or region of ambiguity for a class can be defined as the overlapped region of the considered class with all the other classes. In other words, the overlapped region can be calculated by assuming considered class against combination of all other classes and is shown as

$$P_i = \left(\int_{x_0}^{+\infty} P_i(x|C_i)dx + \int_{-\infty}^{x_0} \max P_j(x|C_j)dx \right),$$

$$j = 1, 2, \ldots, C, \quad j \ne i \tag{7}$$

$$O_i = A_i \cap \left(\bigcup_{j=1, j\ne i}^{C} A_j \right) \tag{8}$$

where C is the number of classes.

Since $A_i = 1$ therefore $O_i \le 1$.

In order to optimize the weights (w_j) for Eq. (3), fuzzy control system has been deployed where the overlappings obtained among various yarn classes for an optical feature using Eq. (8) used as the input parameters and the weight as an output parameter. In the present case, the range of weight is between 0 and 1. The overlapping has been converted into overlapping degree (V) by three linguistic levels namely as 'L' or low, 'M' or medium and 'H' or high, and enumerated as L (=2), M (=1) and H (=0) respectively. Further, the membership functions for the fuzzy input have been defined in terms of low slope trapezoidal fitting functions for a smooth transition between various levels of overlapping (as shown in Fig. 6(a)).

The output, i.e. weight (w) has been represented by triangular membership functions and divided into different levels. In order to facilitate the rule building in fuzzy system, the total number of levels (N_l) were selected such that sum of maximum possible enumerated overlapping denotes the highest level and minimum possible enumerated overlapping denotes lowest level of the output function. Therefore the total levels in output function can be calculated as,

$$N_l = (C \times L) + 1 \tag{9}$$

where C is the total number of classes.

For example, if $C=5$, then $N_l = 11$(from 0 to 10), as shown in Fig. 6(b). If all input optical features possess minimum overlapping i.e. 'L', the output weight can be 1 (or level 10 of the fuzzy output function) whereas in case of maximum overlapping, minimum value, i.e. 0 (or level 0 of the fuzzy output function) can be assigned. Therefore, fuzzy system requires 3^C number of rules and the rule for the ith optical feature can be written as $w_i = \sum_{i=1}^{C} V_i$, where V_i is V for the ith optical feature. The defuzzification of the fuzzy outputs into a crisp weight w^* can be carried out by centroid defuzzification method as follows:

$$w^* = \frac{\int V_i(w)w dw}{\int V_i(w) dw} \tag{10}$$

Table 1
Yarn class specification.

Yarn class	Twist per meter
C2	200
C4	400
C6	600
C8	800
C10	1000

8. Experimentation and results

8.1. Test sample

To generate robust yarn optical features a white polyester yarn of linear density 50 Tex (g/1000 m) was used as the core yarn and a black multifilament polyamide yarn of 16.6 Tex was used as wrapping yarn on hollow spindle frame. Since we had the intention to produce 10 digits, i.e. from 0 to 9 in the form of coded yarns, we prepared five classes of Z-direction twisted yarn samples with different twist levels ranging from 200 TPM (twist per meter) to 1000 TPM (as shown in Table 1). It should be noted that the above-mentioned twists represent the machine-set twists and actual twists are slightly higher than machine set twists, as shown later in the paper. Further we took the assumption that rest five other classes can be prepared by mere changing the direction of twist and keeping all other parameters same. An example of yarns with changed twist directions is shown in Fig. 2(b). Yarn class enumeration is given in Table 1.

8.2. Experimental setup

Prepared wrapped yarns were wrapped over the white flat board and longitudinal views of yarns were captured using a digital camera at known magnifications. All the experiments were carried out in a dark room where the light intensity and light temperature were controlled using Polaroid® 144 LED light panel.

As it is already discussed, the membership functions should represent the best possible distributions of various features' clusters. In our case the membership function parameters are extracted from the experimental data which in turn depend upon image capturing conditions. Therefore, it becomes imperative to analyze the impact of various image-capturing conditions to set optimal conditions for the extraction of parameters for DSS. Alternately, it would also give

Table 2
Image capturing parameters and their levels.

Symbol	Parameter	Unit	Level (−1)	Level (+1)
X1	Magnification		3	6
X2	Light intensity	Lux	200	600
X3	Light temperature	K	3600	5500
X4	Spatial resolution	Pixels per inch	180	90
X5	Salt and pepper noise	%	0	3
X6	Gaussian noise	dB	inf	30
X7	JPEG compression	Q-factor	100	25
X8	Yarn length	cm	2.5	5

an idea for the effect of various factors, which could be a constraint in optical features' extraction.

8.2.1. Experimental plan to test the robustness of DSS

The DSS designed for yarn classification should be robust in order to comply with real industrial scenarios such as non-standardized or poor lighting-conditions and other related parameters. Therefore, the DSS formulation should account for the variability caused by various image capture parameters and optimum for the possible industrial scenarios. In order to extract optimum parameters for the DSS, various parameters were included in this study (tabulated in Table 2). These variables are studied at two different levels coded as −1 and +1 and the corresponding values are listed in Table 2 and briefly explained further. Fractional factorial design of 2^{8-4} was used to predict optimum capturing-conditions. 16 combinations used for the study are given in Table 3.

Images were captured according to the mentioned conditions and noises were added synthetically. It should be noted that 15 images were captured for each combination of factors (given in Table 3) for each class of yarn. The selected image capturing variables are as follows.

8.2.1.1. Light intensity. In order to simulate the lighting conditions with respect to smartphone, the light intensity levels were selected according to smartphone flashlight. For example, light intensity of smartphone flash falls around 200 Lux for 5 MP at 1 m distance and increases as light source comes closer to the object [47]. Therefore, a light intensity of 200 Lux and 600 Lux were used.

8.2.1.2. Light temperature. In order to study the effect of light temperature two most common light sources were referred, i.e. tungsten light and daylight. For simulating tungsten light, a light temperature of 3600 K was used and for simulating daylight, color temperature of 5500 K was used.

8.2.1.3. Magnification and spatial resolution. Magnification of an object in the image can be calculated as a ratio of size of object in the image to the real size. The size of the object in image can be calculated by total number of pixels of divided by pixels per unit length of the image. Therefore, calculation of image magnification is a dependent variable of pixels per inch (spatial resolution), which is the property of the image capturing sensor. In this study, two magnification levels were analyzed on two different spatial resolution levels. These parameters were defined as magnification and spatial resolution in Table 2.

8.2.1.4. Gaussian noise or additive white Gaussian noise. Additive white Gaussian noise (AWGN) is introduced in the image in terms of signal to noise (SNR) ratio. Images obtained from camera were considered at infinite *dB* AWGN and a white Gaussian noise was introduced such that it accounts for 30 dB SNR as compared to the original image obtained from the camera.

8.2.1.5. Salt and pepper noise. A shot noise or salt and pepper (SP) noise of 3% level is introduced into the images, in which, randomly, 1.5% pixels were converted to highest intensity level and 1.5% pixels were converted to lowest intensity level.

8.2.1.6. JPEG compression. JPEG compression is the most common image compression technique used in various image capturing devices. Therefore, in order to study the effect, JPEG image compression was applied to the images. Images obtained from camera were considered as a quality factor (Q) of 100 represented by level '−1'. Further images were compressed to $Q = 25$ and represented by '+1'.

8.2.1.7. Yarn length. Two yarn lengths of 2.5 cm and 5.0 cm were selected for studying the effect of yarn length in captured in each image of yarn.

Further, prior to the discussion of the factor effect, it is important to specify the methodology to characterize and substantiate the distributions of various features obtained under different conditions in statistical terms. As explained earlier, overlapping of various clusters is the measure of uncertainty, and as the variability in data increases, distribution broadens and the overlap likely to increase. Moreover, when the conditions for image capturing are not appropriate, the extracted feature will spread more around the mean value and overlapping will increase. Therefore, in order to quantify the result, overlapping of feature distributions was used. Since we have multiple optical features for each yarn class, overall

Table 3
2^{8-4} fractional factorial design used for the analysis of factor effects.

Sr. no.	X1	X2	X3	X4	X5	X6	X7	X8	$\log_e Y$	$\log_e \hat{Y}$	Residues
1	−1	−1	−1	−1	−1	−1	−1	−1	5.87	5.99	−0.12
2	1	−1	−1	−1	−1	1	1	1	6.01	5.88	0.13
3	−1	1	−1	−1	1	−1	1	1	6.11	6.18	−0.07
4	1	1	−1	−1	1	1	−1	−1	5.98	5.94	0.04
5	−1	−1	1	−1	1	1	1	−1	6.03	6.07	−0.04
6	1	−1	1	−1	1	−1	−1	1	5.99	5.98	0.01
7	−1	1	1	−1	−1	1	−1	1	5.97	6.01	−0.04
8	1	1	1	−1	−1	−1	1	−1	5.95	5.84	0.11
9	−1	−1	−1	1	1	1	−1	1	6.44	6.34	010
10	1	−1	−1	1	1	−1	1	−1	6.12	6.16	−0.04
11	−1	1	−1	1	−1	1	1	−1	6.21	6.20	0.01
12	1	1	−1	1	−1	−1	−1	1	6.06	6.10	−0.04
13	−1	−1	1	1	−1	−1	1	1	6.27	6.23	0.04
14	1	−1	1	1	−1	1	−1	−1	5.94	6.00	−0.06
15	−1	1	1	1	1	−1	−1	−1	6.44	6.30	0.14
16	1	1	1	1	1	1	1	1	6.06	6.18	−0.12

Table 4
Optimum parameters extracted from images captured in best capturing conditions.

Yarn class	Twist per meter		Wrapping area (mm^2)		Wrapping helix angle (°)	
	Mean	Std dev	Mean ($\times 10^{-1}$)	Std dev ($\times 10^{-1}$)	Mean	Std dev
C2	232.2	30.5	9.14	2.40	11.1	2.4
C4	443.5	42.2	3.64	0.59	18.7	3.4
C6	669.3	44.8	2.23	0.35	26.5	2.7
C8	926.9	74.3	1.53	0.37	35.2	4.7
C10	1224.1	94.7	1.22	0.38	45.5	5.6

overlapping (Y) denoted by the sum of individual overlapping for all optical features and for all yarn classes.

$$Y = \sum_{i=1}^{C} \sum_{j=1}^{n} O_{ij} \tag{11}$$

where O_{ij} is the overlapping of ith class of yarn and jth optical feature, C is the total number of yarn classes and n is the total number of optical features.

To calculate the factor effect, we first applied regular-linear model which resulted large residues or prediction errors. Therefore, in order to minimize the residues, we further applied the log-linear model as given below,

$$\ln \hat{y} = \beta_0 + \sum_{i=1}^{F} \beta_i x_i \tag{12}$$

where $\hat{y}$ denotes the predicted overlap, β_0 denote the constant regression term, β_i denotes the first order coefficient of independent variable i (such as magnification, light intensity, etc.), x_i denotes the magnitude of ith variable, F is the total number of independent variables and in our case $F = 8$.

Further, all 16 combinations enlisted in Table 3, can be written in terms of matrix as given,

$$Y = \begin{bmatrix} \ln y_1 \\ \ln y_2 \\ \cdots \\ \ln y_p \end{bmatrix} \quad X = \begin{bmatrix} 1 & X_{11} & X_{21} & \cdots & X_{F1} \\ 1 & X_{12} & X_{22} & \cdots & X_{F2} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ 1 & X_{1p} & X_{2p} & \cdots & X_{Fp} \end{bmatrix} \quad \beta = \begin{bmatrix} \beta_0 \\ \beta_1 \\ \beta_2 \\ \cdots \\ \beta_F \end{bmatrix} \tag{13}$$

where $p = 16$ is the total number of combinations, vector $Y = [\ln y_1 ; \ln y_2 ; \ldots ; \ln y_p]$ denotes the natural logarithm of overall overlappings obtained from experimentation.

Therefore Eq. (13) can be written collectively for 16 combinations as, $Y = X\beta$. Further the unknown coefficients, β can be calculated as $\beta = (X'X)^{-1}X'Y$.

8.3. Results and discussion

Image analysis algorithm discussed in earlier section was used to extract various parameters from images conditioned by various factors, as given in Table 2. Further, the results obtained were converted into histogram and an overlapping degree for each class of yarn for each optical feature was calculated. Overlapping values are given in Table 3. It should be noted that the overlapping is the sum of overlapping of each class of yarn for all measured features. Using the earlier –mentioned method following equation has been derived:

$$\ln \hat{Y} = 6.0906 - 0.0769X_1 + 0.0069X_2 - 0.0094X_3 + 0.1019X_4 + 0.0556X_5 - 0.0106X_6 + 0.0044X_7 + 0.0231X_8 \tag{14}$$

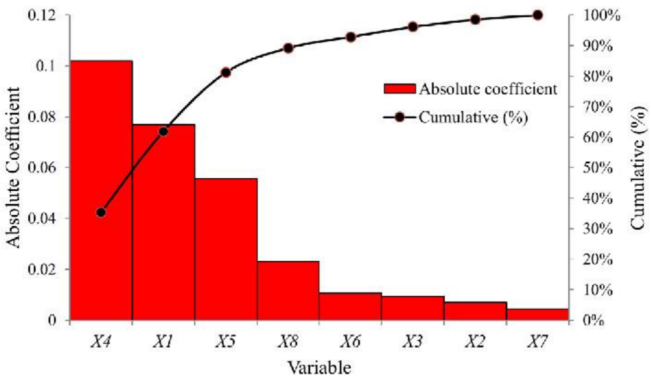

Fig. 7. Pareto graph for factors' effects.

Table 5
Overlapping of the distribution of yarn classes for images captured in best capturing conditions.

	Twist per meter	Wrapping area	Wrapping helix angle
C2	0.003	0.084	0.190
C4	0.012	0.170	0.384
C6	0.037	0.429	0.376
C8	0.109	0.841	0.515
C10	0.080	0.676	0.314
w^*	0.957	0.562	0.619

Based upon Eq. (14) the predicted overlap is listed in Table 3 and the *Pareto* graph is shown in Fig. 7.

It can be inferred from Fig. 7 that X_1, X_4, X_5, X_8 are the main affecting parameters capable to account for ~90% of the total variance, while the rest of variables account for remaining 10% variance and therefore latter were removed from consideration. Further, in order to extract best possible parameters for DSS, image capturing parameters were selected such that they minimizing the Eq. (14). The selected levels' combination was, magnification $X_1 = +1$, spatial resolution $X_4 = -1$, S&P noise $X_5 = -1$, and yarn length $X_8 = -1$. In this case, 30 image of each class of yarn were captured under above-mentioned conditions and optical features were extracted using aforesaid image processing algorithm. Results obtained are listed in Table 4.

Further in designing the DSS, the overlapping of all optical features would be required for the adjustment of weights (w). Therefore, in order to calculate the overlapping, first the mean values and standard deviations were converted into Gaussian distributions and then the overlappings were calculated. The calculated overlapping is listed in Table 5.

8.3.1. Adjustment of weights for DSS

In order to adjust weights in DSS, a fuzzy system was made according to the procedure given in Section 7. Since there were five classes of yarn, five input fuzzy variables were defined. The output was defined as a fuzzy output variable as shown in Fig. 6(b).

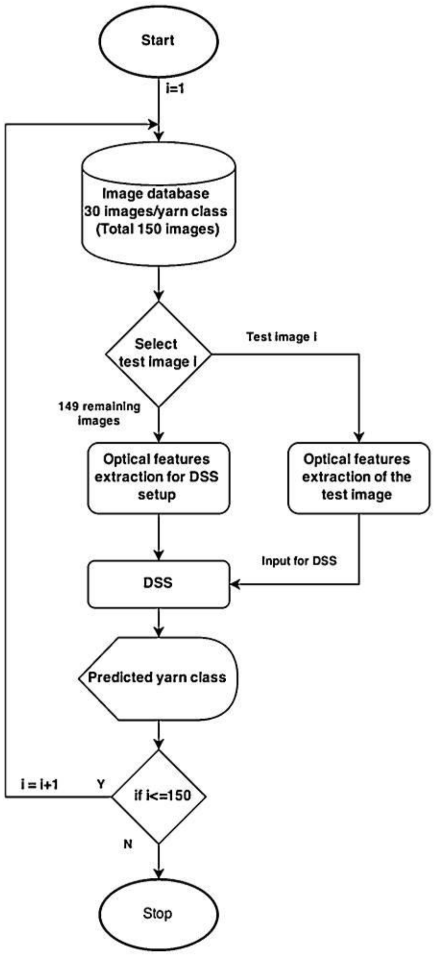

Fig. 8. Flowchart for leave-one-out cross validation.

Further, the adjusted weights obtained by defuzzification are listed in Table 5.

8.3.2. Validation

The validation of developed DSS is an important criterion to analyze the robustness in decision making. Here, the validation was carried out by following leave-one-out cross-validation method. In this method, one test image of yarn was selected and various membership functions were generated by keeping the selected test image out of consideration, as shown in Fig. 8.

Despite of overlaps for the distributions of optical features for various yarn classes, a 100% success rate was obtained in the yarn class prediction. The outstanding success rate of DSS may be attributed to the reason that in a wrapped yarn image, wrapping appears multiple time. Therefore, when the wrappings are analyzed and averaged for the extracted feature, it leads to the reduction of variability and drifts towards the center of distribution or away from the overlapping. Furthermore, the exceptional classification of yarns based upon their features makes them a suitable candidate for information tagging in fabrics.

9. Conclusions and future scope

In this paper, we have originally introduced the idea of the traceability system using fully textile integrated tags, for monitoring activities at the different textile production stages. As the first step of the system development, we have coded a number of yarns by controlling several optical features for casting traceability in the textile structure. Three sets of twist-dependent optical features, namely, twist distance, wrapping area and wrapping helix angle, pertaining to a wrapped yarn were selected for generating different yarn codes. For the yarn code identification, an image processing algorithm has been used for extracting the selected optical features from an unknown coded yarn and identifying its yarn class using DSS. Out of the three selected optical features, twist distance came out as most distinctive feature having maximum contribution in recognition. During the validation of the recognition system by leave-one-out cross-validation method, the success rate of 100% has been obtained.

Furthermore, it is anticipated that the integration of these yarns in a textile structure in a unique sequence can convert a normal textile into a coded textile where the identity of the tag can be formed by combining different yarn code classes. Therefore, future studies can be focused on the integration of coded yarns in different textile structures (from textile design perspectives) and extraction of optical features (image pattern recognition techniques, use of other decision support systems to build a relation between optical features and coding) to retrieve information from textile-integrated coded yarns. Since the coded yarn features are extractable from a continuous length of yarns, therefore the fabric design perspectives can be explored to integrate the coded yarns such that they appear without any interlacement or inter-looping for extracting optical features from the textile surface. The yarn-tagging created during the fabric manufacturing will leave a visible impression on fabric surface. Therefore, it could be challenging for designers to accommodate the yarn-tagged region of the fabric without having any impact on garment design. From real manufacturing scenarios, future studies can also be focused on automatic selection of coded yarns' sequence on knitting or weaving machines for generating a predefined or time-varying code.

The presented yarn coding, classification and identification methodologies open the potential applications not only to woven and knitted fabrics, but also to seamless garments, which are manufactured in a single step, directly from yarns into the final garment. The coded yarns can be directly inserted into the garment during the manufacturing process therefore the resulting garment can not only be traced throughout the supply chain and but also after the point-of-sale. Similarly, the application of coded-yarns (similar or different optical features) based tracking can be explored in transparent composites where yarns are used as reinforcement and are visible on composite surface.

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Paper III

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Technical Paper

Coded yarn based tag for tracking textile supply chain

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ABSTRACT

Traceability has gained considerable attention to facilitate monitored production, product recall, safety and reverse supply chain activities, in recent years. Traceability in manufacturing and distribution involves the use of tracking tags which are attached to the products; consequently, the products are tracked by recording the identity of attached tracking tags in the supply chain. In this context, this paper introduces a new yarn coding-based tracking tag which is fully integrated into textile for tracking the textile supply chain. The new tracking tag involves the use of special yarns which act as information carrier and basic unit of the tracking tag. An implementation scenario is discussed to use the designed tracking tag to monitor the production and authentication purposes. Real prototypes of the fully integrated coded yarn based textile tags are demonstrated in woven and knitted structures and analysed under the effect of washing treatments to simulate realistic conditions. Further, an image pattern recognition based algorithm has been introduced and analysed to extract the information encoded in the tag using coded yarns.

1. Introduction

Traceability is one of the growing concerns and has gained considerable attention for monitored production, quality inspection, recalling, safety, reverse supply chain activities and comply with regulations [1–4]. The modern textile industry is no exception to this due to its fragmented and complex supply chain networks, consisting diverse material suppliers, manufacturers, buyers, and retailers [5–7]. Currently, the majority of the textile-manufacturing is limited to a few developing countries, including, China, India, and Bangladesh, while developed countries are major importers [8–10]. This industrial shift has resulted in a geographical separation among various actors involved in the production and retail; consequently, the transparency in production and distribution has diminished [5,10]. In this context, traceability – which allows various actors in the manufacturing, distribution, and retail to monitor products and product-history beyond their scope – is gaining importance. This is further reinforced by government regulations and customer demands for product history [11,12].

Traceability in the textile industry is implemented by means of tracking tags such as radio frequency identification tags (RFIDs) [13–17], barcodes and QR codes [7,18]. These tags carry unique-ids and are attached to textile products. The footprint of a product is thus tracked in the supply chain by recording the ID of attached tag. Barcodes (1D and 2D) are simple printed machine-readable patterns where information is encoded using graphics, and offer low manufacturing cost and robust readability. They are widely used in many commercial applications including warehousing and transportation. On the other hand, an RFID contains electronic microchip and antenna coil, where former holds the memory of the tag [19]. RFIDs offer large data capacity and non-contact and hidden read-and-write capability. More sophisticated RFIDs also contain additional sensors for smart applications such as automatic recording of temperature and humidity [20]. RFIDs have also been utilized for conveying care labelling information [21]. Despite above-mentioned features of RFIDs and barcodes, there remain some concerns which hinder their full utilization. For example, both barcodes and RFIDs possess low security again copying and reproduction, which means an identical tag can be easily reproduced and placed with a counterfeit product [22]. The tracking tags are removed at the point of sale (POS). Therefore it becomes difficult to trace back the history of a textile product after POS. In this context, EC expert panel for traceability recommends using tracking

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tags integrated physically into the product itself, which not only extend traceability beyond POS but also helps in applications such as sorting during recycling [12]. Integrated form of RFID in textiles can be used in other applications such as care labelling and product return. However, as RFID tags broadcast their serial number to nearby reader, therefore, RFID embedded item can be used to track the user, which creates privacy concerns [21,23]. Textile with embedded chips creates problems in automatic shredding in textile recycling process [24].

Considering the limitation offered by existing tracking tags, this paper focuses on introducing and developing a new textile integrated tagging to implement traceability. We believe, integrated tagging in textiles can be approached via two routes i.e. using foreign materials integrated into fabrics and tagging the fabrics by using fibre-based traceable components. Here integrated means non-detachable, therefore printing of fabric with readable pattern can be an example of foreign material based tagging. However, the easy cloning of the pattern can be a deterring factor for its implementation. The component-based tagging approach has recently gained considerable attention. In this approach, the components are designed in such a way that they produce inherent traceability. For example, Xin et al. [25] use yarn and woven structure to generate a code on the fabric surface during its manufacturing, whereas Blankenburg et. al [22] propose to generate identification signature based upon fabric's inherent features including visual texture, structure, and odour. The component-based approach uses a two-step process where the first step includes selection and designing of components which can inherently create traceability, and the second step includes modification of the manufacturing process to implement the designed component in the production to utilize their traceability property. Individual components act a fundamental unit for traceability, however, they do not contribute to traceability unless they are strategically incorporated into the product during the manufacturing process to generate useful information.

The textile fabrics, excluding nonwovens, essentially consist of yarn as the fundamental unit. Therefore the route to approach component-based textile tagging goes through the development of yarn components first and then the development of textile manufacturing process for its implementation. Yarns can be further formed from the fibres or combining two or more yarns. In the earlier work [6], we have introduced the concept of yarn coding, which covers the step one of component-based traceability. Yarn coding is a technique to introduce optical features in the yarns in a controllable manner. We have implemented the yarn coding using twist-based optical features of yarn which can be generated on a hollow spindle frame. Further, a decision support system was developed to identify the individual yarns based upon their optical features.

This paper covers the second step of traceability, hence it utilizes the previously developed concept of yarn coding and introduces the concept of textile-integrated tags for woven and knitted fabrics. As mentioned earlier, this step includes the manufacturing strategy to use the yarn-coding technique to introduce traceability at fabric stage and then the strategy to extract the coded information to use in the real world applications. We further experimentally fabricate the integrated tagging in woven and knitted textiles and then validate by applying different testing conditions. Since the yarn coding is a technique to introduce optical features, therefore, to decode these optical features at the fabric scale a pattern recognition algorithm is introduced and tested for decoding the information encoded in the tags. The tag consists of all features required for a traceability tag, such as integration into textile, uniqueness, easy authorized production and difficult unauthorized reproduction [6]. Yarn based tags can have certain advantages over other tags. For instance, coded yarns used for manufacturing act as an integral part of textile, therefore they cannot be removed without damaging the associated textile. Textiles have unique feel-features which make them suitable for wearing. Embedding sensors like RFIDs in textiles result in altering their feel. Whereas, coded yarns are normal textiles yarns and integrating them in textiles will result in normal textile feel. Furthermore, RFIDs or other electronic sensors cannot be processed in textile recycling due to their harmful impact [24], while yarn based tags can be recycled without any such problems.

The following parts of the paper are organized as follows. Section 2 describes the concept and design of proposed yarn-based traceability tag. Further, this section describes the implementation strategy in the industrial context. Section 3 describes the procedure for information coding in the proposed tag. Section 4 describes the tag identification and information decoding using pattern-based image analysis. Materials and method used for producing the yarn-based tag are discussed in Section 5 and experimental results obtained from the prepared tag samples are shown in Section 6. Finally, Section 7 concludes the paper and presents the future scope.

2. Concept and implementation process

2.1. Concept

The concept of implementing traceability presented in this work is to tag the textiles during the manufacturing process. This uses special yarns (hereafter called *coded yarns*) embedded in textiles to produce *in situ* traceability marker/tag [6,26]. As yarns are the integral parts of textiles, they can act as a fundamental unit of traceability tag. Coded yarns contain special optical features; consequently, when assembled to textiles, they create an optical stamp or pattern for traceability. In the earlier work [6], it has been demonstrated that robust optical features can be created in a controlled manner in a wrapped yarn assembly. The methodology for production and nomenclature about these yarns are briefly discussed in Section 3. The tag is created using a combination of coded yarns having different and distinguishable optical features (hereafter called *yarn classes*). Therefore, the unique ID of the tag is introduced by using a unique combination of coded yarns belonging to different yarn classes. Further, for the information retrieval, the combination of yarn classes is predicted from the coded yarn feature pattern available on the fabric.

2.2. Design

Design strategy followed for yarn based traceability tags in textiles using coded yarns is somewhat similar to that of barcodes. Barcodes consist of parallel lines having different widths [27]. A line with a combination line-width and inter-line spacing represents a digit, and a set of lines represents the full code. As it is well known that, textiles used in apparel applications are majorly divided into two structures, namely woven and knitted, and they are made-up of yarns. Therefore, some regular yarns can be replaced with the coded yarns to make tracking tags. Analogous to barcodes, which contain lines with different widths, textile tags can be made-up of coded-yarns having different optical features; therefore a coded-yarn represents a digit, and the sequence of all coded yarns represents the full code. Further, the full code can be altered or controlled by changing the coded yarns' sequence in the textile. The following sub-sections discuss the design strategy for coded yarn insertion in woven and knitted structures.

2.2.1. Woven structure

Woven structure consists of two-set of yarns known as warp and weft, interlaced orthogonal to each other (as shown in Fig. 1(a)). The sequence of weft yarns can be controlled during the textile weav-

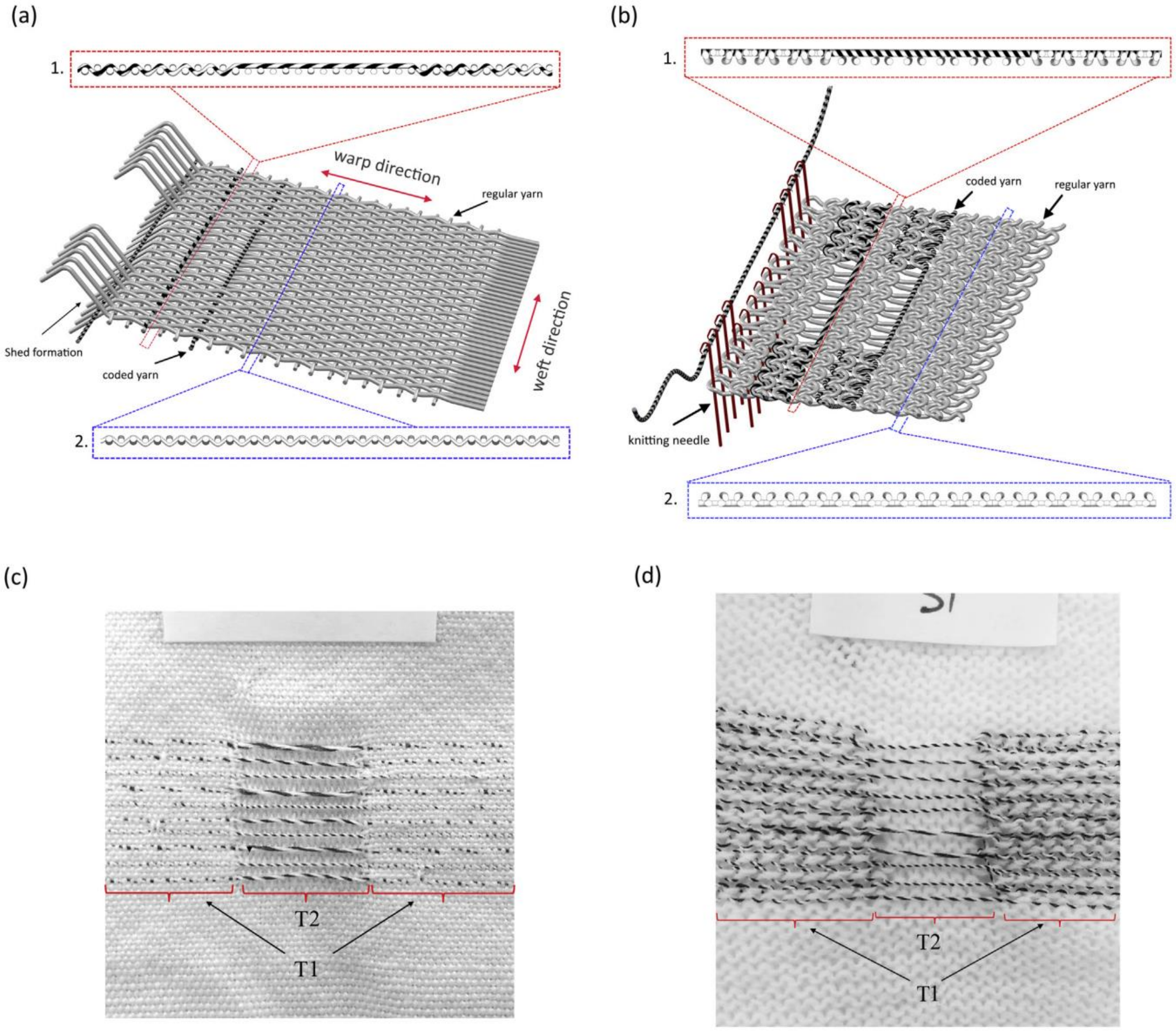

Fig. 1. Proposed (a) woven and (b) knitted structure designs for integrating regular textile with integrated yarn based traceability. Actual produced (c) woven and (d) knitted textiles with integrated coded yarns. Region T1 represents the texture formed by coded yarns embedded inside the structure and T2 represents the texture formed by readable coded yarns..

ing process, whereas the sequence of warp yarns remains fixed for a cloth roll. Therefore, the coded-yarns can be used as weft yarns, and inserted in a predefined sequence into the warp yarns. As warp and weft yarns interlace each other, therefore the one set of yarns in a regular structure appear partially occupied by other yarns (as shown in inset 2 of Fig. 1(a)). Consequently, to make optical features of the coded-yarns visible, a longer float can be used where weft yarn makes no interlacing with the warp yarns (as shown in inset 1 of Fig. 1(a)), therefore the coded yarn appear continuous on one face of fabric. However, the float length should be long enough to extract the yarn features. Between two coded yarns, normal yarns (one or more) can be inserted to separate them. The real woven structure formed using such designing strategy is shown in Fig. 1(c).

2.2.2. *Knitted structure*

Knitted textiles are formed by intermeshing of loops of yarns to form a sheet-like structure. The basic unit of a knitted textile is known as stitch, which can be defined as loop of a yarn passed through the another loop of yarn, using knitting needles as shown in Fig. 1(b). A stitch can be divided into three types, namely normal, miss or float, and tuck. A miss stitch or float is one where the yarn does not pass through the loop formed by the other or the same yarn; therefore it appears continuous/straight on one face of the fabric (as shown in inset 1 of Fig. 1(b)). In order to make an integrated tag in knitted textiles, few yarns can be replaced with the coded yarns and knitting is done in such a way that coded yarns-based miss stitches appear together. Similar to the woven structure, regular yarns can be used between two consecutive coded yarns to separate them. A prototype of such tag is shown in Fig. 1(d).

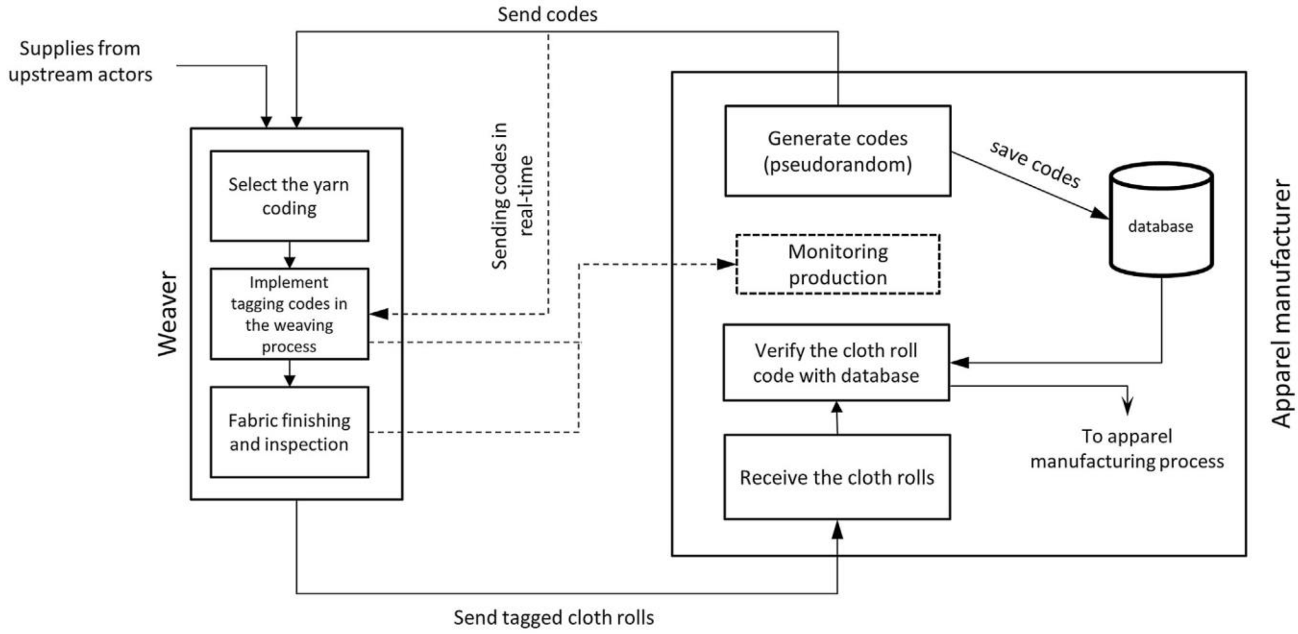

Fig. 2. Implementation framework for textile integrated tag.

Further, a reference coded yarn with known optical features can be inserted at a known location inside the tag. Therefore, the optical features of other coded yarns can be normalized *w.r.t.* the reference yarn to convert optical features into scaled parameters for the recognition system.

2.3. Implementation in the industrial context

The proposed integrated tagging forms an optical stamp over the surface of a fabric, which can be used for tagging. However unlike RFID, once this tagging is formed, it cannot be modified or taken out of fabric because of its integrated form. The integrated form brings security to the product [12], however, it needs advance planning. For example, Fig. 2 shows the implementation of integrated tag in weaving process and the code is handled by the apparel manufacturer.

Apparel manufacturer generates pseudorandom codes in advance for the cloth rolls which is to be manufactured by the upstream supplier i.e. the weaver. This pseudorandom codes can be a time-varying function or encryption of serial numbers and the encryption key or time varying function is handled by the apparel manufacturer. Hence for the weaver, these codes appear as randomly varying numbers. The apparel manufacturer can send all the codes to the weaver before manufacturing starts. Therefore, weaver selects the appropriate yarns and implement the received codes during the weaving process. The other way could be sending the codes in the real-time, directly on the weaving machines during the manufacturing process, therefore weaver does not own or know the code before manufacturing. In the real-time implementation, the apparel manufacturer can directly monitor the production at the weaver as well. Furthermore, the code can be scanned in the future processes such as fabric finishing and inspection hence the scanning logs can help the apparel manufacturer to monitor the supply chain. When the apparel manufacturer receives the supplies, he needs to cross-varify the codes on cloth rolls with the generated codes stored in the database. Once the codes match, apparel manufacturer forward the cloth rolls to next process; however, if any of the codes mismatches, it means the weaver produced cloth roll is not original and has been replaced in the supply chain. It is also important that the weaver receives the codes from apparel manufacturer via a secured communication so that no third party can copy them. The proposed implementation does not provide an absolute power to the weaver because firstly he is dependent on yarn manufacturer for yarn coding and apparel manufacturer for tag codes. This is particularly important for sectors like textile where the brand owner outsources their production activities to offshore manufacturer. It is well acknowledged that if offshore manufacturer has an absolute power, then there are chances that he can produce similar copies (or counterfeit) and sell directly in the market. Therefore, the introduced implementation distributes the power among different actors, hence a single actor in supply chain cannot control it.

3. Tag coding procedure

The principle behind the yarn based tracking tag is the generation of an optical stamp on a fabric using coded yarns. The optical features of coded yarns should be stable so that individual yarns can be identified in the textile. Coded yarns of different optical features (hereafter called *coded yarn classes* or *yarn classes*) should be identifiable based upon their optical features. In our earlier work [6,26], we have shown that robust optical features namely, wrapping helix angle or wrapping angle, wrap area and inter-wrap/twist distance can be generated when one yarn (hereafter called *wrapping yarn*) is wrapped around other yarn (hereafter called *core yarn*). This kind yarn can be made on hollow-spindle spinning-frame, where one yarn (wrapping yarn) is wrapped around the other yarn (core yarn) and the twist density decides the optical features. Fig. 3 shows the schematic of wrapped yarn assembly and Fig. 1(c) and (d) shows the real wrapped yarns integrated into the textile fabrics. The detailed information regarding nomenclature can be found in [6,26].

The optical features of coded yarns act as the identity of the tag. Therefore, for decoding, coded-yarn should be identifiable and distinguishable based upon its optical feature. However, yarn is

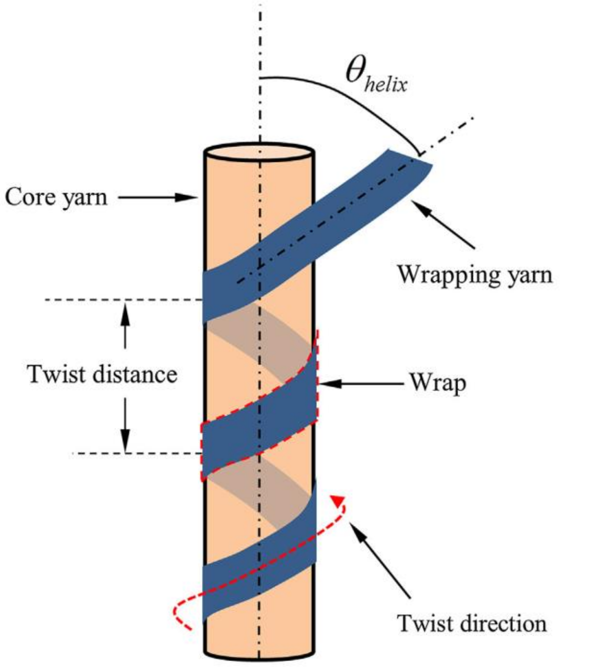

Fig. 3. A cartoon depicting the wrapped yarn assembly. θ_{helix} is the angle between wrapping yarn axis and core yarn axis.

flexible and irregular fibre assembly, therefore, the optical features vary in certain range. Nevertheless, optical features of coded yarns having different twists (yarn classes) exist in clusters; therefore, coded yarns can be classified based upon their membership to various feature classes. Based upon the optical feature distribution, the membership function for a yarn class can be written as [6],

$$d(x,\mu_1,\mu_2,\sigma') = \underbrace{\frac{1}{\sigma'\sqrt{2\pi}}\int_{-\infty}^{x} e^{\frac{-(x-\mu_1)^2}{2\sigma'}}dx}_{A} \times \underbrace{\left(1-\frac{1}{\sigma'\sqrt{2\pi}}\int_{x}^{+\infty} e^{\frac{-(x-\mu_2)^2}{2\sigma'}}dx\right)}_{B} \quad (1)$$

$$\mu_1=\mu-2.25\sigma,\quad \mu_2=\mu+2.25\sigma,\quad \sigma'=\frac{2.5\sigma}{3.129}$$

where, μ and σ are the mean and standard of the optical feature cluster $0<d<1$.

Eq. (1) is formed by the combination of increasing and decreasing Gaussian cumulative distribution functions (GCDFs), represented by A and B respectively. These GCDFs define the initial and final regions of a feature cluster, therefore separating from neighboring clusters. In case a cluster has a probability to overlap only from one direction, then depending upon the direction of overlap, A or B is replaced with unity. For example, a coded yarn with highest twist, has the probability of overlap only from comparatively low twisted yarns, therefore, B is replaced unity while vice-versa is true for lowest twisted yarn.

Furthermore, multiple yarn classes have multiple optical features therefore, the membership value for ith optical feature of jth yarn class can be written as d_{ij}. The aggregated membership values to various yarn classes can be calculated by,

$$Y_j=\left(\prod_{i=1}^{n}(d_{ij})^{w_i}\right)^{1/\sum_{i=1}^{n}w_i} \quad (2)$$

where w_i is weight assigned for ith optical feature and $0\le w_i\le 1\forall i\in[1,n]$, n is the total number of optical features,

The most relevant class c corresponds to the maximal value of all Y_j s, i.e.

$$Y_c=\max\left\{Y_j|j=1,2,\ldots,C\right\} \quad (3)$$

where C is the total number of yarn classes.

If a unique number is assigned to each coded yarn class, then a predefined sequence of coded yarns produces a series of numbers which acts as tag's code. Examples of different coded yarns integrated into the woven and knitted structures are shown in Fig. 1(c) and (d) respectively. Here coded yarns' sequence in vertical direction represents the tag code.

4. Pattern recognition algorithm for tag decoding

Tag decoding implies the extraction of information encoded in the tag by means of coded yarns. It involves multiple objectives, including tag detection, extraction and decoding the coded yarn's optical features. For the successful decoding, positions of coded yarns should be precisely located detected. Since, the coded yarns have certain optical features, which are visible on a fabric surface. Therefore, a pattern recognition algorithm can be designed to locate the tag on fabric surface using the coded-yarn based visible pattern. Based on the observations made from yarn tags shown in Fig. 1(c) and (d), we select certain predefined coded yarn *patterns* that are supposed to exist on the fabric if coded yarns are integrated, as given below,

Pattern 1. Coded yarns appear linear in the region where they make no interlacement or inter-looping; therefore the spatial linearity in the texture details exists in the tag region.

Pattern 2. Two consecutive coded yarns are nearly parallel to each other and well separated from each other.

Pattern 3. Coded yarns leave a strip of visible impression on the fabric surface.

Pattern 4. Coded yarn features are high-frequency contrast features as compared to the rest of fabric.

Pattern 5. Regions above and below the coded yarn do not contain a significant pattern as compared to that of coded yarn makes.

Pattern 6. Coded yarns are horizontal or nearly horizontal in the image.

Further, two error stops were selected in tag decoding process in order to avoid the wrong decoding.

Error 1. Errors occurred during the search of the tag location on the fabric surface. It will cover the following situations:

- The linear pattern (Pattern 1) is not available or linear pattern does not have a sufficient degree of confidence.
- Float yarn region (Pattern 2) could not be traced in the probable tag region.
- Decomposition of coded yarns float region into individual yarns could not be done or the number of decomposed yarns is mismatching the number of yarns available.

Error 2. This consists of errors that can after *Error 1* i.e. during the decoding operation of the tag. *Error 2* includes situations in which it is difficult to identify the yarn class.

These error stops will be helpful in stopping the algorithm to save machine resources and/or avoid incorrect output. Further, there are some *checks* introduced in the algorithm to reject possible ambiguity in the pattern recognition (discussed later). The flow diagram of the algorithm is given in Fig. 4. A detailed stepwise explanation is given as follows.

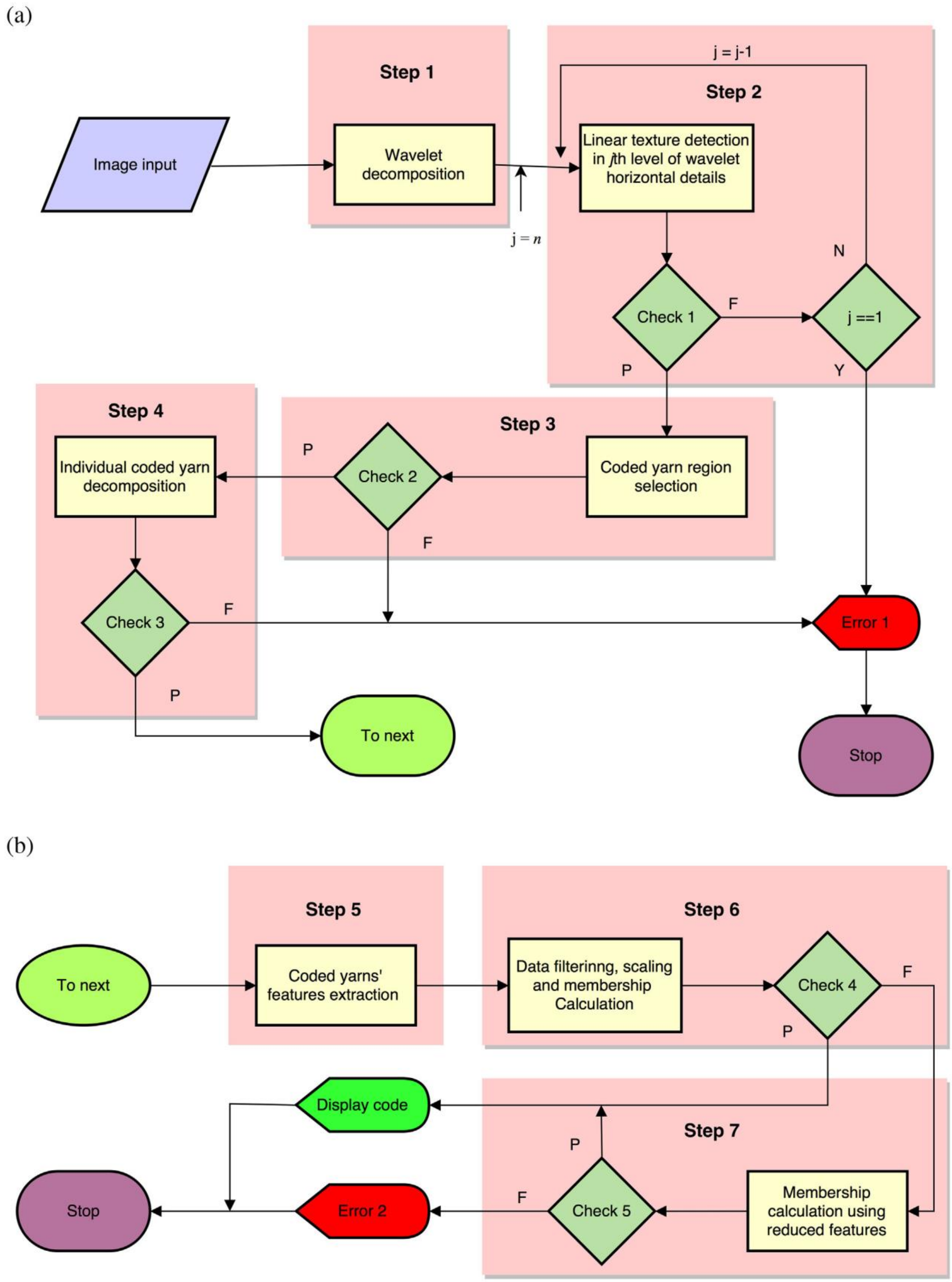

Fig. 4. Flowchart for tag location search and decoding. Here (a) demonstrates the steps for coded yarn pattern recognition and decomposition into individual coded yarns and (b) demonstrates the steps for extraction of features and their conversion into tag code. In the flow diagram P: pass, F: fail, Y:yes and N: no.

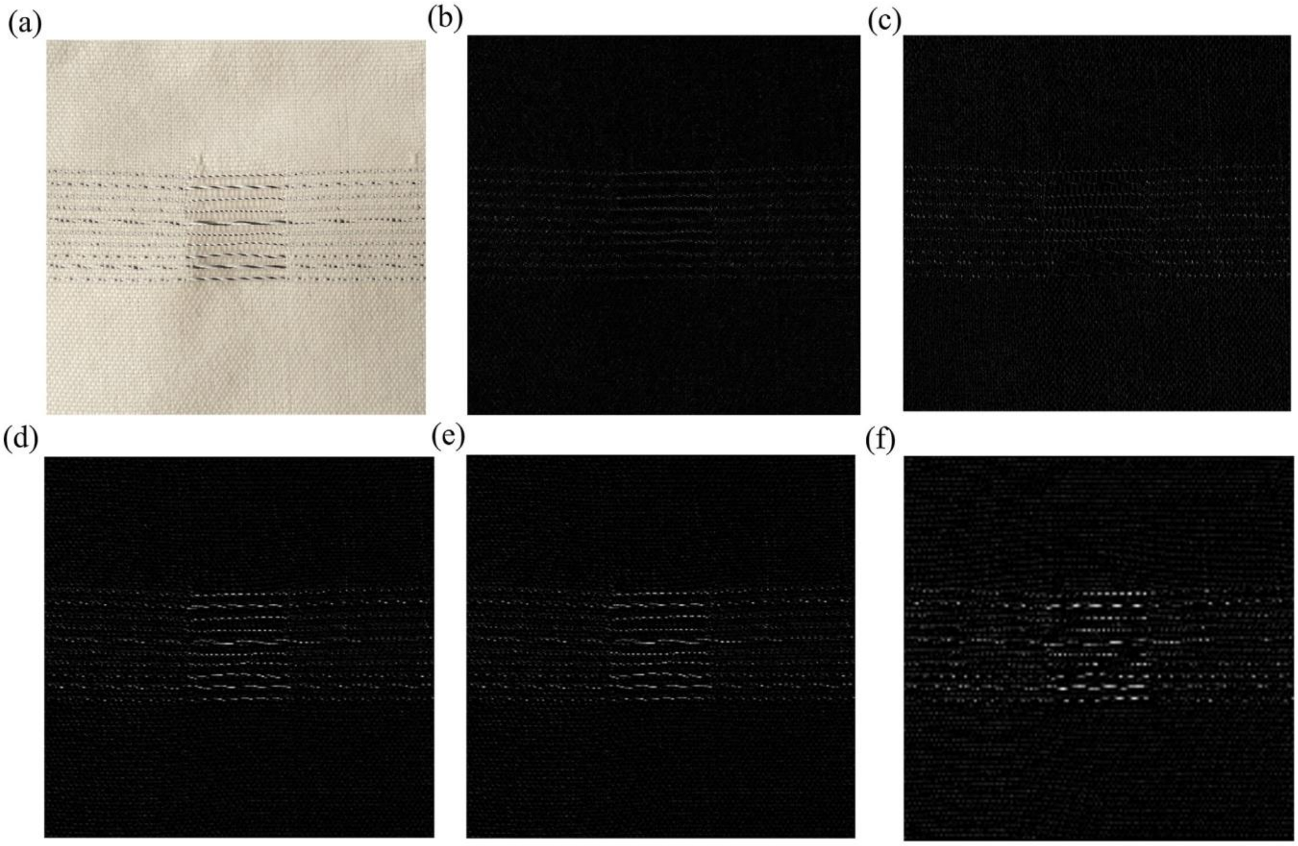

Fig. 5. Wavelet decomposition at different levels. Here (a) shows original image, (b)–(d) show the vertical, diagonal and horizontal details, respectively at wavelet decomposition level 1, (e)–(f) show the horizontal details at wavelet level 2 and level 3. (Images rescaled for illustration).

4.1. Step 1: Wavelet decomposition for tag feature extraction

Wavelet decomposition is a multiresolution-based image analysis used to analyse the information content of an image by fragmenting it at different scales [28,29]. Discrete wavelet transformation is applied on a digital image using I is done using a wavelet function resulting wavelet coefficients, W, and a synthesized I_s. W consists of three coefficients namely horizontal coefficient W_h which contains horizontal image details, vertical coefficient W_v which contains vertical image details and diagonal coefficient W_d which contains diagonal image details. Further, I_s is used as the input image for next level of wavelet analysis. In the past, a large number of wavelet functions have been developed for different purposes, such as Haar wavelet for edge and image details extraction and Daubechies wavelet for image compression [30]. In our case, coded yarns on fabric have distinct features from remaining fabric (as shown in Fig. 5(a)) which is reflected in term of high variation in grayscale values. These features are thus extracted from the image using Haar wavelet [31], which retrieves pixels' grayscale changes in wavelet coefficients. Extracted wavelet coefficients for image Fig. 5(a) are shown in Fig. 5(b)–(d). The coded yarns in Fig. 5(a) carry optical features which are horizontally aligned, therefore, Fig. 5(d), which represents horizontal image details, has most prominent features whereas vertical (Fig. 5(b)) and diagonal coefficient (Fig. 5(c)) show comparatively less details.

The extracted details are often sensitive to image noise or fine texture; therefore, the coded yarn details may get diluted if the fabric has a very fine texture or other noise source. Nevertheless, multiple resolution analysis by wavelet provides an opportunity to compress the image noises and fine details. For example, Fig. 5(d)–(f) shows the horizontal image coefficients decomposed at 1–3 scales. It is evident that higher scale coded yarns features are more prominent. Furthermore, going to a very high level may lose the pattern details significantly. In this study we analyse first three wavelet scales i.e. n in Fig. 4(a) is 3.

4.2. Step 2: Linear texture detection

As it is already mentioned that according to Pattern 1, the texture made by coded yarns in the fabric possess a spatial linearity as coded yarns are integrated in the fabric. Therefore, the texture details coming from wavelet coefficients should possess linearity as seen in Fig. 5(d)–(f). In this step, the texture features extracted using wavelet decomposition are confirmed for linearity. The linearity in texture (such as edges) of an image can identified by applying Hough's transformation on a binary image having edge details only [32]. Therefore in this step we firstly convert the wavelet horizontal coefficients, W_h obtained from last step converted into binary levels 0 and 1 given as,

$$W_{hb}(i,j) = \begin{cases} 1 & \text{if} \quad W_h(i,j) > t \\ 0 & \text{if} \quad W_h(i,j) < t \end{cases} \tag{4}$$

where t is the threshold that can be calculated using technique given in Ref. [33].

Fig. 6(a) and (b) shows the original image and binary image produced from the wavelet coefficients of original image. The image details in the binary image depend on t, which further depends upon wavelet coefficients. As aforementioned, these coefficients are sensitive to image details and noise. For example, Fig. 6(c) shows

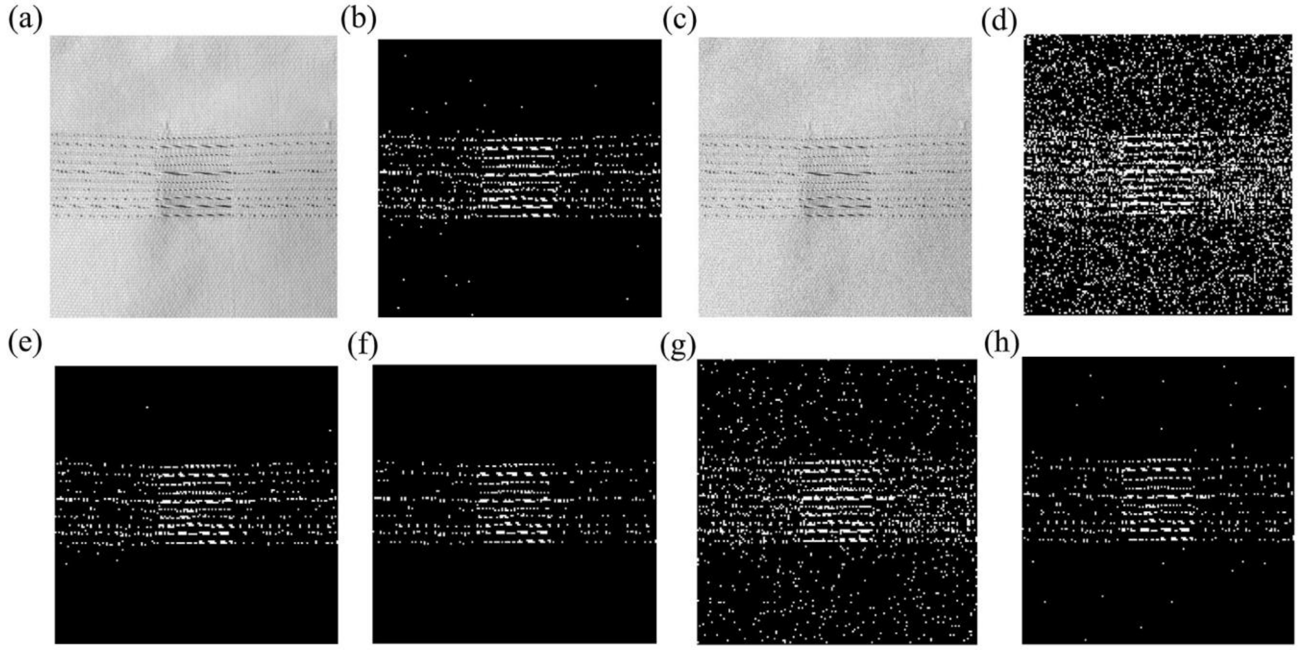

Fig. 6. Horizontal wavelet coefficients conversion into binary level images. Here (a) represents original image whereas, (b) represents binary image formed from wavelet coefficients of (a) considering all wavelet coefficients. (c) Shows the images with Gaussian noise of 0.01 variance and (d) shows the corresponding binary image resulting from all wavelet coefficients of (c). (e) and (f) show binary images from 85% and 70% horizontal wavelet coefficients of (a), respectively. Similarly (g) and (h) show the binary images formed wavelet coefficients of (c). (Images rescaled for illustration).

Fig. 6(a) with additive white Gaussian noise with variance 0.01, and the corresponding binary image obtained using Eq. (4) in shown in Fig. 6(d). It is noteworthy that Fig. 6(d) contains addition details, which belong to noise (since these details are not visible in Fig. 6(b)).

This issue can be minimized by increasing *t*, i.e. removing some weak wavelet details and then converting into a binary image. Effect of removing these details can be seen in Fig. 6, where Fig. 6(e)–(f) show new binary images for the non-noisy image (Fig. 6(a)) by removing 15% and 30% of wavelet details. Fig. 6(g)–(h) show binary images after eliminating 15% and 30% of wavelet details generated from Fig. 6(c). There is a significant improvement in noisy-binary images whereas the non-noisy images do not show any significant reduction in image details. Therefore, few wavelet details can be discarded while calculating threshold *t* using Otsu method [33].

Further, the linearity of the texture is confirmed by applying Hough's transformation of the binary image. The principal behind Hough transformation is to convert the high-level pixels of a binary image from 2*D* Cartesian coordinates (x,y) into polar coordinates (ρ, θ) with the following relation$\rho = x\cos\theta + y\sin\theta$ [32]. Here, θ is restricted to the interval $[0, \pi)$ which results to form a unique point (known as *Hough's peak*) on $\rho - \theta$ plane for all mutually linear points in *x-y* plane. Hence, the Hough transformation is applied on W_{hb}, and collinear image details are identified using Hough's peaks [32,34]. Fig. 7 shows the identified coded yarn region (Fig. 7(b)) based upon 15 Hough's peaks (shown in Fig. 7(a)) for the image shown in Fig. 6(a).

Further, if there are *N* coded yarns in the tag, we analyse top *p* ($p \geq N$) Hough peaks in order to cover all *N* yarns. The orientation of the Hough peaks in our case should be nearly horizontal ($\pm 15^0$) because coded yarns are horizontally aligned in the image (pattern 6). Further, a predefined number of peaks should point out the horizontal alignment for a confident decision, which is confirmed by *Check 1* (Eq. (5)).

Check 1

$$check\,1 = \begin{cases} P & if\ n_p \geq K \\ F & otherwise \end{cases} \tag{5}$$

where n_p is the number of peaks with alignment $\pm 15^0$, *K* is the peak threshold number such that $K \leq N$. In this study we have 10 coded yarns in each tag and we use K = 5.

Once the *Check 1* passes (*P*), region with horizontal lines represents the probable location of the yarn-based tags. Therefore, the original input image can be cropped to the area bound by the Hough lines, as shown in Fig. 7(b).

However, if the *Check 1* fails on *j*th level of wavelet which is probably due to the lack of details, the above procedure is repeated on *j* = *j-1*th level which contains more wavelet details. This procedure is repeated until either *Check 1* passes, or the current wavelet decomposition scale is unity.

4.3. Step 3: Yarn floats detection

Coded yarns are embedded in the fabric in such a way that they make certain float. This arrangement generates two different textures in the coded yarn region, one in the region where coded yarns are fully embedded inside the fabric (say T1) and second where the yarn floats/miss-stitches are available (say T2) as shown in Fig. 1(c)–(d). Further, T2 is horizontally surrounded by T1. Therefore, in order to identify T2 region, a horizontally variance profile *f* of the coded yarn region is calculated, where the variance of *k*th row of the image can be computed as,

$$f_k = \frac{1}{(h \times x) - 1} \sum_{i=k-(w/2)}^{k+w/2} \sum_{j=1}^{h} \left(x_{ij} - \bar{x}\right)^2, \quad \bar{x} = \frac{1}{h \times w} \sum_{i=k-(w/2)}^{k+w/2} \sum_{j=1}^{h} x_{ij} \tag{6}$$

where *w* is the width of the variance window, *h* is the height of cropped region which is identified using Hough transformation, x_{ij} represents the pixel intensity of pixel present in *i,j*th position in the cropped region.

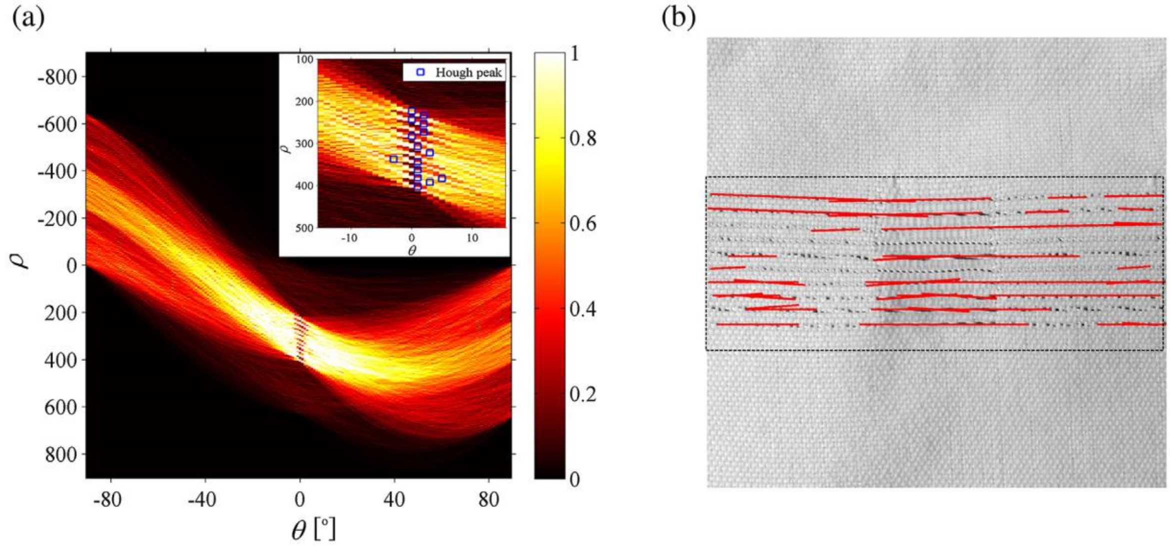

Fig. 7. Detection of coded yarn region using Hough's transformation. Here (a) shows the Hough peaks formed for the image and the magnified window shows top 15 Hough peaks and (b) shows the coded yarn detected using top 15 Hough peaks.

The transition region between T1 and T2 is detected by locating the high absolute magnitude change between consecutive extrema of the variance vector *f*. Assuming Γ $\left(\Gamma = \Gamma_{x_1}, \Gamma_{x_2}, \ldots, \Gamma_{x_l}\right)$ vector represents the magnitudes at local extrema of *f* at locations *x* ($x = x_1, x_2, \ldots, x_l | x_1 < x_2 < \ldots < x_l$) then,

$$\partial_i = |\Gamma_{x_{i+1}} - \Gamma_{x_i}| \quad \text{and} \quad X_i = \frac{x_{i+1} + x_i}{2} \tag{7}$$

Therefore, the coded yarn floats or miss-stitches texture bound to transition regions (S_1 and S_2) can be detected by the following equation,

$$S_1 = X_k | \partial_k = \max_1(\partial) \quad \text{and} \quad S_2 = X_k | \partial_k = \max_2(\partial) \tag{8}$$

where $\max_1(\partial)$ and $\max_2(\partial)$ represent the first and second maximum values of the vector ∂ $\left(= \partial_1, \partial_2, \ldots, \partial_{l-1}\right)$.

An example of readable coded yarn region, i.e. T2 is shown in Fig. 8. Fig. 8(a) shows the image extracted using Hough peaks in Step 2. Fig. 8(b) shows the horizontal variance profile for Fig. 8(a) using Eq. (6). It can be seen that the variance of T2 is higher than the surrounding region. Thus region T2 is located by analysing the variance profile using Eq. (7) and Eq. (8) as shown in Fig. 8(c).

Further *Check 2* checks if the extracted potential region for the tag has dimensions (length/width or $\frac{|S_1 - S_2|}{h}$) in acceptable limit. In our case, we set the range 0.5-2. If the tag dimensions fall outside this range, it will result in the *Error 1*.

$$check \quad 2 = \begin{cases} P & if \quad 0.5 \leq As \leq 2 \\ F & otherwise \end{cases} \tag{9}$$

where, *As*=|*s1-s2*|/*h*.

Once *Check 3* is *P*, the region bounded by S_1 and S_2 represent the real tag where yarn floats are present and can be represented by *T*.

4.4. Step 4: Individual yarn decomposition

According to *Pattern 2*, the coded yarns are nearly parallel and do not touch each other. This is further reinforced by the fact that there are regular yarns inserted between two coded yarns (explained in Section 2). Further, if we convert the grayscale image *T* (decomposed in the previous step) into a binary image T_b (using Otsu thresholding [33]) where yarn wraps represent the foreground and

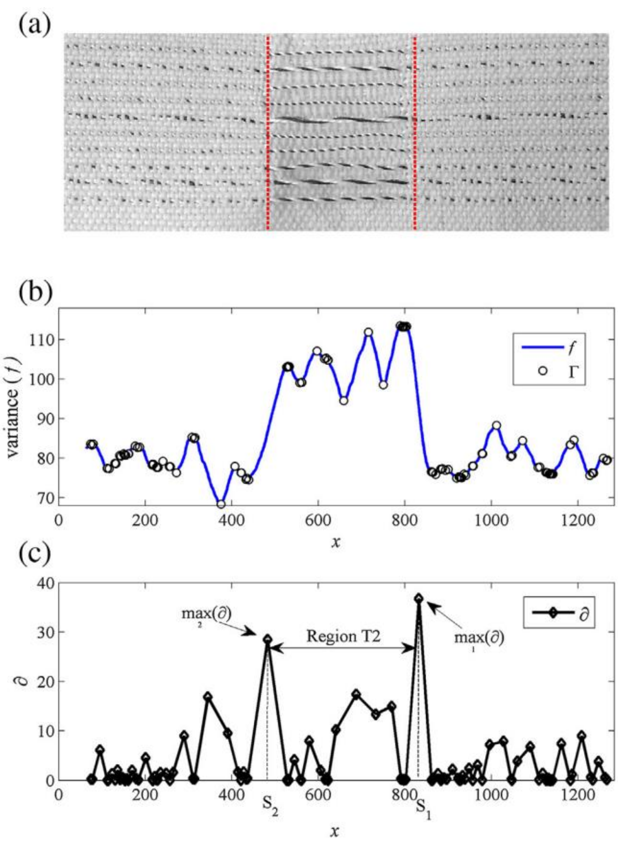

Fig. 8. Detection of readable coded yarn region using pixel variance profile. Image (a) represent the coded yarn region detected using Hough's peak and (b) shows the corresponding horizontal variance profile. Further, (c) shows the detected readable coded yarn region (Region T2) by analysing the variation in variance profile.

remaining as background, then the wraps pertaining to a coded yarn will appear horizontally and two coded yarns wraps will be separated completely by background pixels (as shown in Fig. 9). Assuming, *s* ($s = s_1, s_2, \ldots, s_w$, where *w* is the number rows or pixels in

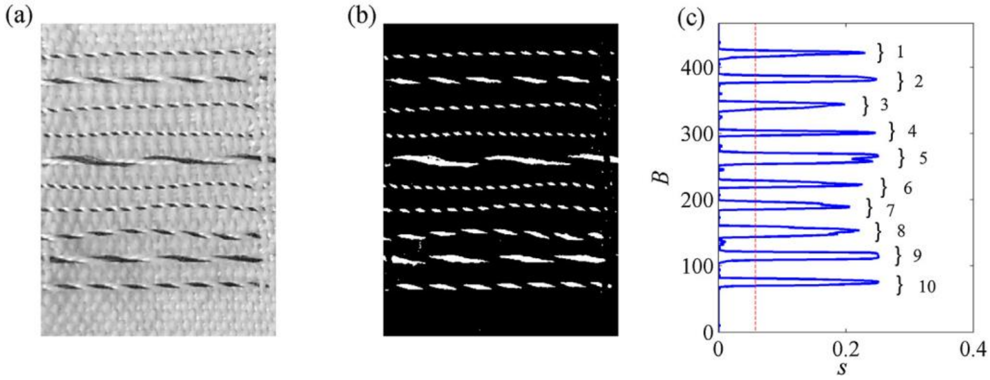

Fig. 9. Decomposition of tag area into individual coded yarns. Here (a) shows the detected coded yarn region in grayscale and (b) shows the corresponding binary image obtained after inverting grayscale image. Further, (c) shows the detection of individual coded yarns using standard deviation peaks and dotted vertical line represents t_B.

vertical direction in T_b) be the standard deviation of the rows of T_b, there must exist rows containing background pixels only between the consecutive coded yarns, where $s_B = 0 \forall B \in t$ and $s_B \neq 0 \forall B \notin t$, where t denote the pixel rows of T_b having only background pixels (i.e. no coded yarn). Therefore, the vector s will have clusters of zeros and non-zero elements, where nonzero element clusters are denoting coded yarns and zero element clusters act as separators. The foreground pixels generated by noise may create false non-zero s, therefore, to avoid this, nonzero clusters of s are calculated by thresholding s by t_B such that $t_B = a \times mean(s_B \forall B \in t)$ i.e. a times the mean of non-zero entries of s. For example, Fig. 9(c) shows the 10 peaks of s with a = 0.5, corresponding to 10 coded yarns. Further the tag image is decomposed along the peaks to divide into individual coded yarns.

Check 3 is introduced to confirm the correct decomposition of individual coded yarn described as follows.

Check 3 This step determines the correct decomposition of the coded yarns by comparing the number of calculated yarns (C_l) with the actual number of coded yarns (N) i.e.,

$$check \quad 3 = \begin{cases} P & if \quad C_l = N \\ F & otherwise \end{cases} \tag{10}$$

4.5. Step 5: Coded Yarn features extraction

In this step, individual yarn is analysed for yarn features using image processing procedure given in our previous publications [6,26].

4.6. Step 6: Data filtering, scaling and membership calculation

Yarns and fabric are flexible in nature therefore; there are enough chances for errors in the extracted features from the fabric tag. For instance, yarn is not straight or a wrap is not completely visible in the fabric may result to an inappropriate output. Therefore, extracted features are filtered using 'Modified Thompson Tau' method for outliers [35]. Further, the direction of twist is accounted only if 70% of the extracted wraps possess one direction of twist, otherwise, the twist output is converted into uncertain and *Error 2* is flagged. The filtered feature data is further scaled and the membership values are calculated using Eq. (1). To generate a confident decision of membership values, *Check 4* is introduced.

Check 4 confirms whether the membership to a yarn class is sufficient to believe. This check is introduced to avoid situations where the aggregated degree of memberships obtained using Eq. (1) is very low for all classes of yarns, or memberships for two classes are too close. Assuming d ($d = [d_{ij}]_{n \times C}$; $i = 1,2,\ldots,n$; $j = 1,2,\ldots,C$; where n is total number of features and C is total number of classes) denotes the membership values for individual yarn features for various yarn classes and Y ($Y = Y_1, Y_2, \ldots, Y_C$) contains the aggregated membership values for various classes. The *Check 4* can be described by Eq. (11).

$$Check \quad 4 = \begin{cases} P & if \quad \max(Y) > K_1;\ \max(Y) - Y_i > K_2 \forall Y_i < \max(Y) \\ F & otherwise \end{cases} \tag{11}$$

Here K_1 and K_2 represent the membership threshold and difference threshold, respectively. K_1 defines the minimum membership required to assign the final yarn class. K_2 defines the difference among the membership values required for two highest membership classes.

In case *Check 4* fails, the step '*Membership calculation using reduced features*' is followed otherwise, the generated code is accepted.

4.7. Step 7: Membership calculation using reduced features

This step is followed in case a confident membership value is not obtained in the previous step. In this step, aggregated membership values are again generated after discarding the feature which follows a distinct trend from remaining features.

Here, feature x is discarded which has maximal value of the mean distance R_x i.e.

$$R_x = \max(R_k) \forall k \in [1, n] \tag{12}$$

where

$$R_k = \frac{\sum_{l=1}^{n} \left\{ \sqrt{\sum_{m=1}^{C} (d_{km} - d_{lm})^2} \right\}}{n}$$

Further, new feature space is produced after discarding the feature variable x and new aggregated membership (Y') is calculated using reduced number of features. The aggregated membership is checked for a membership threshold K_3 using *check 5* given as,

$$check \quad 5 = \begin{cases} P & if \quad \max(Y') > K_3,\ \max(Y') - Y'_i > K_2 \forall Y'_i < \max(Y') \\ F & otherwise \end{cases} \tag{13}$$

K_1, K_2, K_3 depends upon the overlapping of membership functions of the various yarn features and the overlapping for the coded-yarn features are described in Ref. [6]. Higher overlapping leads to more chances of having less difference among two close yarn classes whereas increases the membership values. For experimental verification K_1 and K_3 are selected as 0.3 and 0.5 respectively, whereas K_2 is selected as 0.15. It should be noted that aggregated membership in Step 7 is based on reduced number

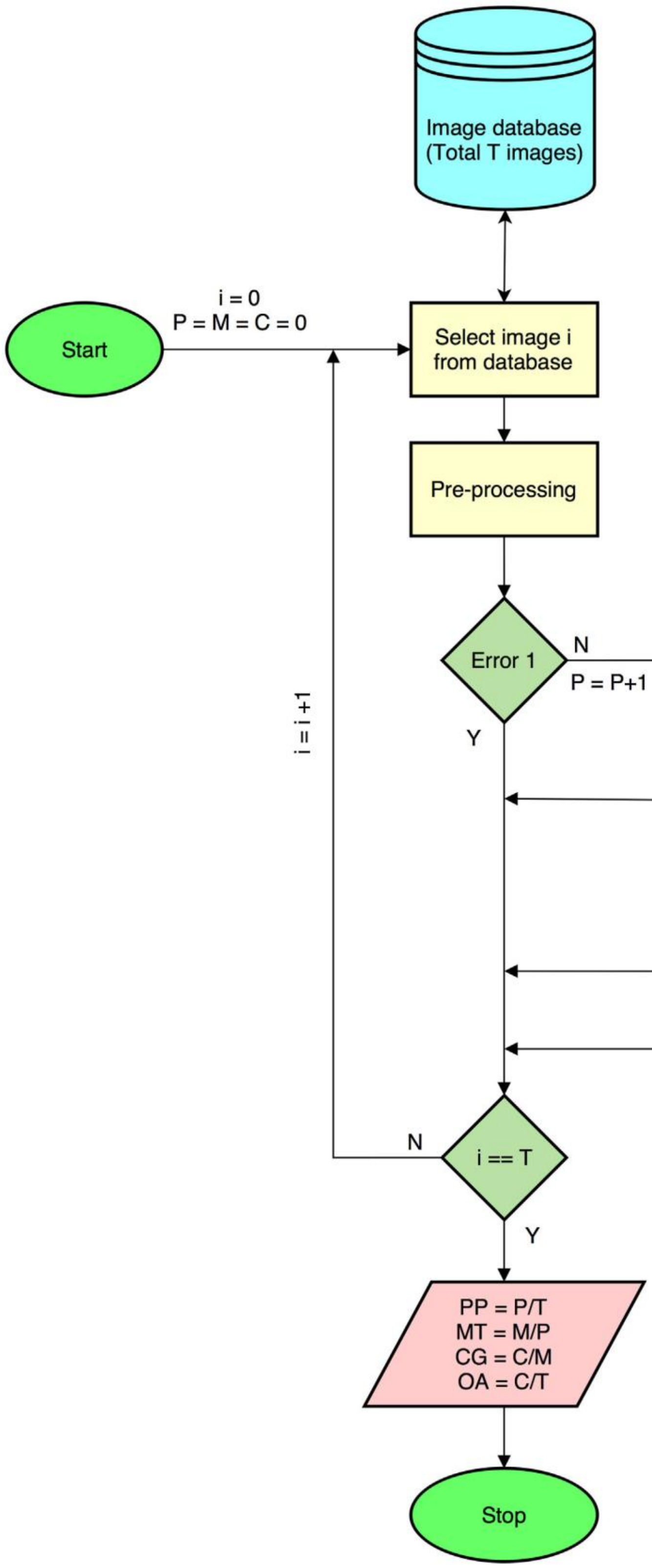

Fig. 10. Flow diagram for the process followed for the analysis of tags. Different success rates are defines as, PP: pre-processing, MT: membership threshold, CG: Code generation and OA: overall. Y: yes, N: no.

of features which have similar pattern to their individual memberships to different yarn classes and results to a higher value. Therefore the aggregate membership threshold for Step 7 i.e. K_3 was taken higher as that of Step 6 i.e. K_2.

5. Materials and method

In this research we utilize previously developed the yarn coding technique [6] to generate the optical features using white core yarn (i.e. polyester yarn of 50 Tex) and black wrapped yarn (i.e. multifilament polyamide yarn of 16.6 Tex). Five different sets of yarns were prepared with machine set twists i.e. 200TPM, 400TPM, 600TPM, 800TPM and 1000TPM with Z twist direction.The values of,μ σ for used in Eq. (1) and weight (w_i) used in Eq. (2) for various mentioned classes can be obtained from [6]. Further, the fabric samples were prepared in two textile structures, namely, plain woven and weft knitted textiles. Coded yarns were embedded inside the textile with the procedure given in Section 2. As we already know that maximum interwrap distance is ∼5 mm (i.e. 200TPM yarn), therefore the length of floats is kept ∼1.5 cm such that every float possesses at least two complete wraps. The knitted fabrics are more stretchable than woven fabrics, therefore the length of the coded yarns outside the fabric (i.e. the length of mis-stitch) was kept ∼1.2 cm. A slight stretched to the knitted fabric was provided to straighten the yarns while capturing the image, which releases more yarn in tag region. Further, it should be noted that, the coded yarn characteristics are scaled features. Therefore, in order to convert the optical features of coded yarns into scaled parameters, a reference scale is required. In case of conventional barcodes, their dimensions act as reference scale. However, textile structures are flexible and resilient, and unlike barcodes, there is no definite boundary to define dimensions. Therefore, instead of using the tag dimensions, we inserted a reference coded yarn on a predefined position in the tag whose optical features were already known, and rest of the coded yarns were normalized with respect to it. Total 27 woven tags and 43 knitted tags were prepared for the analysis. Further, the prepared tags were captured using a digital camera in normal daylight conditions. The noises were introduced synthetically to the images. The proposed algorithm was applied to the captured tag images with the help of MATLAB® R2009b on a computer with 8GB RAM and Core i5 3GHz processor. The position of the reference yarn was supplied during the algorithm execution.

It is well known that, clothings undergo mechanical agitations during their use. Therefore, it becomes imperative to investigate the effect of mechanical agitation on the tag readability. Moreover, tag readability is very much dependant upon the image capturing conditions. Therefore, the analysis process was divided into two steps, namely, tag analysis and algorithm analysis, where former deals with the robustness of the tag against mechanical agitation, while the latter deals with the image capturing parameters.

5.1. Tag analysis

As aforementioned, textiles undergo mechanical agitation during their use. One of the major agitations is during washing where they are stressed, sheared and tumbled [36]. Therefore, to simulate this effect, we treated the samples for five normal washes in domestic laundry machine at 50 °C for 40 min, each wash followed by a tumbled drying for 30 min.

5.2. Algorithm analysis

For this section, two commonly occurring noises namely, Salt and Pepper (S&P), and Zero-mean Gaussian (ZMG) noises were synthetically introduced to the images. The S&P noise was introduced at three levels i.e. 3%, 6% and 9%. It should be noted that, x% of S&P noise means x/2% is salt noise and x/2% is pepper noise. Similarly, ZMG noise was also introduced randomly at three variance levels i.e. 0.01, 0.02 and 0.03.

6. Results

The results are presented here in terms of three success rate parameters, namely, pre-processing, membership threshold and code generation. Pre-processing is a collective term representing the region shown in Fig. 4(a). In brief, it includes *Check 1* and *Check 2*, i.e. correct coded yarn region recognition and correct decomposition of individual coded yarns, respectively. Therefore, pre-processing success rate implies the percentage of input images correctly identified and decomposed into individual coded yarns. Membership threshold implies to the optical features extraction and membership value calculation to various optical features, as shown in Fig. 4(b). Further, Membership threshold success implies the percentage of successfully pre-processed images has crossed various membership threshold values (defined in Eq. (11) and Eq. (13)). Similarly, the Code generation (or decoding) success implies the percentage of successfully crossed membership threshold images has correct code generated. A brief flowchart of this process is given in Fig. 10.

It should be noted that one image is tested only once, which means, if any of the errors (Error 1 or Error 2) occurs, image is discarded and new image is analysed. Therefore, aforementioned success rates actually signify the success rate of that particular process. The Overall success rate is the success rate of the whole system, which is the multiplication of all above-mentioned success rates.

6.1. Tag analysis

Fig. 11 shows the effect of washing treatments on woven and knitted tags' success rates for aforesaid parameters. The overall system success rate before washing was found to be 67% and 59%. However, the correct code generation, which actually define the actual success of tag decoding was obtained ∼80% for both types of tags. After five washes, the overall success rates have been observed to be decreased by 6.33% and 3.63% for woven and knitted tags, respectively. Further, a decreasing trend has been observed for pre-processing and code generation success rates.

It is interesting to note that, woven tags show negligible effect of washing on membership threshold and code generation success rates, and the change in overall success rate is attributed to the change in pre-processing success rate. Knitted tags show a negligible change in pre-processing while most of changes occurred in membership threshold and code generation success rates. Pre-processing is, in fact, depends on coded yarn separateness in the coded yarns floats, as discussed in Section 4.4. Due to rubbing and mechanical agitation during the washing process, coded yarns become flabby, and the only way to straighten them is by stretching the fabric. Knitted fabrics are stretchable whereas woven fabrics are very less stretchable at low loads, therefore coded yarns are more likely to be separable in knitted tags as compared with woven tags. Consequently, less effect has been observed for knitted tags as compared to woven tags. However, minor changes in membership threshold and code generation success rates confirm that yarn characteristics were least affected by washing.

Interestingly, the membership threshold for knitted tags shows nearly the same rise as code generation shows a decline, which alternately endorses the fact that the pseudo-improvement in success rate is compensated by code generation success. Therefore, the overall success rate of the system is slightly affected by change in

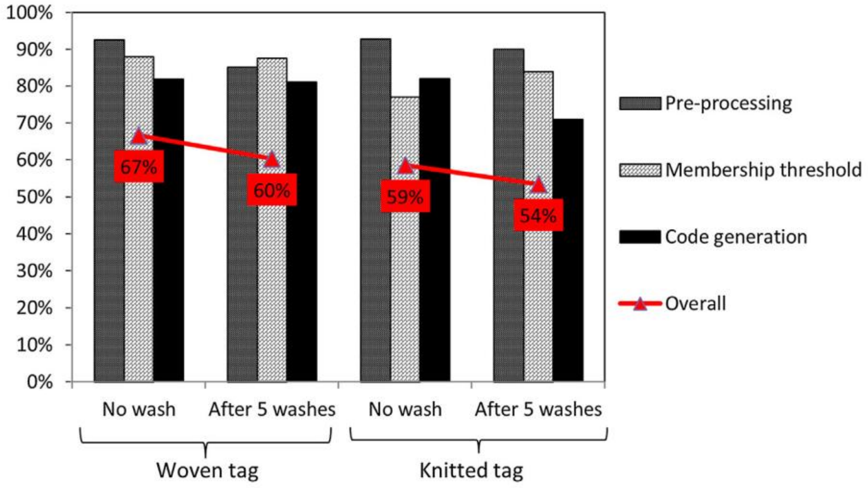

Fig. 11. Effect of washing treatments on tag readability.

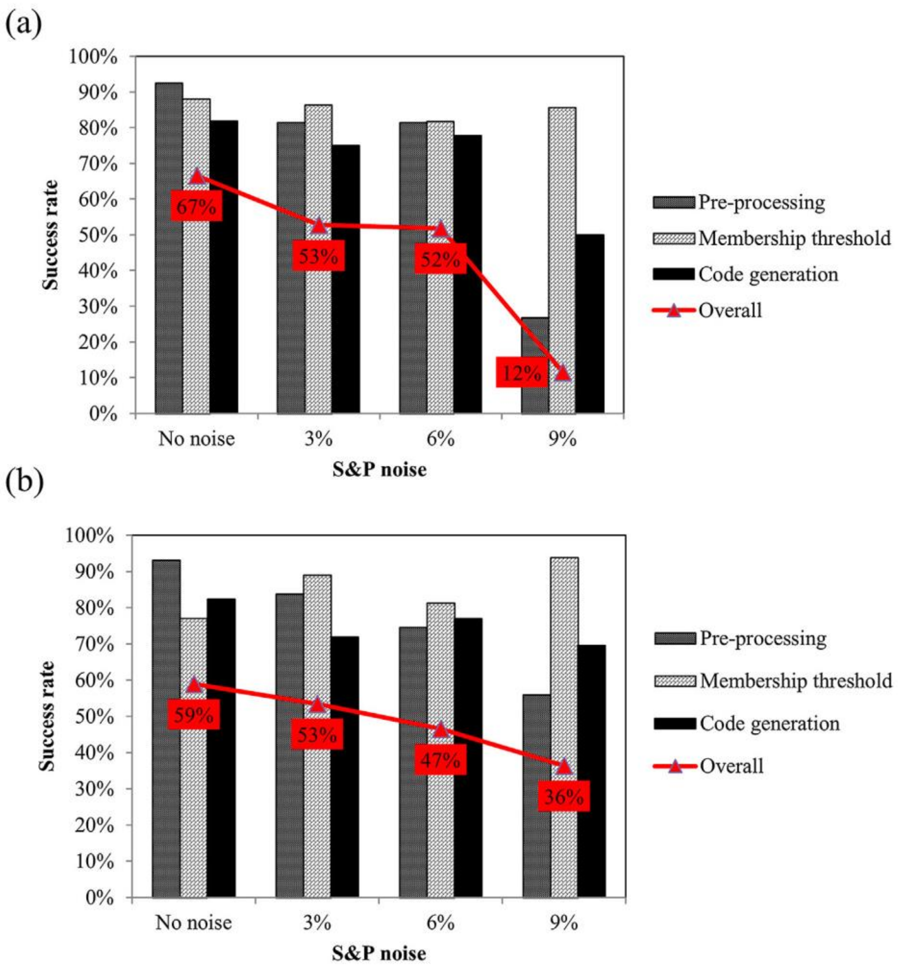

Fig. 12. Effect on S&P noise on various success rates of (a) woven tags and (b) knitted tags.

membership threshold or code generation success rates. Nevertheless, the results confirm that yarn based tags can withstand washing treatment, which exerts a combined shear, tensile and compressive stresses.

6.2. Algorithm analysis

Fig. 12 shows the effect of S&P noise on woven and knitted tags. A decreasing overall success rate has been observed for both tags. A sudden drop has been observed in the overall success rate for

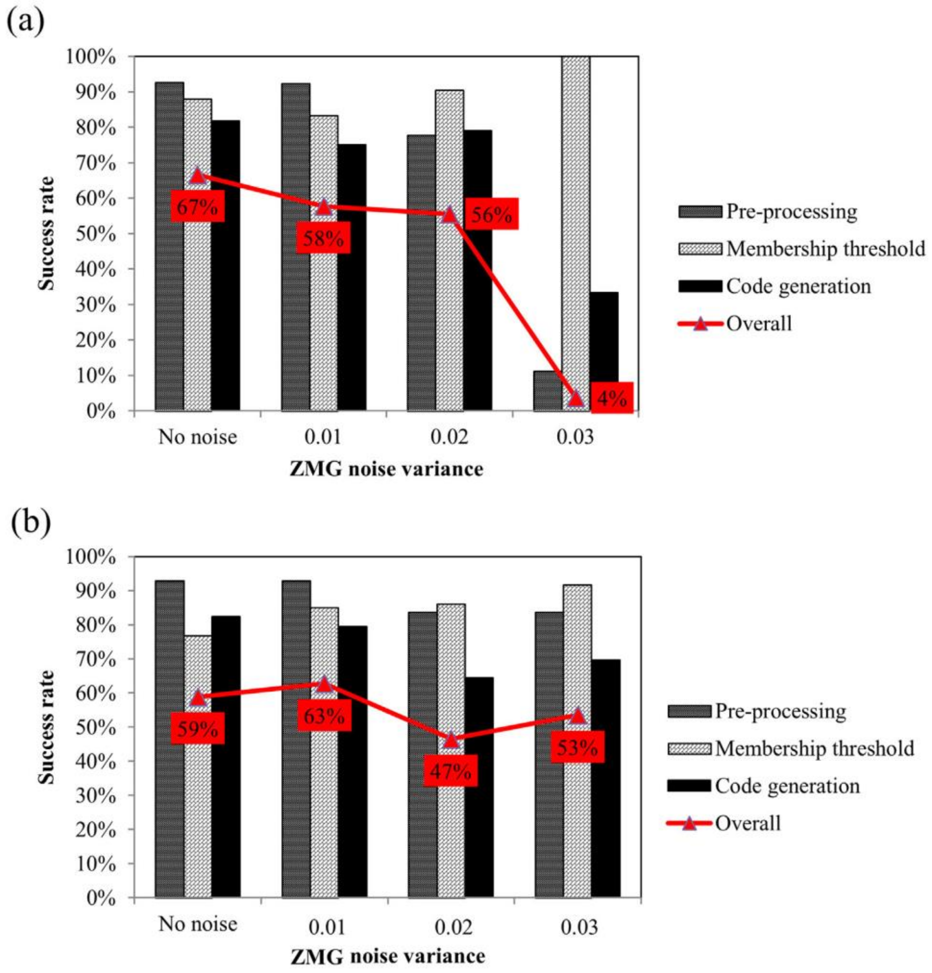

Fig. 13. Effect of ZMG noise on various success rates of (a) woven tags and (b) knitted tags.

woven tags after 6% of S&P noise, which is not same for the knitted tags. This trend is highly correlated to the pre-processing success rates for both types of tags. At 'no noise' level, pre-selection success rates are same for both types of tag, which means that coded yarns pattern recognition and individual yarn separation is same for both of the cases, however, as noise is added, pre-processing success drops instantly for woven tags. Further, Fig. 13 shows the effect of ZMG noise on woven tags and knitted tags, respectively at various levels of variance.

Here, woven tags follow the same trend as that of S&P noise i.e. pre-selection success rate is mostly affected in the given range of noise, whereas the knitted tags show no clear trend. This variation in behaviour can be understood by the process followed for pre-selection process, which involves the decomposition of coded yarns based upon their pattern on fabric surface. This pattern involves two distinguishable patterns formed by coded yarns on fabrics (as explained by T1 and T2 in Section 4). For knitted tags, these patterns are quite prominent (where T2 is visually more prominent than T1) while for woven tags, only T1 prominent while T2 is weakly perceivable. Therefore, when the noise in image increases, it dilutes the whole image texture, and weakly perceivable texture T2 of woven tags affects at the first place. Once the noise becomes capable enough to overcome T2 of the woven tags, tag readability drops instantly. On the other hand, T2 of knitted tag is very much prominent as compared to that of woven tag, hence, comparatively less effect has been observed for knitted tags on the same noise level. Furthermore, it is interesting to notice that in the given range of noises, membership threshold and code generation success rates are comparatively less affected than that pre-processing (particularly for woven tags). Therefore, it signifies that, to minimize the effect of noises for woven tags, structure can be modified in such a way that coded yarns create a strong pattern when embedded inside the fabric.

6.3. Computation time

In order to substantiate the resource consumption during the tag decoding process, the image pattern recognition and decoding algorithm was divided in two parts namely Pre-processing time and Decoding time. Pre-processing time includes the time required for tag region identification and individual yarn decomposition (i.e. Step 1–Step 4), while decoding time includes the execution time for coded yarns' features extraction and conversion into information (i.e. Step 5–Step 7). For a 4 million pixels (MP) image, the mean pre-processing takes 1.28 s and mean decoding time is 0.70 s, as shown in Fig. 14.

The error bars show the standard deviation in the execution time. It has been observed that the majority of the preprocessing time goes in multiple level wavelet decomposition and Hough's transformation to detect linear texture. Furthermore, the first check is introduced after linear detection; therefore, minimum cycle time (if no linear texture is detected) can be the time required for cross-

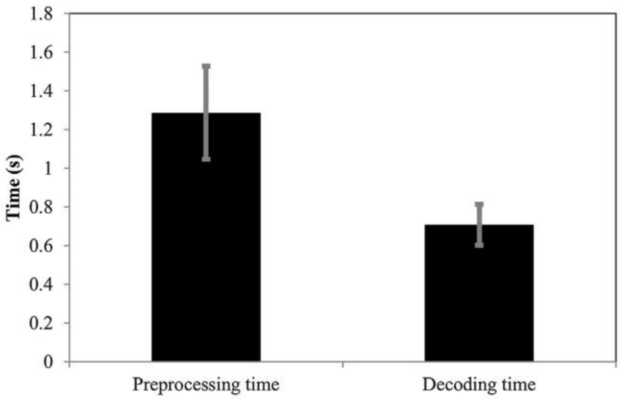

Fig. 14. Processing time for 4MP images.

ing *check 1*. To improve the computation time of the pre-processing, alternate ways can be opted. For example, pre-processing can be done at reduced/compressed image size; therefore, the computation time can be reduced.

7. Conclusions and future scope

Traceability is an ongoing concern in the manufacturing sector. Traceability is textile sector is currently implemented using RFIDs and barcodes which have certain inherent limitation to provide complete traceability. In this paper, we introduced and demonstrated a novel coded yarns-based tracking tag for textiles which is specifically designed for a simplistic production by conventional textile manufacturing processes. Further, a coding scheme has been discussed to introduce uniqueness in each tag. An image pattern recognition based algorithm has been developed for tag identification and decoding. The code generation was found to be ~80% for both types of tag (without noise and washing), whereas the overall success rates of the system were found to be 67% and 59% for woven and knitted tags respectively. Washing has slightly affected the overall success of the system, whereas higher levels of selected noises (ZMG noise and S&P noise) have more impact on the overall success rate of the system. Although the reported decoding rate is lower than the existing barcodes, it should be noted this is the first and foremost attempt to test a completely new kind of tracking tag designed for textiles. Nevertheless, the present study shows that yarn-based tag can be used for tracking textiles. In future, more rigorous methodologies will be adopted to improve the system. For instance, in the present work, no tag identification mark was used and tag was detected using the pattern. Therefore, in order to increase the readability, some fixed identification marks e.g. a different colored yarn can be added in the tag area can be included for fast and better code detection. Moreover, in the present study, the correct decoding was confirmed manually. However, in the real production scenario, error checksum helps in confirming if the correct information is decoded or to identify the probable region with incorrect decoding [37]. Physical analysis of the tag shows that it can withstand the common mechanical action during washing. Further, woven tags were found to be more sensitive to image noises. Particularly, tag detection on the fabric surface was found to be affected by the noise, while once the tag detected, decoding rate has shown less effect. Since, the reproduction of these tags is not easy like other tags, including barcodes and RFIDs, they can provide enhanced security to textile products from counterfeits. In the case of reverse supply chain, these tags can play an important role since these are integrated into the fabric. Further, from the economic aspect, yarn based tags are normal textile, therefore, there is no need of special material components and in-house production in a textile industry can be done.

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Paper IV

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Developing a Framework for Traceability Implementation in the Textile Supply Chain

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Abstract: Traceability has recently gained considerable attention in the textile industry. Traceability stands for information sharing about a product including the product history, specification, or location. With the involvement of globally dispersed actors in the textile supply chain, ensuring appropriate product quality with timely supplies is crucial for surviving in this industry with ever increasing competition. Hence it is of paramount importance for a supply chain actor to track every product and trace its history in the supply chain. In this context, this paper presents a framework to implement traceability in the textile supply chain. A system approach has been followed, where firstly the usage requirement of traceability is defined, and then a framework for implementing intra-actor or internal traceability and inter-actor or external traceability is discussed. This article further presents a sequential diagram to demonstrate the interaction and information exchange between the actors in the supply chain, when the traceability information is requested. An example is also illustrated for data storage using a relational database management system and information exchange using XML for the textile weaver. Finally, the article discusses challenges and future studies required to implement traceability in the textile supply chain.

Keywords: supply chain traceability; traceability framework; textile; RDBMS; XML

1. Introduction

Globalization has played a major role in the relocation and outsourcing of textile manufacturing to destinations where less stringent laws, cheap labor, and the availability of supplies is possible [1–3]. The modern textile supply chain consists of a dispersed network of manufacturing sectors, each having a series of complex operations [1,4]. The outsourcing of manufacturing activities helps the textile and clothing (T&C) retailers/brand owners to reduce risks by not owning any production facilities, therefore keeping the supply chains flexible and encouraging the constant search for quality-conscious and cost-effective producers [5,6]. Flexibility is particularly important regarding today's short-lived fashion, where fashion trends change quickly [7]. However, due to geographical separation and institutional differences between different partners, effective information sharing has become a key issue and inadequate information sharing hampers the flexibility and synchronous functioning of the textile supply chain [7,8]. Information is a value creating entity in the modern textile industry, which relates to transparency, product safety, and supply chain management. For instance, outsourcing enhances the chances for buyers to get better quality at a lower price, but it also has a risk side. The increased reliance on global suppliers, raw material providers, and transporters intensify the need for visibility and the risk associated with regulatory compliance during the production or sourcing phases. For example, the NYU-Stern report on supply chain and sourcing revealed a series of discrepancies related to wages and working records, where the suppliers have fabricated these records for compliance with regulatory or code standards [9]. Subsequently, it has become imperative to brand owners to have full information about their supply chains.

Another important aspect of information relates to product recall and end-user safety. An increasing trend of product recalls has been observed in the European Union (EU) for non-food categories as reported by RAPEX (also known as the Rapid Alert System for dangerous non-food products). Textile and fashion products are reported among top contributors in these recalls and an increasing trend has been observed over the past decade [10]. In 2014, 530 recalls were observed from the clothing, textile, and fashion product category among a total of 2435 recall notifications [11]. To manage the execution of product recalls efficiently, it is important that recall handling agencies have authentic information about product distribution from the brand owner or distributor, which essentially relies on the ability to trace-back the origin of the identified products for recalling [12]. Moreover, regulation addressing these issues, such as materials procurement from conflict zones, requires due diligence to comply with the regulations, such as the implementation of origin assurance on the products [13]. Moreover, European regulations on chemicals including dyes and other reagents used in textile chemical processing has put the responsibility on the industry to manage the risks associated with their imported chemicals; hence it becomes imperative to trace the supplies they import [14].

In the context of information sharing, traceability has emerged as a viable solution for current manufacturing and distribution sectors. Traceability extends the informational boundaries of the supply chain actors beyond their organizational scope which helps in informationally integrating the whole supply chain. Further, traceability assists in communicating the important information, which contributes to the better management of globally dispersed supply chains [15]. Experts suggest implementing traceability to assure product safety and proper recall execution [12]. From the customer side, there is a growing interest in the history of products [16–18]. End users are even willing to pay higher for traceable items [19] and consider traceability as equivalent to certification [20]. For the current practice in clothing retail, the most of traceability information is limited to the country-of-origin—which is conveyed using printed labels. However, according to Henninger [21], these labels are not enough to convey the customer-expected traceability information. Hence the implementation of information exchange based traceability is expected to inevitably emerge in the future for clothing brands.

The focus of this research is to develop a framework to implement traceability, which would support the internal and external traceability for different actors in the textile supply chain. Presently, organizations tend to use Product Lifecycle Management (PLM) and Product Data Management (PDM) to organize the product and/or process specific information locally [8]. However, the lack of explicit semantics and the content of information are major problems towards integrating and exchanging the locally stored information among different partners in the supply chain. In such a scenario of fragmented information where integration may be tough due to technical complexities and organizational issues, interoperability is considered a promising approach [22]. Furthermore, from the implementation perspective, it is imperative to address traceability from the standpoint of data management strategies and related operational techniques, which essentially relies on some kind of framework [23]. Framework provides guidelines to the involved supply chain actors to streamline their operation processes with each other in order to implement and maintain traceability. Therefore, this paper focuses on the framework from the technical aspect of the implementation of traceability and a framework for implementing traceability is discussed which includes planning, gathering, arranging, and exchanging the traceability information in the textile supply chain. According to Bechini et al. [24], "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". Therefore, this paper follows a generic data model for traceability implementation in the textile supply chain.

In this paper, we follow the methodological framework proposed by Thakur and Hurburgh [23] and Hu el al. [25]—which is based on a systematic approach to implement traceability by using business integration tools including requirement planning, enterprise modeling, and integration. We first define the usage requirements of the traceability model, followed by the development of data gathering and management at an individual actor level. These steps focus on traceability at the intra-actor level—which not only complies with the requirements posed by other supply chain actors but also by regulatory requirements. The purpose of this paper is to propose a generic framework for traceability. Therefore we define the traceability requirements loosely (i.e., not limiting to a specific case) using a use-case diagram and then utilize the IDEF-0 (Integrated Computer-Aided Manufacturing (ICAM) Definition Part 0) model to show its implementation at an actor level. Furthermore, this paper illustrates the integration of the different supply chain actors to exchange the traceability information and realize full supply chain traceability using a Unified Modeling Language (UML) sequential diagram and the eXtensible Markup Language (XML). The contribution of this paper can be seen as a very first step of real traceability implementation, proposing a framework for traceability based upon the supply chain characteristics of the textile industry.

The subsequent part of the paper is organized as follows: Section 2 describes the related work and Section 3 discusses the usage requirement of traceability in the textile industry. Sections 4 and 5 discuss the framework for internal and external traceability, respectively. Section 6 illustrates an example for the management of traceability data. Finally, Section 7 concludes the paper and states the future scope.

2. Related Work

Traceability has gained more attention recently in a variety of industries [2,15,26,27]. According to GS1 system [28], traceability is defined 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". Furthermore, a detailed definition proposed by Moe [29], which is probably one of the frequently used definitions, is given as, "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)". The history of traceability dates back to the 1930s with regards to the origin of high-quality products such as French champagne [13]. Over the decades, institutions have made guidelines for product safety and security which mandate the implementation of traceability in some sectors. Government regulation is a major factor for traceability implementation in sectors including agrifood and medicines. The EU law for food safety mandates companies to record the one step forwards–one step backwards suppliers' information [23]. Hence all the actors involved in the food supply chain act as links for traceability. The textile industry does not have a long history of promoting traceability, however, recently it has become a large concern for the industry [7,16].

Traceability acts as a vital link for sharing information within and between the partners, such as design details, component description, procedures, bill of materials, etc. Therefore, it helps to integrate the supply chain. Traceability brings more transparency in the supply chain by systematically managing the product related information. Moreover, information sharing is an integral part of supply chain management. According to Lam and Postle [7], the supply chain can be defined as, "All the activities involved in delivering a product from raw material through to the customer including [...] and the information systems necessary to monitor all of these activities." Information management and sharing, product tracking, and tracing have been reported in the other definitions of the supply chain as well [30–32]. Information sharing has been seen as a primary requirement for sustainable and effective green supply chain strategy [33–36]. Studies in the past have attempted to determine the effect of information sharing in inventory management [37,38], organizational efficiency [39], and supply chain performance [40,41]. Lam and Poste [7] identified "no information sharing" as a major barrier in the supply chain in the textile and apparel sector in Hong Kong and argued that lack of standardized semantics or a common framework to share information is one of the reasons behind this. A recent study [42] reveals that the poor state of traceability in the textile sector—which enlisted 59 clothing brands or retailers in Australia in the report for their traceability. From the enlisted companies in abovementioned report, it can be concluded that only 61% retailers fully identified their immediate suppliers while only 8% of the retailers knew fully about the fiber suppliers for their products [42]. In fact, traceability is a mutual effort of involved supply chain stakeholders, and regulatory enforcements play an important role by engaging the stakeholders. For example, the food companies in the European Union have regulatory requirements for minimum traceability levels for product safety [43]. As a result, traceability in the food sector is considered one of the most effective implementations [44]. However, the textile industry does not have any formal regulations for traceability, which act as a deterring factor in traceability implementation. Nevertheless, voluntary traceability initiatives are gaining momentum, for example, the Union of the Italian Chambers of Commerce has promoted the adoption of a voluntary traceability system for the entire supply chain which can be applied to a range of manufacturing sectors [2]. Furthermore, the textile supply chain actors have started to realize the potential of traceability [45]. For example, with the involvement of globally spread actors, the quality of the final product largely depends on the supplies. Appropriate product quality with timely availability is necessary for surviving in the ever increasing competition. The textile supply chain consists of multiple actors and the total production lead-time can be as high as 12–24 months, whereas the fashion trend changes almost every season [46]. Any delay in production or quality issues can hamper the brands severely. Hence it is of the utmost importance to have a synchronous production, and the tracking of products and their quality throughout the supply chain [14]. Furthermore, traceability is considered an essential tool for attaining sustainability goals by tracing the raw material through complex supply chains and ensuring good practices throughout the processes [4,13]. A stream of researchers in the past has investigated the use of traceability information in the context of textile industry. Guercini and Runfola [47] studied traceability as a tool for inter-organizational control and as a marketing tool including "made-in" to be used by clothing brands. Traceability as a tool for inter-organizational monitoring and customer safety is further confirmed by Gobbi and Massa [2]. Cheng et al. [48] investigated traceability to control quality and maximize the profit of the textile supply chain. According to Guercini and Runfola [47] addressing traceability involves at least three facets—the information content to be shared, coding of the information and the way it is transferred, and the extent of information access with the other actors in the supply chain. However, studies technically addressing the above mentioned or related facets have gained limited attention. For instance, Alves et al. [14] presented a generic solution to implement traceability with the help of semantic web technology and demonstrated the application in the textile sector. From the implementation perspective, it is imperative to address traceability from the standpoint of data management strategies and related operational techniques, which essentially relies on the standardized framework [24]. However, limited attention is paid to comprehend the abovementioned aspects from the textile supply chain perspectives.

3. Usage Requirement of the Traceability Information in the Textile Supply Chain

Traceability is fundamentally data management about a product. Furthermore, traceability should be helpful in understanding the relationships that exist within and across product lifecycle information, including requirements, design details, component description, product and production specification, process information, and actor information [49]. Traceability information should be reusable at any point when it is necessary. The textile supply chain consists of multiple players, therefore it is important for all of them to understand and exchange the traceability information and use the uniform/standard semantics for information exchange [8,26].

To design a traceability framework, we firstly briefly describe the textile supply chain and then define the usage requirement of traceability.

The textile supply chain is a relatively long and complex network; it involves a number of actors located worldwide and deals with diverse raw materials and processes such as fibre industries, spinning mills, weaving mills, chemical processing industries, apparel manufacturers, and retailers, beside various logistical actors involved in transportation and distribution [50]. Most of the textile supply chains are driven by the retailers or brand owners, who monitor the market demands and place the order for upstream suppliers [46]. A retailer generally does not own any production facilities and acts as a reseller who procures the products from the upstream suppliers and sells them to the customers [46]. Therefore, all the actors excluding the retailer are considered as B2B (business-to-business), whereas the retailer is considered as B2C (business-to-customer) as shown in Figure 1.

Despite not owning any production facility, retailers act as the most dominating actors in the textile supply chain who forecast the market demand and place orders to the upstream suppliers [7]. Therefore, demand flows upwards in the supply chain and the demand fulfillment flows downwards, which can be termed as pull dynamics in the supply chain. It should be noted that logistics partners interconnect various actors, but legally they do not own or alter the products. Therefore, we do not take them into consideration. Moreover, the actors—excluding the retailer—are B2B and act as a linkage in the supply chain. At the macro-scale, each link takes the raw material as an input from the previous supplier(s), applies operations, and produces the final product. This process repeats over and over again until it reaches the retailer.

To define the usage requirement, we follow a system-level approach as also followed in defining traceability in the food and vegetable sectors, which involves the use case diagram technique commonly used in the UML [23,25]. A use case captures the behavior of the actors of a system and the use case diagram graphically demonstrates the relationship between the actors and helps in understanding the most important parts of the system and user requirements [51]. Moreover, the use case-based analysis contributes to understanding a complex system by the explicit representation of the important parts of the system. Figure 2 shows the use case diagram to capture traceability information in the textile supply chain network. As mentioned before, B2B actors work similar to each other, i.e., transform the inbound raw material physically or chemically into the outbound product. Accordingly the B2B actors are shown as similar components capturing/contributing to the similar sorts of information as shown in Figure 2. The retailer acts as a B2C and the customers are an independent component. Consequently, the use case diagram contains three components as shown in Figure 2.

As B2B actors are the product transforming actors by the application of various processes, they act as the main contributors to the traceability information. Whereas, the retailer controls the information flow between the B2B actors and the consumers.

There are a large number of processes performed by each actor. As a result, there is a significant amount of information created by each actor. Information is a critical component of a supply chain, therefore it is important that each supply chain actor controls the flow and protects confidential information [52]. The use case diagram shows two layers of information, namely primary information and secondary information. Primary information consists of all the information available with a B2B actor, whereas the secondary information is the processed information generated from the primary information, a part of which (i.e., shareable information in Figure 2) can be shared with other supply chain actors. The following shows the information components of the use case diagram.

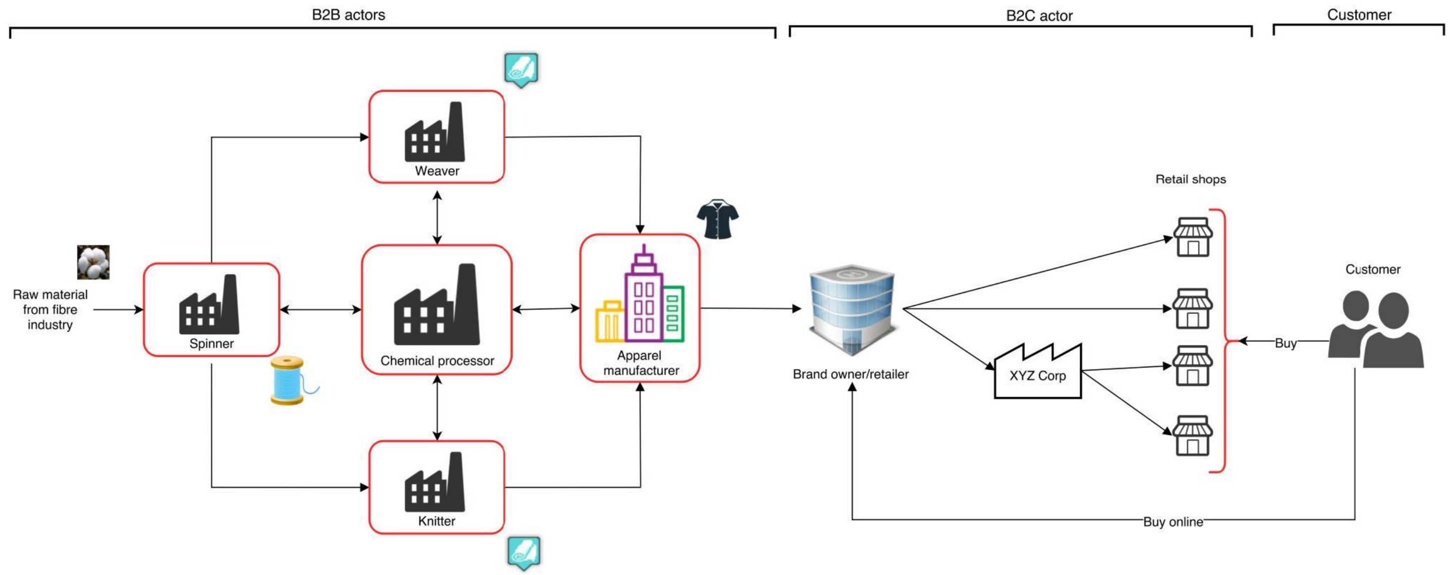

Figure 1. Textile supply chain network.

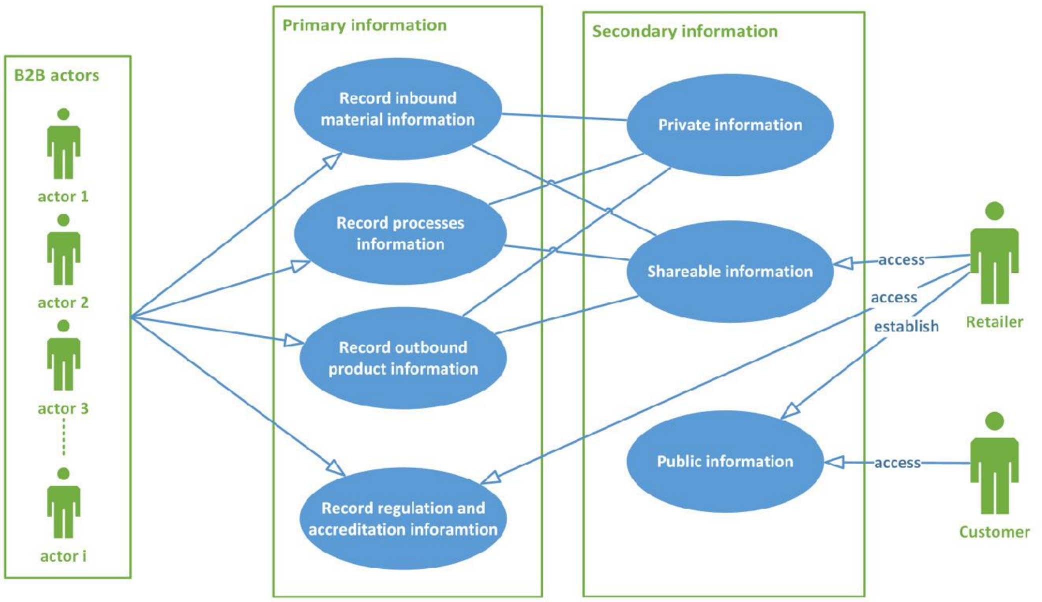

Figure 2. The use-case diagram for the traceability information.

3.1. Record Inbound Material Information

The inbound material is the material procured by an actor from an upstream supplier/actor in the supply chain. Therefore the actor should record the input material information such as material quality characteristics and specifications, supplier information, lot number, etc., so that a material transformed after various processes can be recalled for its history.

3.2. Record Process Information

Process information includes the information related to the processes carried out by an actor to transform the inbound material into the outbound material. As mentioned before, only B2B actors carry out processes to transform inbound material. Therefore, this information is recorded by respective B2B actors.

3.3. Record Outbound Product Information

The outbound material characteristics are different from the inbound material characteristics. As a result, an actor should record the outbound material characteristics such as specifications, buyer information, the difference between the requested specifications and actual specifications, etc.

3.4. Record Regulation and Accreditation Information

Every actor should record the certification, accreditation and other information required for regulatory requirement about the materials/processes/production practices, etc., so that this information can be used by other actors for their claims or practices. For example, The European Confederation of Linen and Hemp (CELC) requires every actor to follow standard prescribed materials and processes to use their stamp on a retail product [19]. Consequently, every actor should follow and record material/process related information which show how does it conform to certain claims (e.g., certification)

3.5. Private Information and Shareable Information

The information mentioned in above sections is the primary information. As aforementioned, it is important to protect confidential information from sharing in the supply chain. Hence the actors should segregate the primary information into private and shareable information. Private information remains with the actor, while the shareable information is shared with the buyer (or the next actor in the supply chain). Private information is used in case of crisis, such as in product recalls.

3.6. Public Information

Public information is the information established by the retailer, accessible to the consumer based on secondary information and certification/accreditation information which are made available to the retailer. The extent of the public information depends on the willingness of the retailer and agreement of actors in the supply chain. For instance, actors may agree to share the information between each other; however, disclosing the complete information in public may invite unforeseen consequences from competitors. Moreover, all the recorded information may not be relevant to the customers. As a result, the retailer establishes the information which can be accessed by the public.

4. Intra-Actor or Internal Traceability

4.1. Traceability Information Identification and Planning

The textile supply chain consists of multiple independent actors, working synchronously with each other. As mentioned earlier, each actor acts as a link, therefore, for implementing traceability, firstly each actor should effectively capture the traceability information and secondly communicate it in the supply chain. For the former, it is important that each actor identifies the essential traceability information which is not only required for the next actor but also to verify the claim. Moreover, the system development process involves the various phases from the practical context, including planning, design, analysis, and so forth, and these processes involve the coordination and communication within and between industries. Following the references [23,25], we use IDEF-0 modeling to define a plan to capture the required internal traceability information. IDEF-0 was initially developed by the Air Force Wright Aeronautical Laboratories and extensively used the developing function models [53]. It uses basic structured analysis (SA) boxes linked hierarchically to define a network of data and control relationships [53]. Figure 3a shows the structure of a basic SA box for the internal traceability of a B2B actor. Here, horizontally inwards and outwards arrows represent the input and output, respectively. Similarly, vertically downwards and upwards arrows represent the control and mechanism, respectively, for setting up internal traceability [53]. While designing a framework for traceability for an actor, guidelines from accreditation and regulatory authorities act as inputs and control along with traceability requirements from internal needs and the information available from the last actor. Furthermore, the captured information should also comply with the obligation from the next supply chain actor, hence requested traceability acts as another input while designing traceability, as shown in Figure 3a. The output of this framework would be traceability information segregated as private and shareable information which comply with the accreditation and regulations from the local government and/or third parties.

Furthermore, Figure 3b shows the detailed steps for implementing traceability and is discussed as follows:

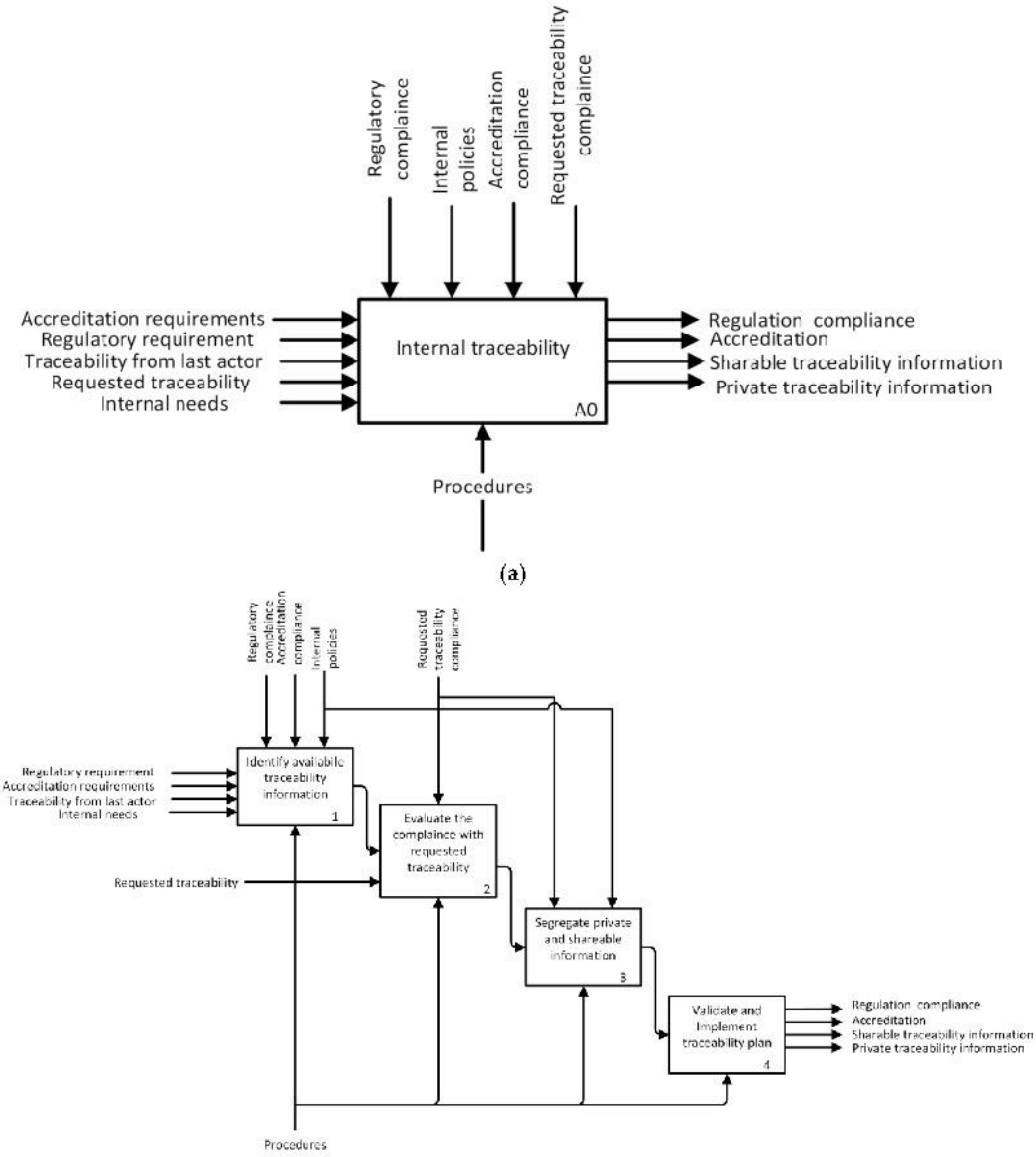

Figure 3. Integrated computer-aided manufacturing definition Part 0 (IDEF0) model for the internal traceability framework. (**a**) shows the basic structured analysis (SA) box and (**b**) shows the step-wise process for implementing internal traceability.

4.1.1. Identify Available Traceability Information

This step includes the identification of all available traceability information in an organization. Traceability information serves different purposes for an actor and supply chain; therefore, it is important to identify all available traceability information for satisfying internal policies, regulations and accreditation requirements, and take into account the previously available traceability information. Government generally has certain regulations related to traceability; therefore, it is important to take these into account for performing business activities. Similarly, accreditations (such as those provided by International Organization for Standardization or ISO) have their requirements for traceability which should be accounted for while planning the framework for traceability implementation.

4.1.2. Evaluate Compliance with Requested Traceability

Traceability has supply chain wide importance and every actor in the supply chain acts as a link for traceability. Accordingly, after the identification of all available traceability information inside an organization, it is important to verify that the collected traceability information in Process 1 contains the traceability data requested by the next actor. The requested traceability information may be due to the buyer's internal requirements including supply chain management, transparency, or local government regulation.

4.1.3. Segregate Private and Shareable Information

Information sharing is an important and crucial step in the supply chain. Any unwanted information shared with the buyer can give an undue advantage. Therefore, this step segregates the traceability information into private and shareable parts. The sharable part includes the information requested by and accessible to the buyer while the private part includes all the information which is available with the supplier only. Furthermore, there is some common components of information, such as the item number or lot number that is available in both parts of the information, to link these parts together.

4.1.4. Validate and Implement Traceability Plan

In this step, the designed traceability plan is validated for all the requirements using real information. The information is stored in database management systems, and reports are generated to validate if the designed system fulfills all the requirements posed by various controls including regulations, accreditation, internal policies, and the buyer. The actor should also use a unified data storage strategy and semantics for an unhindered communication with other actors in the supply chain.

Currently, the industry uses PDM/PLM, which stores the information and has a scope limited to one department or intra-organization. Consequently, the actors freely choose the technology or semantics. However, the limited interoperability due to different semantics, technology, or data storing strategy limits the use in traceability, and it has been identified as a major issue [7]. Companies find it tough to use different semantics for various suppliers/buyers not only due to increased financial investment but also due to maintenance of the system. Financial investment acts as a significant deterring reason for small organizations to implement traceability [7].

4.2. The Traceability Data Sorting and Storing Model

The traceability system has some core requirements for implementation including gathering and sorting product and process related data, lot forming information, upstream and downstream actor details, etc. [54]. These requirements are managed by the proper identification and classification of information, and the classification helps with easier identification of entities and relationships of various ingredients to form the traceable entity [25,54]. The traceable entity can be a batch of products, lot, or a single product. In other words, on requesting the information about a traceable unit, the supply chain actor should be able to recall the relevant traceability information regarding the traceable unit such as ingredients or constituting materials, applied processes, and supplier as well as buyer details. Many approaches have been adopted in the past to visualize the data modeling plan, including entity relation modeling (ERM) and the unified modeling language (UML) which formalize the relationship among various data entries. The ERM approach uses static entities of data and a clear relation between different entities, which allow users to design databases more naturally. However, the discrete relationship makes it less flexible and more appropriate for a clear purpose/use. On the other hand, the UML diagram is a generic modelling tool, which provides better support during comprehension of the data models as compared to ERM [55]. In the present paper, we intend to propose a generic framework which should allow the readers or subsequent studies to modify it according to their specific needs, technology of implementation, and other unforeseen concerns, which would inevitably require a better comprehension of the proposed framework; subsequently we use the UML approach. Figure 4 shows the static UML diagram model developed for implementing mutual relations among various pieces of information related to a traceable entity.

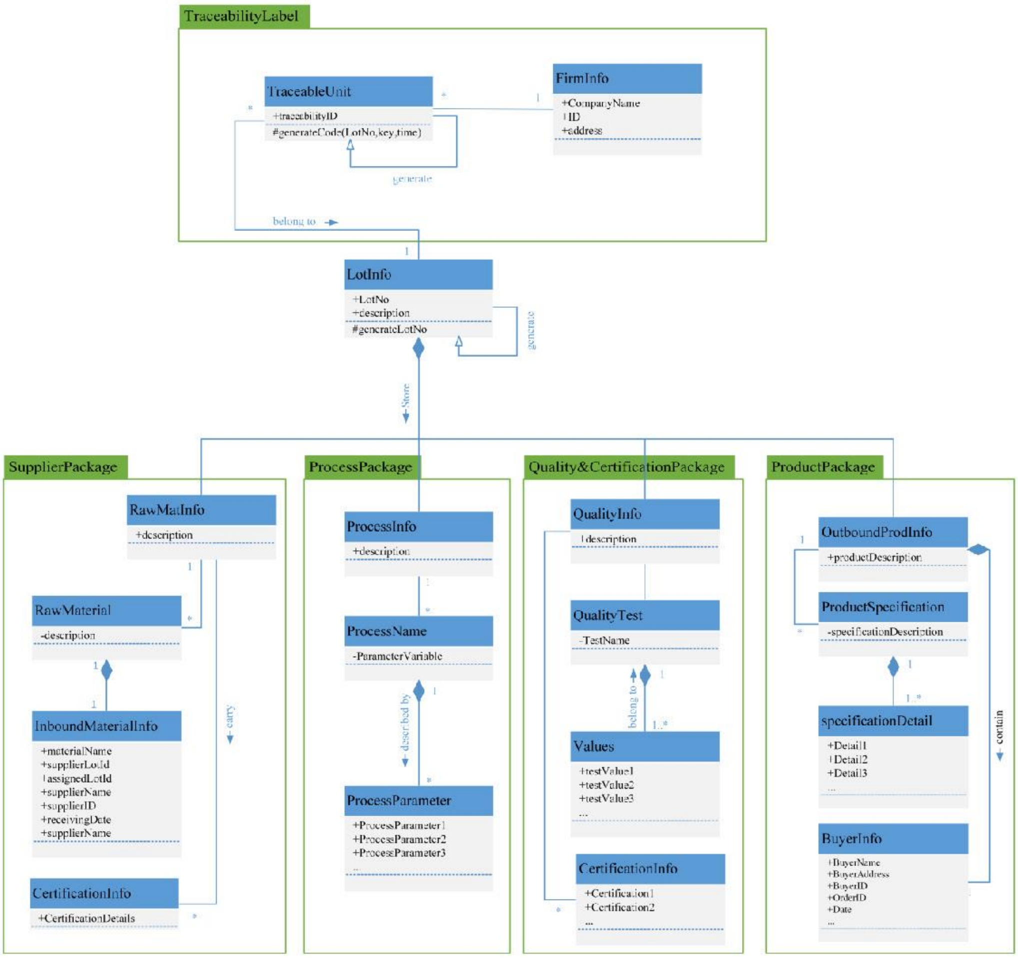

Figure 4. Unified modeling language (UML) static diagram for traceability information sorting and storing.

As mentioned before, the B2B actor imports the supplies from upstream actors and then transforms them physically or chemically by applying various processes. Therefore, it is important to preserve the link to inbound to outbound material information and applied processes during the implementation of traceability. Figure 4 shows the mutual traceability relation among various pieces of information. It primarily contains five packages, i.e., TraceabilityLabel, SupplierPackage, ProcessPackage, Quality&CertificationPackage, and ProductPackage which are targeted to store all relevant traceability information. Furthermore, these packages are linked to the product lot, i.e., LotNo, as a lot generally has products with the same attributes and process parameters. Therefore, the database contains the lot information along with the links to each traceable unit (as discussed in the later part of the paper). It should be noted that here we focus on a lot which represents a discrete entity, where each lot has items with identical attributes. Although in some special processes, a lot may not be represented as a discrete event. For example, a continuous dyeing process requires the continuous addition of dyes and chemicals to maintain the required concentration throughout the process; hence defining the batch or lot is difficult. In such case, alternate routes including the use of some special markers (acting as imaginary start and end) on the material can be used to define a batch or lot, which can be tracked throughout the processing [56]. Therefore the produced entities can be represented by the same traceability data. To identify or trace each item or batch of items uniquely in the supply chain, they are tagged as a traceable resource unit (TRU). The number of items in a TRU depends upon the resolution of required traceability, which signifies the preciseness of the identification. For example, if a TRU is assigned to a batch of 100 products, then each group of 100 articles can be identified uniquely but the articles within the batch are indistinguishable. The UML model in Figure 4 shows the data stored with reference to the individual lot; subsequently, each TRU carries a unique traceability ID which should be capable of recalling the lot number (LotNo) so that respective lot information can be retrieved from the database. The tracking number in the present case can be generated using a function as traceabilityID = generateCode (LotNo, time, key) which takes "LotNo", "time", and "key" as inputs. The "time" variable keeps updating at every instance so that the traceabilityID is always unique. The "key" variable is a private key which ensures that no unauthorized person can generate a duplicate traceabilityID. Therefore it needs to be protected by the producer. As the data is sorted in the database with respect to the LotID, the traceabilityID of the respective TRU needs to be turned back into the LotNo to recall the traceability information. It can be done by applying the inverse function on the traceabilityID with the help of the "public_key", i.e., (LotNo, time) = inverseGenerateCode (traceabilityID, public_key) which deciphers the LotNo from the traceabilityID. The "public_key" variable is dependent on the "key" variable. As traceability requires the forward track and backward trace of the product in the supply chain [57], the lot information consists of upstream suppliers' information to trace the lot backward and buyer information for tracing the product. Furthermore, the process and quality information are stored in the relevant fields by respective departments of a firm as shown in Figure 4. One purpose of keeping the information in packages is that each of the packages can be controlled and maintained by the respective department.

5. Inter-Actor or Full Supply Chain Traceability

Inter-actor or full supply chain traceability refers to the ability to track and trace the responsible actors, activities, and location of entities throughout the supply chain. It occurs when one actor hands over a TRU to another actor. Hu et al. [25] describe traceability as a risk management security system which also allows auxiliary functions including the flow of information documentation from raw materials to finished products in the supply chain. Furthermore, the TRU source and Traceable Item Recipient must communicate and record identification for maintaining the information flow [28]. The following sub-sections explain the strategies to be followed for implementing inter-actor traceability.

5.1. *Traceability Information Management and Sharing*

Information sharing is the fundamental requirement for implementing traceability in the supply chain. Traceability has different objectives for different stakeholders in the supply chain. Therefore, the information sharing should fulfill their respective objectives. Data storage and sharing among the actors can be carried out using mainly four types of database structures, including central, cumulative, one-up one-down, and network [12]. In the central database structure, all actors store the data on one centralized server; subsequently, whole traceability data remains in one place. On the other hand, in the cumulative configuration, all the data is collected and transferred to a downstream supply partner. Consequently, the data keeps growing cumulatively as the product physically advances in the supply chain, which offers challenges in terms of cost, data security, and implementation. The major barrier with the above-mentioned database structures is the confidentiality of the data and intellectual property (IP), as the confidential information cannot be shared in a free manner in the supply chain. European regulations mandate the one-up one-down model in the food sector [23]. This system ensures that each actor is responsible for linking the traceability information with one upstream actor and one downstream actor. Hence, the traceability works as a chain where every actor acts as a link. This system distributes the responsibility and each actor needs to keep the traceability information for immediate upstream and downstream actors. Nonetheless, a chain is only as strong as its weakest link. In the one-up one-down arrangement, if any of the actors goes inoperative, the traceability breaks—which is a major drawback of this system. On the other hand, the central system works irrespective of the existence of an individual actor in the supply chain since the data remains at one place. Conversely, the central database is favourable when one single actor is acting as the captain—which controls all the links in a supply chain. Hence the supply chain captain can force all the actors to use uniform semantics and store data on a central database. The fourth type of database structure, i.e., the network database, relies on sharing the traceability number instead of sharing the data. The traceability number acts as a reference for information retrieval from the respective actor. Bechini et al. [24] proposes the use of a third party to store and maintain the traceability numbers and the respective information about the supplier/manufacturer. In case someone requires the traceability information regarding a product, he/she needs to send the respective traceability number to the third party which decodes the supplier information and points the request to respective supplier's database. Furthermore, the supplier replies with the appropriate information to the third party, and the third party forwards the received information to the request generator. Following this mechanism, supply chain actors are responsible for their traceability data. According to [12], the network model is simple and the most efficient, which supports anti-counterfeiting policies with the ability to completely retrace product information. Nonetheless, the actors should follow the specified data format for assigning the traceability key so that the other supply chain actors can identify the respective traceability data owner to retrieve the relevant traceability data.

The textile supply chain consists of many small actors, which often face financial constraints; therefore, one-up one-down traceability could be a viable option as each of the actors would need to invest only on traceability required to link to the immediate upstream and downstream actors. However, all supply chain actors should be operative to provide full supply chain traceability. On the other hand, network traceability needs a third party to maintain the traceability network. Therefore, to design a robust data storage and sharing system, it is important to consider the interaction of the supply chain stakeholders.

The textile supply chain, similar to other supply chains, consists of multiple actors arranged in a hierarchical manner such as first tier supplier, second tier supplier, and so on, and as aforementioned, the retailer or brand owner acts as the main actor in most of the cases. Additionally, there are brokers, agents, and logistic partners which act as middlemen. These middlemen serve as mediators, who only handle the products and do not add any traceability information from the process or product perspective. Hence the first tier suppliers mean the suppliers (not the mediator) that directly interact with the retailers, whereas second tier suppliers are those suppliers that interact with the first tier suppliers. According to Lambert and Cooper [58], the supply chain network consists of multiple actors and integrating them is not only a complex issue but also counter-productive, since all the members are not equally important. Some links are more critical in terms of innovation and value creation (such as actors dealing with specialized materials) than other actors (such as actors which deal with regular materials). As a result, a firm tends to pay more attention to the former suppliers rather than the latter. Based upon this argument, for a company, the suppliers can be divided into mainly four categories—managed process links, monitored process links, non-managed process, and non-monitored process links [58]. Managed process links are the most important links for a buyer, which he/she would like to manage and make direct contact with them, whereas the remaining links are not that important, hence the buyer does not directly control them. For example, the retailer acts as supply chain captain in the textile sector which monitors the market demands and places orders to the upstream supplier. At the same time, the fashion industry is an innovative product-based industry where a firm needs to provide a steady stream of innovation [7]. The absence of design protecting regulations gives an easy edge to the imitator, which erodes the competition advantage available on innovative products [59]. Therefore, the retailer would like to manage all the actors who directly affect any innovation. The managed-links essentially consist of the 1st tier supplier. However, these can go beyond 1st tier suppliers [60].

The monitored process links involve the resources which are not critical to the brand owner, who acts as the supply chain captain. Therefore they are not directly managed by the supply chain captain; rather, they are occasionally audited. Similarly, not-managed process and non-monitored process links are neither actively monitored nor critical enough to use resources. Consequently, they are not integrated by the supply chain captain.

Based upon the above discussion, the managed links are directly in contact with the retailer, whereas the remaining links are not directly monitored. For appropriately managing and exchanging the traceability information, a hybrid inter-actor traceability configuration is shown in Figure 5. It involves the use of central traceability for managed-links and one-up-one-down traceability for the remaining links. Here central traceability does not necessarily imply that all actors will use only database. It implies that the supply chain actors have their own databases and they exchange the sharable information via a central data server which is maintained by the retailer. Therefore the retailer acts as a mediator which stores the information being exchanged between the managed links and controls the information flow. The region shown by direct links is the 1st tier suppliers only, whereas the managed links region shows the suppliers operated by the retailer using the managed links. Hypothetically, if one-up one-down traceability covers the whole supply chain, the retailer's direct reach for traceability is limited to direct links only. Whereas for traceability information related to retailer-owned managed links, the retailer has to go through a 1st tier supplier. This will inevitably lead to an increased response time. On the other hand, if the central traceability system is implemented to all the managed links, the retailer can directly reach all of them, bypassing the intermediaries (as shown in Figure 5). This can provide an advantage to the retailer regarding better control and more transparency. Moreover, from the application point of view, it is important for the retailer to hold the valuable information that could affect the business. Providing traceability to the consumers directly gives a financial advantage to the retailer, which can offset the investment in the central traceability system implemented. Moreover, the retailer, as the most influential actor in the supply chain, can force the managed-actors to follow the central traceability.

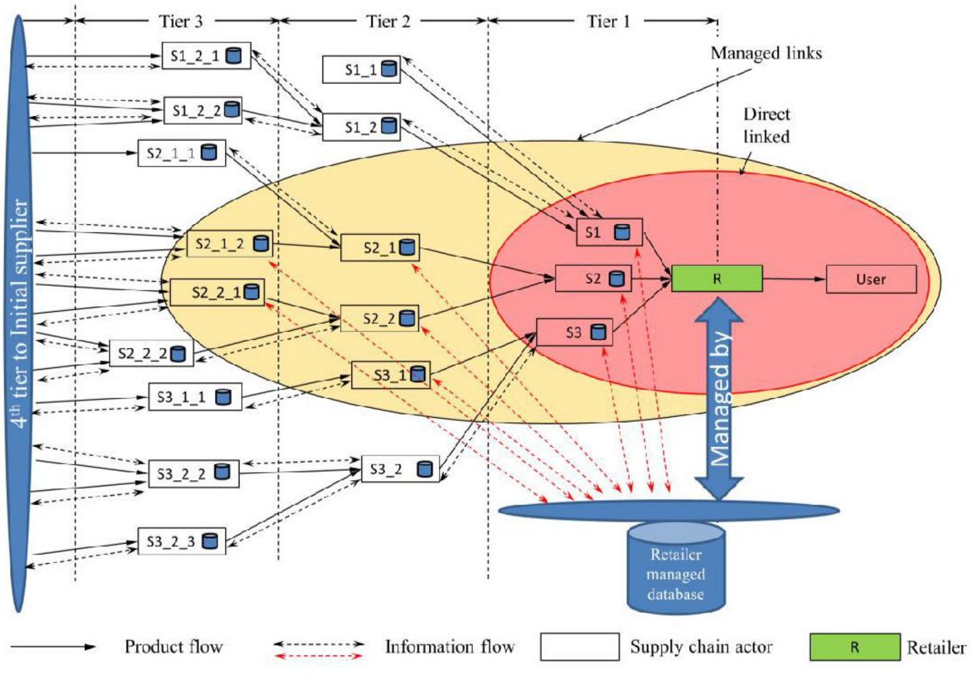

Figure 5. Supply-chain wide traceability (adapted from Lambert and Cooper [58]).

The other links, excluding managed links, are not directly controlled by the retailer; therefore, they interact indirectly with the retailer. In such scenario, one-up-one-down traceability is the most favourable approach, in which an actor maintains data for immediate upstream and downstream suppliers. Since the inter-actor traceability works by the participation of individual actors, the internal traceability should be maintained by individual actors as discussed in Section 4.

Figure 6 demonstrates an example of traceability in the textile supply chain and the corresponding information exchange between the actors for a hybrid traceability server using the UML sequence diagram. Figure 6a shows the retailer managed links from the fabric industry (weaver) to consumers; accordingly, the retailer places order directly to the fabric industry, dyeing industry, and apparel producer. The sequence of actions which needs to be followed for retrieving the traceability information is given in the form of the UML diagram as indicated in Figure 6b. It shows that the traceability information is initiated by the user, which can be a regulatory agent such as RAPEX or the customer. Based upon the extent of information, the traceability events take place combining different actors. For example, if some critical parameters of the fiber are requested, the traceability request takes place from the retailer to the fiber industry through intermediary actors and then the requested information is provided to the user via these intermediaries. Similarly, if the requested traceability information belongs to dyeing process which is directly managed by the retailer, then the retailer directly contacts the dyer and gets the appropriate information for the user.

5.2. *Traceability Information Exchange and Mapping*

Electronic data interchange (EDI) and XML are the means for information exchange in the industry. EDI uses a sequence of messages transmitted from the sender to the receiver. The transmission uses structured data which is agreed upon for both ends. Consequently, the sender and receiver should use a common framework to understand the transmitted data. XML, on the other hand, also uses structured data for transmission. The tag attributes in XML are used to separate the data fields, which help in understanding the data. Unlike EDI, XML uses a nested tree structure to transmit the information. A supplier's database would contain a large amount of data and when the traceability data is exchanged between two parties, that would involve the data belonging to a specific TRU. Therefore it is important that each TRU is marked with a traceabilityID (as discussed earlier) which points to the specific entry (i.e., lotNo) in the database. Therefore, when someone requests the traceability information about a specific TRU, he sends the traceability ID (marked on the TRU) to the respective supplier and the supplier replies with the information belonging to the particular TRU having the provided traceability ID. These unique codes can be implemented on products using radio frequency identification RFID tags and printed barcodes which are attached to the physical products. Recently, a yarn based-traceability tag has been devised for textiles which can be directly woven or knitted into the product [15]. This includes the use of special yarns which can be integrated into the fabrics; then the coding is directly implemented on the textiles. An example of traceability information exchange using XML is shown in the next section.

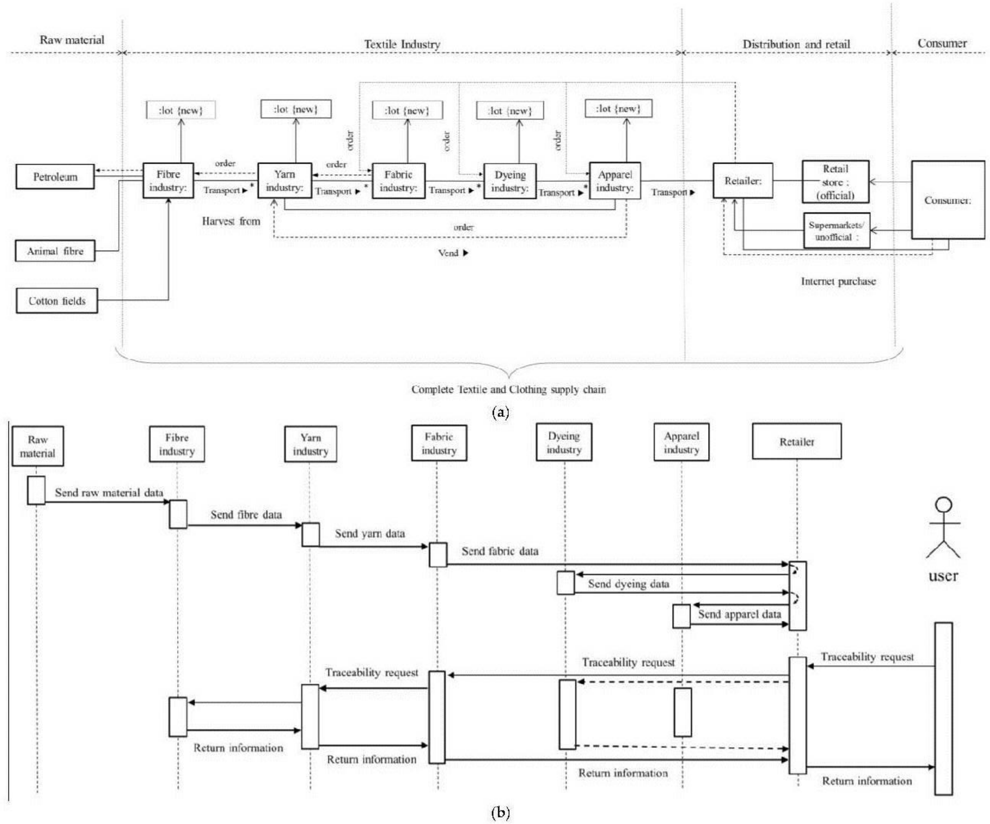

Figure 6. Supply chain illustration (**a**) shows the order and material movement in the supply chain and (**b**) shows the UML sequence diagram for traceability retrieval.

6. Illustration of Traceability Data Management Using RDBMS and Exchange Using XML

In this section, we shall describe an illustrative example of traceability information management using a relational database management system (RDBMS) for a textile weaver, following the framework mentioned in the earlier sections. Textile weaver primarily takes yarns as an input raw material and transforms them into the greige fabric using a weaving process. Besides weaving, there are many operations carried out by the weaver, which includes sizing, desizing, inspection, etc. For the purpose of the illustration, we take weaving and sizing as operations to store the information. Figure S1 (in the Supplementary File) shows the RDBMS formed according to the traceability information sorting the UML diagram as illustrated in Figure 4. It demonstrates the interaction of various small databases that can be designed for storing the critical traceability information. Furthermore, we consider a lot containing a finite number of traceability units, each having a unique traceability code; whereas the traceability information for the lot remains the same. Accordingly, the relation between Lot ID and Traceability ID is related using one-to-many cardinality.

In this example, we show that the traceability ID package contains the Lot ID. However, the traceability ID can be a generated value by the function which takes the input as the Lot ID, as discussed in an earlier section of this paper. Consequently, the Lot ID can be generated by the decryption of the traceability ID (i.e., by applying the inverseGenerate function as shown earlier) and the Lot No. related information can be requested or retrieved from the database. Figure 7 shows the partial view of the XML sheets generated for a record entry, i.e., the Lot ID, from the data stored in the databases. Here the data entries are separated using opening and closing tags such as <*Lot_ID*> xxxx </*Lot_ID*>. Furthermore, the lot data is nested in the lot tags . The XML sheet in Figure 7 contains all the available information related to a lot including the critical information that the weaver may not like to disclose to the downstream buyer. As a result, the weaver trims the information and provides only the component information which is required according to the agreement with the downstream buyer. Furthermore, both parties can agree on common unified semantics such as that defined by the XML Schema Definition (XSD) to follow for exchanging traceability data. XSD defines the rules that specify the elements and structure of an XML document. Therefore, having a standardized XSD would not only help in the smoother exchange of information, but also with cross-border partner organizations that have different working languages and with a standardized format; each one needs to translate the XML tags in their known language before communicating the traceability data to the next counterpart. Figure S2 (Supplementary File) shows the XML sheet for sharing information between the weaver and the downstream buyer. As previously mentioned, a lot contains a finite number of traceability units, each having a unique traceability code. Therefore the XML sheet in Figure S2 indicates the traceability ID instead of the Lot ID, and the information is referenced with the traceability ID. However, when the downstream player needs or requests extra information about the traceability unit, the downstream actor extracts the traceability ID available on the item in the form of a barcode or RFID and sent it to the weaver. The weaver then need to decipher the Lot ID for the corresponding traceability ID and obtains the Lot ID related full information from the database to provide to the downstream actor.

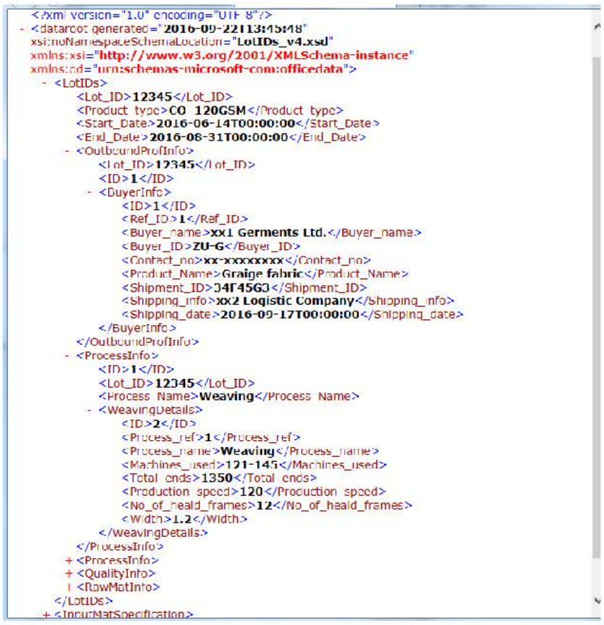

Figure 7. XML data sheet representing the traceability data for a lot.

7. Conclusions

Traceability has been a great concern in today's complex and opaque supply chains. A typical textile supply chain consists of multiple stakeholders—who are located in different parts of the world, specialized in distinct operations and following different regulations set by local bodies. Many supply chain actors combine raw materials from various suppliers and apply operations to create an outbound product with changed physical or chemical characteristics than that of the input materials. Subsequently, it becomes difficult to identify the providers of the input raw materials based on the outbound material if the proper information is not managed during the mixing, combining, or processing of the raw materials. Furthermore, the textile supply chain consists of multiple actors arranged in a sequential configuration; as a result, the identification of initial suppliers is far more complex because it involves the merging of diverse material lots at multiple levels of the supply chain by different actors. In this context, this article presents a traceability framework to capture, manage, and communicate the traceability information in the textile supply chain. The main task of implementing traceability is to identify the critical information to record or preserve, which is not only essential for an organization for better functioning or management and record-keeping purposes (such as to comply with regulations), but is also usable or required for the other supply chain stakeholders in the supply chain. Furthermore, the identified traceability information should be stored, managed, and linked properly in the databases so that it is accessible when some authorized body or organization in the supply chain requests it. Furthermore, information exchange semantics need to be standardized to reduce language barriers. Therefore, regulations from the governments can play an important role by formulating the guidelines for various actors and for the minimum required traceability.

From the risk perspective, as previously mentioned, the supply chain risk increases with the involvement of the global supply chains and more reliance on suppliers, which intensifies the need for visibility and supply chain information. In this context, the described traceability framework illustrates the process so that brand owners can have better information about their supply chains. In the case of quality issues or a recall, this information can be efficiently utilized to trace-back the involved suppliers to rectify the issue. However, traceability is a technology-driven concept, which relies on the adoption of appropriate technologies and maintenance of the system at each level of the supply chain [44]. According to Probst et al. [44], one of the major issues that companies confront is a lack of a skilled workforce to implement and maintain the traceability system. Moreover, the textile supply chain consists of actors dealing with specialized processes or activities and the critical information about them is kept confidential or is disclosed with only specific actors to avoid copying by competitors. In this context, any inadequacy in the protection of the traceability information can potentially increase the risk of disclosing critical data which can jeopardize the relation with other actors and benefit competitors. Nonetheless, the present article provides a generic framework to handle the situation related to traceability implementation in the textile supply chain. The next step would be to implement the proposed framework in an actual textile supply chain with real requirements; which would provide a better comprehension of the limitations and further modifications required for the refinement of this framework. Traceability is an information and communication technology (ICT)-based model, which also acts as a basis for other concepts including "smart cities" and the "Internet of Things" (IoT). Subsequently, future studies can be focused to align these concepts with traceability information and the amendments required in the proposed framework.

Supplementary Materials: The following are available online at www.mdpi.com/2079-8954/5/2/33/s1, Figure S1: RDBMS for data management at the weaver, Figure S2: Traceability data exchange between the weaver and downstream buyer.

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Paper V

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Article

Supply Chain Strategies for Quality Inspection under a Customer Return Policy: A Game Theoretical Approach

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Abstract: This paper outlines the quality inspection strategies in a supplier–buyer supply chain under a customer return policy. This paper primarily focuses on product quality and quality inspection techniques to maximize the actors' and supply chain's profits using game theory approach. The supplier–buyer setup is described in terms of textile manufacturer–retailer supply chain where quality inspection is an important aspect and the product return from the customer is generally accepted. Textile manufacturer produces the product, whereas, retailer acts as a reseller who buys the products from the textile manufacturer and sells them to the customers. In this context, the former invests in the product quality whereas the latter invests in the random quality inspection and traceability. The relationships between the textile manufacturer and the retailer are recognized as horizontal and vertical alliances and modeled using non-cooperative and cooperative games. The non-cooperative games are based on the Stackelberg and Nash equilibrium models. Further, bargaining and game change scenarios have been discussed to maximize the profit under different games. To understand the appropriateness of a strategic alliance, a computational study demonstrates textile manufacturer–retailer relation under different game scenarios.

Keywords: game theory; supply chain management; quality inspection; strategic management

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1. Introduction

The supplier–buyer strategic business relation management is an important aspect for both the supplier and the buyer in the supply chain [1]. This is particularly important when the success of one actor in the supply chain is highly dependent on the other. For instance, production outsourcing is one of the contemporary practices followed in the textile industry, where retailers do not own the production facilities and outsource their production activities to various suppliers [2]. Subsequently, the retailers are highly dependent upon the manufacturers for the product quality [3]. Production outsourcing helps the retailers in terms of reduced risk by not owning the production facilities and the reduced production cost since the manufacturer are located in countries where cheap labor is available, however, at the same time creates other responsibilities including proper quality inspection of the supplier-delivered products. Due to the increased manufacturer/supplier–retailer distance, the retailer cannot observe the production activities at a distantly located supplier. Further, there exist uncertainties in the supply chain associated with the demand, delivery time and customer requirements, which relate to the performance of the supply chain [4]. As supplier and retailer may have divergent priorities in terms of investment in production quality, this gives an advantage as well as the malicious opportunity to the suppliers to provide defective or inferior products to the retailer [5]. In this context, the responsibility of the retailer is to implement an optimal quality inspection strategy to minimize or avoid the risks associated with defective products.

Quality inspection helps in identifying the defective or non-conforming items or supplies provided by a supplier. However, as all the product characteristics are difficult to inspect due to technological and financial constraints, there is always a possibility of defective products reaching the end-user customer [3]. In such events, it is important for the retailer to provide a fair compensation on product returns (such as product repair, replacement, discount, etc.) to ensure the confidence of customers [6–8]. Furthermore, the financial liabilities associated with the above-mentioned product return-based compensations have prompted practitioners and researchers to reassess the quality inspection policies and share the defective product borne liabilities with the supplier who is the originator of the defect.

With the increasing importance of quality inspection aspect, many researchers have explored the potential of different supply chain practices. Cheng et al. [3] described inspection measures in two categories: ex-ante and ex-post. Ex-ante includes the traditional quality inspection techniques where the supplier and retailer formulate a quality contract and the retailer inspects the supplies by random inspection methodology. The effect of quality/inspection policies with/under inventory policies [9], penalties [10], rewards, joint lot sizing [11,12], return policies [8,13], uncertain demand [14] and ordering policies [15] on supply chain contracts have been discussed. Heish and Liu [5] have discussed the optimal investment in quality and inspection activities with different degrees of information revealed among the manufacturer and supplier.

More recently, increasing attention has been paid to traceability-based ex-post quality inspection techniques [3,16,17]. Traceability-based ex-post inspection extends the quality inspection perspective beyond the point of supply transaction and any quality-related issue can be traced back at any stage of the product lifecycle using the traceability information. One of the primary reasons for the move toward ex-post inspection is the limitation associated with traditional inspection-based contracts (ex-ante), which provide an opportunistic prospect for malfeasance by the supplier due to the imperfect inspection techniques and expenses [3]. The extended quality inspection by traceability-based ex-post quality inspection is particularly important for textile products which have a large number of quality characteristics, and measuring them is not only time-consuming, but technologically and monetarily expensive [3,18]. Subsequently, it is more effective for the retailer. According to GS1 Global Traceability System [19], traceability is defined as "the ability to track forward the movement through specified stage(s) of the extended supply chain and trace backwards the history, application or location of that which is under consideration." Therefore, any quality-related issues identified beyond the point of supply transaction (where ex-ante inspection ends) can be traced back to its origin. Studies to approach different business objectives using traceability have been discussed in the past. For the food and agribusiness, traceability has been discussed in relation with safety, recalls, inventory management and other related aspects including quality management system, product and process history [10,16,17,20,21]. Cheng et al. [3] explored traceability for optimizing supply chain quality from a textile supply chain perspective.

The textile sector has also seen a large transformation arising due to several factors, including migration of the industry towards certain countries resulting in complex supply chains, and the emergence of concepts like fast fashion, which has significantly reduced the fashion lifecycle. Further, there are a number of uncertainties associated with market demands, changing product variety, the rate of product innovation, production lead-time, delay in logistics delivery, failure of firms to deliver the product or raw material, etc. [22]. In addition, issues like vendor-managed inventory are a general concern for supply chain management [23]. Concerning this, Christopher et al. [24] addressed the fashion market as a system with a high level of "chaos". Supply chain actors are becoming more collaborative to plan the strategies to minimize different risks and uncertainties, and improving the efficiency of the supply chain [4]. According to Martino et al. [25], the first step to manage the various risks associated with such a chaotic supply chain is to analyze the internal processes to isolate the most relevant weakness factors. In this context, quality is a key competitive factor in the textile industry, however, it is attained as a result of successive quality management strategies implemented at different levels in the supply chain [3,18]. Generally, a supply chain actor will be willing to invest in producing a better product or a quality inspection system (or any other context) as long as it benefits him directly or indirectly. Furthermore, the investment and benefits are also affected by the relation with the other actors in the supply chain. Several researchers have identified the supply chain management factors affecting the quality of products [26] and have quantified the benefits of product quality or related investments in terms of profit, using different relationships with other supply chain members and associated uncertainties [3,5,8,14]. In the context of quality inspection strategies, most of the literature has either focused on random quality inspection based ex-ante techniques [7,27,28] or traceability-based ex-post techniques [10,17]. Furthermore, limited attention has been paid to combining these techniques simultaneously with different supply-chain dynamics (such as power asymmetries and cooperation between the supply chain actors). Nevertheless, Cheng et al. [3] illustrated the optimization of a fashion supplier–manufacturer chain with inspection control and traceability control methodologies.

Thus, this article aims to demonstrate the appropriateness of simultaneously implementing a conventional random quality inspection (ex-ante) technique and a recently emerged traceability-based (ex-post) technique in the supply chain using a game theory approach. The objective is to maximize the profits of supply chain actors considering different power asymmetries in the supply chain, which covers a research gap observed in the literature.

Here the focus is given to a textile manufacturer–retailer relation under product return policy using game theoretic approach, where the textile manufacturer and retailer try to maximize their respective profits by controlling investments in production and quality inspection (ex-ante and ex-post), respectively. Retailers in a supply chain act as a link between the final consumer and the manufacturer/supplier [29]. Retailers act as "gatekeepers", determining the market demands and placing orders with the manufacturer [30]. For a given cost of the product paid by the retailer to a textile manufacturer, the textile manufacturer's main objective is to maximize his profit by minimizing the investment in production (or product quality). Whereas, the retailer would like to have maximum product quality so that he has a less product returns. Moreover, the retailer also considers opting for random inspection policy and traceability. Random quality inspection allows filtering of non-conforming products received from the textile manufacturer, whereas traceability ensures that if a consumer reports a fault or returns the product, the retailer can identify the textile manufacturer to penalize him. Traceability has in fact recently highlighted the necessity for the retailers from various perspectives including warehouse management, supply chain visibility, safety, security, product recalls and economic incentives associated traceability information [17,31]. In the textile supply chain, a retailer is often associated with multiple suppliers for different types of product. Therefore traceability helps the retailer to identify the manufacturer of different products [32].

The subsequent parts of the paper are organized as follows: Section 2 describes our model framework. Section 3 describes the textile manufacturer–retailer relations in four different game scenarios, among which three (two Stackelberg games and one Nash game) are non-cooperative, and one is a cooperative game scenario. Section 4 discusses the suitability of different game models from the textile manufacturer's and retailer's perspectives, the possibility of bargaining and forced cooperation among the actors for the profit maximization. Section 5 demonstrates a numerical example for illustrating the models. Finally, Section 6 concludes this paper and provides suggestions for future research.

2. Model Framework

According to Surana et al. [33], "A supply chain is a complex network with an overwhelming number of interactions and inter-dependencies among different entities, processes and resources." Present global supply chain networks consist of numerous enterprises linked together through a complex interplay of products and services, consistently work to improve the supply chain effectiveness and decision making to sustain an advantage against the competition generated by growing number of industries [34,35]. In this context, mathematical models coupled with behavior and organizational theories provide a sound framework for practices and decision-making in complex networks of collaborating enterprises [27–30]. Since the supply chain consists of multiple enterprises integrated by some common goals but having different constraints and conflicting objectives, these enterprises can be seen as players in a game [36–38].

We use a game theory approach to analyze the relationship between the textile manufacturer and the retailer. The model used in this paper is based on supplier-buyer relation under constant demand used in the past [27,28,39]. It should be noted that in the supply chain literature, the terms vendor, seller, supplier, and manufacturer have been used interchangeably to represent the manufacturer. Similarly, the terms retailer, buyer, and distributor have been used to represent the retailer. To avoid ambiguity in this paper we use the terms textile manufacturer and retailer. The model assumes three components of the supply chain, namely textile manufacturer, retailer, and customer, which is similar to that of used in the literature (e.g., [3,16,17,28]). The textile manufacturer serves the retailer and the retailer serves the end-use customer. As proposed in the literature, a customer's buying preference is influenced by multiple factors, including product quality, product specification, brand value, trends, and services such as product return policies and traceability where the customer can trace back the product and raw material history [40,41]. In light of constant demand and price assumptions, we neglect the factors such as brand preference and trend. In order to counterbalance any quality-related issues, we assume the retailer provides fair compensation to the customer so the customer comes back to the retailer in future and maintains a constant demand. Further, we assume traceability as a tool for the retailer to identify the textile manufacturer, not a tool for consumers to know the product history. Therefore, the level of traceability does not affect the customer or product quality. Furthermore, the retailer accepts all product returns in case of a defect; however, we treat the probability of return by a customer as an exogenous function. It should be noted that when only one textile manufacturer and one retailer are involved in the supply chain, it is obvious that the retailer can fully identify the textile manufacturer in the case of a product return, without needing to use any traceability. In practice, multiple textile manufacturers may serve a single retailer (e.g., the Swedish clothing brand H&M has ~750 suppliers [42]). Therefore, traceability helps in identifying which particular product belongs to which supplier. In this paper, we represent the same situation by one retailer and one textile manufacturer (also considered in a similar way in the literature e.g., [17]), where the retailer has a certain probability s to identify the textile manufacturer and then there is a $1 - s$ probability that the retailer cannot identify the textile manufacturer.

2.1. Assumptions

In order to reduce the complexity we make the following assumptions in the proposed textile manufacturer–retailer relation:

i. All the actors are rational.
ii. All parameters are deterministic and known in advance.
iii. Demand and market price functions (I_1, I_2, I_3) are constant. Although the demand and product quality are related to each other but we assume that retailer provides enough compensation to satisfy the consumer when the consumer reports a faulty/non-conforming product. Following Ref. [17], we assume $I_1 > I_2 > I_3$.

iv. Production quality, random quality inspection level and traceability level are controllable and follow their respective cost functions (i.e., $C_p(P)$ and $C_{Qs}(Q,s)$) (also used in the literature, cf. [3]).
v. Return of the product is applicable to the faulty products, which were sold as a good product by the retailer. The return rate i.e., probability of a product return is an exogenous function.
vi. The retailer can accept a faulty product but cannot reject a non-faulty/conforming product to the textile manufacturer.
vii. Both actors should individually make a positive profit to remain in the game.

The remaining assumptions are described in the text when they appear.

2.2. Textile Manufacturer–Retailer Interaction

We assume that the textile manufacturer knows how to produce a retailer-ordered conforming product and the production cost follows a production cost function $C_p(P)$, where P is the probability that the product produced by the manufacturer conforms to the retailer's requirements. The production cost function is an increasing concave function, i.e., $C_p(\bullet) > 0, C'_p(\bullet) > 0, C''_p(\bullet) > 0$. Similar to [3,43], we chose the production cost functions in the form $C_p(P) = \alpha_p + \frac{1}{2}\beta_p P^2$.

After receiving the shipment from the textile manufacturer, the retailer invests in random quality inspection and traceability. The retailer firstly inspects the received product and generates an appraisal by quality inspection, Q, where Q represents the probability that the retailer identifies a product as non-conforming. Similar to reference [3], it is assumed that the retailer can commit Type-I errors, i.e., he may not identify a non-conforming product as conforming, but cannot commit Type-II errors, i.e., he cannot appraise a conforming product as non-conforming. As it is well acknowledged in the literature that for the textile products it is rather difficult to monitor or measure all the quality characteristics due to technological or cost constraints [3,44], therefore there exists a probability of Type-I error. Nevertheless, the identified non-conforming products are sold in the market at a lower market price (I_2) than that of conforming product (I_1). In order to recover the loss caused by a non-conforming product, the retailer penalizes the textile manufacturer. For rationality, the retailer sets the penalty cost as A, where $A = I_1 - I_2$, therefore, retailer earns the same selling price (i.e., $I_2 + A$) as for a conforming product (i.e., I_1). Selling faulty textiles at a lower price is the general practice in the textile supply chain where retailer may remove the retailer's/brand's identification marks such as logos and labels from garments and then sell them at a lower price. By selling faulty textiles as a generic garments (i.e., without any brand information), retailer/brand owner protects himself from a negative brand image.

Further, as mentioned above, since the retailer can commit Type-I errors, there is a certain probability that he cannot identify all the non-conforming inbound products. In this context, the retailer invests in traceability implementation so that he can identify the manufacturer if a consumer returns a non-conforming product that has escaped the quality inspection. Here traceability, s, is defined as the probability that the retailer can identify the manufacturer, i.e., $0 \le s \le 1$, as defined by [17]. Further, to protect the brand value, the retailer gives a discount B (so the net selling price is $I_3 = I_1 - B$) to the customer to satisfy the consumer and places a penalty (B) on the textile manufacturer to recover the loss because of the discount.

As discussed by [3] the quality inspection and traceability implementation cost to the retailer follow an increasing concave function. Therefore we use, $C_{Qs}(Q,s) = \left(\alpha_Q + \beta_Q \frac{Q^2}{2}\right) + \left(\alpha_s + \beta_s \frac{s^2}{2}\right)$, $(\alpha_Q, \alpha_s, \beta_Q, \beta_s) > 0$ such that $C_{Qs}(\bullet) > 0$, $\frac{\partial C_{Qs}(\bullet)}{\partial Q} > 0$, $\frac{\partial C_{Qs}(\bullet)}{\partial s} > 0$, $\frac{\partial^2 C_{Qs}(\bullet)}{\partial^2 Q} > 0$, $\frac{\partial^2 C_{Qs}(\bullet)}{\partial^2 s} > 0$, hence $C_{Qs}(Q,s)$ is an increasing concave function.

The textile manufacturer–retailer relation is shown in Figure 1. A list of the nomenclature used in this paper is shown in Table 1.

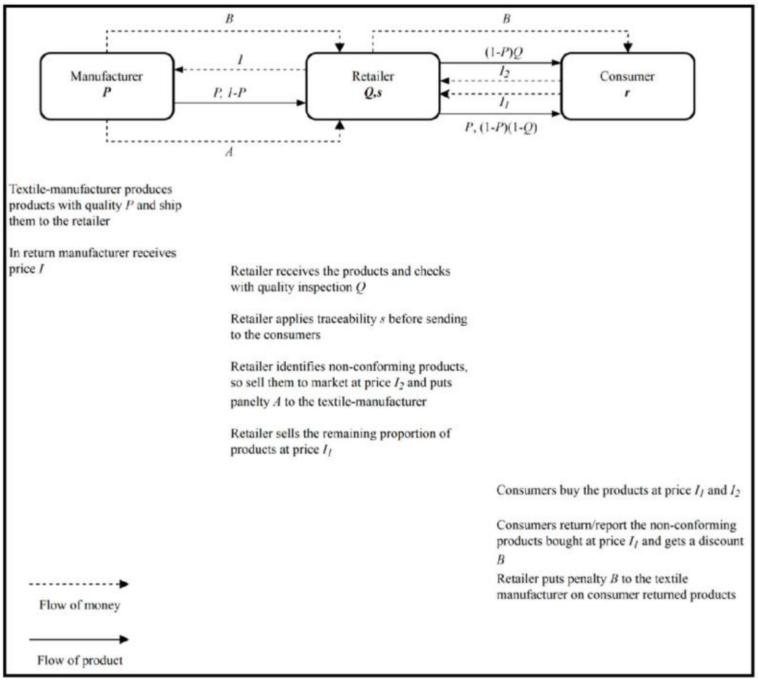

Figure 1. Product and money flow in the textile manufacturer–retailer game.

Table 1. Notations.

Notation	**Description**
A, B	Penalty costs to the textile manufacturer for the non-conforming products identified in random quality inspection and traceability respectively
$C_p(P), C_{Qs}(Q,s)$	Cost functions for implementing product quality (P), and quality inspection techniques (Q, s) respectively
I	The price per product charged by the manufacturer to the retailer
I_1	Selling price charged by the retailer to the consumer
I_2	Selling price of non-conforming product identified by the retailer
I_3	Net selling price of the non-conforming/defected product identified by the consumer
K	Coefficient deciding the profit proportion of the follower
P	Product quality rate, as proportion of product that succeed to meet the retailer's quality requirement or conformation, $0 \leq P \leq 1$
Q	Random quality inspection rate, as the proportion of nonconforming products detected in quality inspection, $0 \leq Q \leq 1$
r	Return rate, as the proportion of the non-conforming product returned by the consumer. $0 \leq r \leq 1$
s	Traceability success rate, as the proportion of the return successfully identified by the retailer to the manufacturer. $0 \leq s \leq 1$
α_P, β_p	Coefficients related to cost function $C_p(P)$
$\alpha_Q, \alpha_s, \beta_Q, \beta_s$	Coefficients related to cost function $C_{Qs}(Q,s)$
γ	Factor related to relative bargaining power of the textile manufacturer and the retailer
Π_{TM}	Manufacturer's profit per product
Π_R	Retailer's profit per product
Π	Total supply chain profit, $\Pi = \Pi_{TM} + \Pi_R$

Superscripts *TM*, *R*, *N* and *C* have been used with the above parameters to represent that they belong to the Stackelberg's textile manufacturer game, the Stackelberg's retailer game, the Nash game and cooperative game, respectively.

2.3. Textile Manufacturers Model Formulation

The textile manufacturer's objective is to maximize his profit by investing in product quality P to minimize the penalty from non-conforming products. Similarly, the product cost i.e., I is decided by the textile manufacturer to maximize his profit. Based upon the discussion in the last section, the following textile manufacturer's objective function, Π_{TM}, can be formulated:

$$\Pi_{TM} = I - \underbrace{(1-P)\,QA}_{x} - \underbrace{(1-P)\,(1-Q)\,srB}_{y} - C_p\,(P) \tag{1}$$

where the term denoted by x represents the penalty cost to the textile manufacturer imposed by the retailer for the non-conforming products identified during the retailer's random quality inspection, and y represents the penalty cost to the textile manufacturer imposed by the retailer for traceable non-conforming products returned by the consumer. The division of the product into various components is shown in Table 2.

Table 2. Description of various components' division during product flow.

Sr. No.	Description	Proportion
1	Proportion of good products among total produced products	P
2	Proportion of non-conforming products among identified in retailer's random quality inspection	$(1-P)\,Q$
3	Proportion of traced non-conforming products which were not identified in retailer's random quality inspection but returned by the consumer	$(1-P)\,(1-Q)\,sr$
5	Proportion of non-conforming products which were not identified in retailer's random quality inspection and also did not return by the consumer	$(1-P)(1-Q)(1-r)$
6	Proportion of non-traceable non-conforming products which were not identified in retailer's random quality inspection but returned by the consumer	$(1-P)(1-Q)(1-s)r$
	Total	1.0

Since $\frac{\partial^2 \Pi_{TM}(P)}{\partial P^2} < 0$ therefore Π_{TM} can be maximized for a fixed value of I by applying the first-order condition to Equation (1) i.e.,

$$\frac{\partial \Pi_{TM}(P)}{\partial P^2} = 0 \Rightarrow P^* = \frac{QA + (1-Q)\,srB}{\beta_P} \tag{2}$$

It should be noted that * denotes the optimum parameter.

According to the condition $0 \leq P \leq 1$, Equation (2) can be written as:

$$P^* = \min\left\{1, \frac{QA + (1-Q)\,srB}{\beta_P}\right\} \tag{3}$$

Further, as it can be seen in Equation (1) that Π_{TM} is linear function of I, the value of I (denoted by I_0) that results to $\Pi_{TM} = 0$ can be calculated as:

$$I_0 = (1-P)\,QA + (1-P)(1-Q)srB + C_p(P) \tag{4}$$

According to assumption vii, every actor needs to make a non-zero positive profit for a successful contract. Hence, $I > I_0$ or $I = KI_0$ where K is >1 [45]. Therefore the optimum I can be calculated as:

$$I^* = K\left\{(1-P)QA + (1-P)(1-Q)srB + C_p(P)\right\} \tag{5}$$

2.4. Retailer's Model Formulation

Retailer's objective to maximize his profit by optimizing his random quality inspection and traceability. Retailer's objective function can be formulated based upon Figure 1 as:

$$\Pi_R\,(Q,s) = \{P + (1-P)(1-Q)(1-r)\}\,I_1 + (1-P)Q(I_2 + A) + (1-P)(1-Q)sr(I_3 + B) + (1-P)(1-Q)(1-s)rI_3 - I - C_{Qs}(Q,s) \tag{6}$$

$\Pi_R\,(Q,s)$ is a concave function *w.r.t.* s for a fixed Q (since $\partial^2\Pi_R\,(s,Q)\,/\partial s^2 = -\beta_s < 0$), therefore the value of s that maximizes Equation (6) can be calculated by applying the first-order condition to Equation (6) *w.r.t.* s, i.e.,

$$\frac{\partial \Pi_R}{\partial s} = 0 \Rightarrow s\,(Q) = \frac{r(1-P)(1-Q)B}{\beta_s} \tag{7}$$

Similarly, $\Pi_R\,(s,Q)$ is a concave function *w.r.t.* Q for a fixed s (since $\partial^2\Pi_R\,(s,Q)\,/\partial Q^2 = -\beta_s < 0$), therefore the value of Q that maximizes Equation (6) can be calculated by applying the first-order condition to Equation (6) *w.r.t.* Q, i.e.,

$$\frac{\partial \Pi_R}{\partial Q} = 0 \Rightarrow Q\,(s) = \frac{(1-P)(1-s)rB}{\beta_Q} \tag{8}$$

Further, optimum values of Q and s can be calculated by plugging Equation (7) into Equation (8) and then solving for Q and s:

$$s^* = \frac{\beta_Q r(1-P)B - r^2(1-P)^2B^2}{\beta_Q\beta_s - r^2(1-P)^2B^2} \tag{9}$$

$$Q^* = \frac{\beta_s r(1-P)B - r^2(1-P)^2B^2}{\beta_Q\beta_s - r^2(1-P)^2B^2} \tag{10}$$

To follow the conditions i.e., $0 \le Q \le 1$ and $0 \le s \le 1$, Equations (9) and (10) can be rewritten as:

$$s^* = \begin{cases} 0, & \text{if } (\beta_Q\zeta - \zeta^2)(\beta_s\beta_Q - \zeta^2) < 0 \\ 1, & \text{if } \frac{\beta_Q\zeta - \beta_s\beta_Q}{\beta_s\beta_Q - \zeta^2} > 0 \\ \frac{\beta_Q\zeta - \zeta^2}{\beta_s\beta_Q - \zeta^2}, & \text{else} \end{cases} \tag{11}$$

$$Q^* = \begin{cases} 0, & \text{if } (\beta_s\zeta - \zeta^2)(\beta_s\beta_Q - \zeta^2) < 0 \\ 1, & \text{if } \frac{\beta_s\zeta - \beta_s\beta_Q}{\beta_s\beta_Q - \zeta^2} > 0 \\ \frac{\beta_s\zeta - \zeta^2}{\beta_s\beta_Q - \zeta^2}, & \text{else} \end{cases} \tag{12}$$

where, $\zeta = r(1-P)B$.

Additionally, the supply chain profit Π can be calculated by adding the individual profits of textile manufacturer i.e., Π_{TM} from Equation (1) and that of the retailer i.e., Π_R from Equation (6), given as:

$$\Pi = \Pi_{TM} + \Pi_R = \{P + (1-P)(1-Q)(1-r)\}\,I_1 + (1-P)QI_2 + (1-P)(1-Q)srI_3 + (1-P)(1-Q)(1-s)rI_3 - C_{Qs}(Q,s) - C_p(P) \tag{13}$$

3. Formulation of Game Scenarios

Game theory is one of the most widely used tools employed in the past to analyze situations involving conflict and cooperation [38,46]. In the textile supply chain, there exists a dynamic field of conflicting and cooperative objectives in the supplier-retailer relation [30]. Cooperation is described as a favored situation benefitting the whole supply chain [30,47], however, when the conflicting interests of actors outweigh the cooperating interests, the supply chain efficiency is reduced [48]. Recently, with the increased level of outsourcing, buyer firms are placing more emphasis on the relations with the suppliers, hence moving towards more cooperative scenarios [49]. In the case of textile manufacturer–retailer relations, the power is often skewed toward either of the parties. For instance, big retailers placing big orders are often able to exert power on smaller suppliers to reduce prices [50]. Therefore, in the quest to achieve higher profit coupled with power dominance, the retailers tend to move away from cooperation [51]. Although, a non-cooperative contract may help the power-dominating player earn more profit, the overall profit of the supply chain is hindered [30]. Such a relationship can be termed as a vertical alliance between a leader and a follower. When both the parties involved in a contract have equal power and both target their strategies simultaneously at maximizing their profits, the relation again moves away from cooperation to a polarized non-cooperating game [38]. When the actors, either cooperatively decide a strategy to maximize the profit of the supply chain (cooperative game), or simultaneously and non-cooperatively set their strategies to maximize the own profits, their alliance in the contract can be termed as a horizontal alliance. In the latter case, both actors act as "supply chain captains", working toward their profit whereas in the former case, none of the actors acts as supply chain captain.

In the light of scenarios discussed above, we discuss the textile manufacturer–retailer relation in two types of games namely, non-cooperative and cooperative games. The non-cooperative game has three cases depending upon the dominance of the actors i.e., dominant textile manufacturer (Stackelberg's textile manufacturer game), dominant retailer (Stackelberg's retailer game) and both having equal power (Nash game).

3.1. Non-Cooperative Games

In this section, we model various relations between the textile manufacturer and retailer in the non-cooperative way, i.e., an actor in the textile manufacturer–retailer network works toward optimizing his own profit. The non-cooperative games are discussed in the three following scenarios.

3.1.1. The Stackelberg's Textile Manufacturer Game

In the Stackelberg's textile manufacturer game, the textile manufacturer is power dominant and acts as leader, while the retailer acts as a follower. The leader has absolute power to maximize his profit while leaving the follower with the minimum profit needed to retain him in the contract [38,52]. Therefore, firstly the textile manufacturer takes the retailer's controlled optimum parameters i.e., Q and s then adjusts his own controlled parameters i.e., P and I so that the textile manufacturer maximizes his profit. As can be seen in Equation (1), the textile manufacturer's profit Π_{TM} is a linearly increasing function of I, where the manufacturer keeps on increasing I to maximize his profit and leave the retailer with zero profit i.e., $\Pi_R = 0$. I for $\Pi_R = 0$ (denoted by I_0) can be written as:

$$I_0 = \{P + (1-P)(1-Q)(1-r)\} I_1 + (1-P)Q(I_2 + A) + (1-P)(1-Q)sr(I_3 + B) + (1-P)(1-Q)(1-s)rI_3 - C_{Qs}(Q,s) \quad (14)$$

According to assumption vii, every actor needs to have a non-zero positive profit for a successful contract. Therefore, we take $I < I_0$ or $I = \frac{I_0}{K}$ where $K > 1$, which results $\Pi_R > 0$.

Further, the textile manufacturer's objective function can be written as:

$$\max_{P,I} \Pi_{TM} = I - (1-P)\, QA - (1-P)\,(1-Q)\, srB - C_p\,(P) \quad (15)$$

subject to:

$$0 \leq P \leq 1 \quad (16)$$

$$s = \begin{cases} 0, & if\ (\beta_Q\zeta - \zeta^2)(\beta_s\beta_Q - \zeta^2) < 0 \\ 1, & if\ \frac{\beta_Q\zeta - \beta_s\beta_Q}{\beta_s\beta_Q - \zeta^2} > 0 \\ \frac{\beta_Q\zeta - \zeta^2}{\beta_s\beta_Q - \zeta^2}, & else \end{cases} \tag{17}$$

$$Q = \begin{cases} 0, & if\ (\beta_s\zeta - \zeta^2)(\beta_s\beta_Q - \zeta^2) < 0 \\ 1, & if\ \frac{\beta_s\zeta - \beta_s\beta_Q}{\beta_s\beta_Q - \zeta^2} > 0 \\ \frac{\beta_s\zeta - \zeta^2}{\beta_s\beta_Q - \zeta^2}, & else \end{cases} \tag{18}$$

$$I = \left[\begin{array}{r} \{P + (1-P)(1-Q)(1-r)\} I_1 + (1-P)Q(I_2 + A) + (1-P)(1-Q)sr(I_3 + B) + \\ (1-P)(1-Q)(1-s)rI_3 - C_{Qs}(Q,s) \end{array} \right] / K \tag{19}$$

It should be noted that the subscript TM is used with the above-optimized parameters in later sections (i.e., $P^{TM}, I^{TM}, s^{TM}, Q^{TM}$) to represent the optimized parameters during the comparison with the other game scenarios.

3.1.2. The Stackelberg's Retailer Game

In this game scenario, we model a retailer-dominated textile manufacturer–retailer relation using the Stackelberg's retailer game model. The retailer has absolute power to maximize his profit while leaving the textile manufacturer with the minimum profit to retain him in the contract. Therefore, firstly the retailer takes the textile manufacturer controlled optimum parameters i.e., P and I then adjusts his own controlled parameters i.e., Q and s so that the retailer maximizes his gains. Therefore, the retailer's objective maximization problem can be written as:

$$\begin{aligned} \max_{Q,s} \Pi_B = \{P + (1-P)(1-Q)(1-r)\}I_1 + (1-P)Q(I_2 + A) + (1-P)(1-Q)sr(I_3 + B) + \\ (1-P)(1-Q)(1-s)rI_3 - I - C_{Qs}(Q,s) \end{aligned} \tag{20}$$

subject to:

$$0 \le Q \le 1 \tag{21}$$

$$0 \le s \le 1 \tag{22}$$

$$P = \min\left\{1, \frac{QA + (1-Q)\,srB}{\beta_P}\right\} \tag{23}$$

$$I = K\{(1-P)QA + (1-P)(1-Q)srB + C_P(P)\} \tag{24}$$

3.1.3. The Nash Game

In this section, we follow the Nash game model to formulate a textile manufacturer-retailer game model where both the actors non-cooperatively and simultaneously maximize their own profits on their own. Therefore, in this game, we have two objective functions to maximize with the following conditions:

$$\begin{aligned} \max_{Q,s} \Pi_R = \{P + (1-P)(1-Q)(1-r)\}I_1 + (1-P)Q(I_2 + A) + (1-P)(1-Q)sr(I_3 + B) + \\ (1-P)(1-Q)(1-s)rI_3 - I - C_{Qs}(Q,s) \end{aligned} \tag{25}$$

subject to:

$$0 \le Q \le 1,\ 0 \le s \le 1 \tag{26}$$

and:

$$\max_{P,I} \Pi_{TM}(P,I) = I - (1-P)\,QA - (1-P)\,(1-Q)\,srB - C_P(P) \tag{27}$$

subject to:

$$0 \leq P \leq 1 \tag{28}$$

As can be seen from Equation (27) Π_{TM} is a linear function of I, thus the textile manufacturer will obtain his maximum profit by increasing with a value of I which obviously leaves the retailer with a zero profit. Similarly, Π_R is a negative linear function of I (Equation (25)) thus to maximize Π_R the retailer needs to have the minimum possible value of I which will obviously leave the textile manufacturer with zero profit. In this conflicting scenario, we incorporate a hypothesis as used in Ref. [52,53]: if the textile manufacturer and the retailer make their decisions simultaneously then they both receive equal margin so that both the parties get equal profit, i.e., $\Pi_{TM} = \Pi_R$, which results in:

$$I = \frac{1}{2}\left[\begin{array}{r} \{P + (1-P)(1-Q)(1-r)\}\, I_1 + (1-P)Q(I_2 + 2A) + (1-P)(1-Q)sr(I_3 + 2B) + \\ (1-P)(1-Q)(1-s)rI_3 - C_{Qs}(Q,s) + C_P(P) \end{array}\right] \tag{29}$$

The optimum Q and s have been solved for Π_R in Equations (11) and (12), and P has been solved for Π_{TM} Equation (3). Thus the Nash equilibrium can be obtained by the following parameters:

$$P^N = \begin{cases} 0 & if\ (\beta_Q rB - \xi^2)(\beta_P\beta_Q - \xi^2) < 0 \\ 1 & if\ \frac{\beta_Q rB - \beta_P\beta_Q}{\beta_P\beta_Q - \xi^2} > 0 \\ \frac{\beta_Q rB - \xi^2}{\beta_P\beta_Q - \xi^2} & otherwise \end{cases} \tag{30}$$

$$Q^N = \begin{cases} 0 & if\ (\xi(\beta_P - rB))(\beta_P\beta_Q - \xi^2) < 0 \\ 1 & if\ \frac{\xi(\beta_P - rB)}{\beta_P\beta_Q - \xi^2} > 1 \\ \frac{\xi(\beta_P - rB)}{\beta_P\beta_Q - \xi^2} & otherwise \end{cases} \tag{31}$$

$$s^N = 0 \tag{32}$$

where $\xi = (rB - A)$.

3.2. Cooperative Game

In this section, we formulate a cooperative game model where both the actors work together to maximize the whole supply chain's profit. The whole supply chain's profit is given in Equation (13) and the controlling parameters in the supply chain are P, Q, and s. It should be noted that the internal payment function I controls the profit of individual players, but the whole supply chain profit is independent of I. Moreover, the proportion of profit division depends on the bargaining power of each actor [52]. The supply chain objective function can be written as:

$$\begin{aligned} \max_{P,Q,s} \Pi = \{P + (1-P)(1-Q)(1-r)\}I_1 + (1-P)QI_2 + (1-P)(1-Q)srI_3 + \\ (1-P)(1-Q)(1-s)rI_3 - C_{Qs}(Q,s) - C_P(P) \end{aligned} \tag{33}$$

subject to:

$$0 \leq P \leq 1$$

$$0 \leq Q \leq 1$$

$$0 \leq s \leq 1$$

Taking the first order derivative of Equation (33) w.r.t. P, Q and s, we get the following:

$$\frac{\partial \Pi}{\partial P} = QA + (1-Q)rB - \beta_P P \tag{34}$$

$$\frac{\partial \Pi}{\partial s} = -\beta_s s \tag{35}$$

$$\frac{\partial \Pi}{\partial Q} = (1-P)(rB-A) - \beta_Q Q \tag{36}$$

Thus the optimum values of P, Q and s can be calculated by applying first-order conditions on Equations (34)–(36), respectively, i.e.,

$$P = \frac{1}{\beta_P}\left(QA + (1-Q)rB\right) \geq P^* \tag{37}$$

$$s = 0 \leq s^* \tag{38}$$

$$Q = \frac{(1-P)(rB-A)}{\beta_Q} \tag{39}$$

Proposition 1. *The textile manufacturer needs to invest more on quality at a given return rate for the cooperative game as compared to that of the Stackelberg's retailer non-cooperative game. Traceability remains at the lowest level in a cooperative game.*

Proof. As it can be seen, Equation (37) $\geq$ Equation (23), which means for a given r, P in the cooperative game is equal to or more than P in the Stackelberg's retailer game. Similarly, $s = 0$ for all r as can be seen in Equation (38), therefore traceability remains at the lowest level in the cooperative game. Hence the proposition is proved.

The optimum parameters, i.e., $P^C$and Q^Ccan be obtained by simultaneously solving Equations (37) and (39) while taking into account $0 \leq P^C, Q^C \leq 1$. Solving these equations would lead to the solution given in Equations (31) and (32), thus $\Pi^C = \Pi^N$.

The individual profits of retailer and textile manufacturer depend on I, i.e., the internal payment, which depends on the mutual agreement. In order to have a mutual agreement, both the players should have a higher profit than in any alternate game. For instance, the textile manufacturer will agree to a cooperative game only if $\Pi^C_{TM} > \max\left(\Pi^R_{TM}, \Pi^{TM}_{TM}, \Pi^N_{TM}\right)$ i.e., the textile manufacturer's profit is higher in the cooperative game as compared to that of a non-cooperative game. Similarly, the retailer will agree to a cooperative game only if $\Pi^C_R > \max\left(\Pi^R_R, \Pi^{TM}_R, \Pi^N_R\right)$ i.e., the retailer's profit is higher in the cooperative game as compared to that of a non-cooperative game. The possibility of a cooperative game is discussed in the subsequent sections.

4. Bargaining Feasibility and Game Change Scenarios

4.1. Game Change and Bargaining

Bargaining between the textile manufacturer and retailer is possible in a cooperative game where both the actors agree to work together to maximize the supply chain profit, and both benefit from the increased profit. As mentioned in Section 3.2, the profit of an individual actor depends upon the bargaining power of each actor, since I, which is one of main parameters affecting the profit, is an independent parameter. Furthermore, parties will agree on cooperation if and only if their profits are more than with other games [52,54]. For instance, for the Stackelberg's textile manufacturer game, the textile manufacturer is the main player who decides the profit. Therefore, a textile manufacturer can bargain with a retailer for a cooperating game if:

$$\Delta\Pi^{TM}(r) = \Pi^C(r) - \Pi^{TM}(r) > 0 \tag{40}$$

It should be noted that the r in parentheses above denotes the parameters for a given return rate r. Here $\Delta\Pi^{TM}(r)$ denotes the supply chain's surplus profit when the textile manufacturer changes from a non-cooperating game to a cooperating game for a given return rate *r*. Therefore, the textile manufacturer can bargain with the retailer to go to a cooperative game and share the profit $\gamma\Delta\Pi^{TM}$, where $0 \leq \gamma \leq 1$. If the retailer accepts the cooperating game then the retailer gets overall profit $\Pi_R^C(r) = \Pi_R^{TM}(r) + \gamma\Delta\Pi^{TM}(r)$, whereas the textile manufacturer gets profit $\Pi_{TM}^C(r) = \Pi_{TM}^{TM}(r) + (1-\gamma)\Delta\Pi^{TM}(r)$. The factor γ depends on the relative bargaining power of the textile manufacturer and the retailer. When $\gamma = 0.5$ both the textile manufacturer and the retailer share the surplus profit equally, whereas for $\gamma < 0.5$, the manufacturer is dominating and if $\gamma > 0.5$ the retailer is dominating in bargaining. For $\gamma > 1$, $\Pi_{TM}^C(r) < \Pi_{TM}^{TM}(r)$ or for $\gamma < 0$, $\Pi_B^C(r) < \Pi_B^{TM}(r)$ hence the cooperative game is not feasible.

Similarly, for the Stackelberg's retailer game, surplus profit ($\Delta\Pi^R(r)$) from changing from a non-cooperative to a cooperative game can be written as:

$$\Delta\Pi^R(r) = \Pi^C(r) - \Pi^R(r) \tag{41}$$

when $\Delta\Pi^R(r) > 0$, the profits in the cooperative game can be written as:

$$\Pi_R^C(r) = \Pi_R^R(r) + \gamma\Delta\Pi^R(r) \tag{42}$$

$$\Pi_{TM}^C(r) = \Pi_{TM}^{TM}(r) + (1-\gamma)\Delta\Pi^R(r) \tag{43}$$

4.2. Competition among Non-Cooperative Games

Non-cooperative games aim to maximize the profit an actor without cooperating with the other actor. As aforementioned, in the case of Stackelberg games, the leader tries to get maximum profit and shares the minimum profit with the follower to retain him in the game. However, in the case of the Nash game, both the actors act non-cooperating with each other and try to simultaneously and non-cooperatively maximize their profits. The benefit of latter over former game is that none of the parties has to bother about other party to retain in contract since both are gaining the equal profit as long as the contract exists i.e.,

$$\Pi_{TM}^N(r) = \Pi_R^N(r) = \frac{\Pi^N(r)}{2} \tag{44}$$

Therefore, the change in game from the Stackelberg's textile manufacturer game is possible when, $\frac{\Pi^N(r)}{2} > \max\left(\Pi_{TM}^{TM}, \Pi_R^{TM}\right)$, such that $\Pi_{TM}^N(r) > \Pi_{TM}^{TM}(r)$ and $\Pi_B^N(r) > \Pi_B^{TM}(r)$. In the changed game (i.e., from the Stackelberg's textile manufacturer to the Nash game), the textile manufacturer remains non-cooperating while the retailer changes from an adherent to non-cooperative, and both gain higher profit than that of the former game. Similarly, for the Stackelberg's retailer game scenario, the retailer (as dominant) will agree to switch the game if $\frac{\Pi^N(r)}{2} > \max\left(\Pi_{TM}^R(r), \Pi_R^R(r)\right)$.

4.3. Forced Game Change and Cooperation

The benefit of becoming the leader in the game theory is having extreme power and getting the opportunity to maximize gain [51]. However from this power follows the responsibility that the leader should provide minimum incentives to the follower to keep him in the contract. Therefore, an actor in the supply chain would like to be the leader as long as he gains more profit than with alternate games scenarios (such as a cooperating game or as follower in the non-cooperating game). Assuming for case of textile manufacturer, the textile manufacturer would like to be the leader for a given return rate as long as:

$$\Pi_{TM}^{TM}(r) \geq \max\left(\Pi_{TM}^C(r), \Pi_{TM}^R(r)\right) \tag{45}$$

Similarly, for the case of retailer, the retailer would like to be the leader as long as:

$$\Pi_R^R(r) \geq \max\left(\Pi_R^C(r), \Pi_R^{TM}(r)\right) \tag{46}$$

However, for the scenario with a given return rate r, $\Pi_R^R(r) < \max\left(\Pi_R^C(r), \Pi_R^{TM}(r)\right)$ and $\Pi_{TM}^{TM}(r) < \max\left(\Pi_{TM}^C(r), \Pi_{TM}^R(r)\right)$ both the actors would like to change the game and since nobody would like to be the leader, the only solution to settle an optimum profit is a cooperative game, which is the common choice for both actors.

In the case of $\Pi_R^R(r) < \min\left(\Pi_R^{TM}(r), \Pi_R^C(r)\right)$ and $\Pi_{TM}^{TM}(r) \geq \Pi_{TM}^R(r)$, it is better for the retailer to either participate in a cooperation game or a follower game (Stackelberg textile manufacturer game). The Stackelberg's textile manufacturer game is favorable when $\Pi_{TM}^{TM}(r) > \Pi_{TM}^C(r)$ or a cooperative game is favorable when $\Pi_{TM}^C(r) > \Pi_{TM}^{TM}(r)$. In the above two games, no cooperative game is possible when $\Delta\Pi^B(r) < \Pi_{TM}^{TM}(r) - \Pi_{TM}^B(r)$.

Similarly, when $\Pi_{TM}^{TM}(r) < \min\left(\Pi_{TM}^B(r), \Pi_{TM}^C(r)\right)$ and $\Pi_B^B(r) \geq \Pi_B^{TM}(r)$, it is better for the textile manufacturer to participate either in the cooperative game or a Stackelberg's retailer game. The Stackelberg's retailer game is favorable when $\Pi_B^B(r) \geq \Pi_B^C(r)$ or the cooperative game is favorable when $\Pi_B^C(r) > \Pi_B^B(r)$. In two above games, no cooperative game is possible when $\Delta\Pi^{TM}(r) < \Pi_B^B(r) - \Pi_B^{TM}(r)$.

5. Results and Discussion

In this section, we provide numerical examples to calculate the various parameters for maximizing profits under different established game scenarios and locate the best strategies for different return rates. We select the following parameters for the demonstration, $I_1 = 250$, $A = 70$ ($I_2 = I_1 - A = 180$), $B = 150$ ($I_3 = I_1 - B = 100$), $\alpha_s = \alpha_Q = 30$, $\beta_s = \beta_Q = 80$, $\alpha_P = 50$, $\beta_P = 150$, $K = 1.3$.

Graphical results corresponding to the abovementioned parameters are shown in Figure 2. Except for a very high return rate, the textile manufacturer's product quality remains high for a textile manufacturer-dominated game (P^{TM}) whereas it remains lowest for the retailer-dominated game (P^R) (Figure 2a). The retailer's quality inspection Q remains at the lowest level for $r < 0.4$ for all the games except textile manufacturer-dominated (Q^{TM}) game (Figure 2b). Traceability remains at the lowest level for the games where there is no single supply chain captain (i.e., either both are cooperative (s^C) or both are non-cooperative (s^N)), whereas the traceability level in the manufacturer-dominant game (s^{TM}) exceeds that in a retailer-dominatant game (s^R) (Figure 2c). Nevertheless, non-zero traceability confirms that companies should invest on traceability when the two actors are non-cooperating in the supply chain. Figure 2d shows the change in internal transfer payment I for different game scenarios with varying return rate (r).

As the return rate increases, the supply chain profit (Π) of all the games reduces (as seen in Figure 2e). This is due to the fact that with the increase in return rate, the probability of defective products being returned by the customer is higher and thus profit is being lost in the form of compensation. Higher return rates can be expected for expensive products, therefore if a firm is trying to obtain higher profit by inflating the product price, the simultaneous increase in return rate might have the opposite effect, as seen in a decrease in profit due to higher return rates. Also, the whole supply chain profit is highest in the cooperative game $\left(\Pi^C\right)$ as compared with the Stacketberg's textile manufacturer and the Stacketberg's retailer games. For non-cooperative games, the order of supply chain profit changes with return rate i.e., for $r < 0.35$ $\Pi^N \geq \Pi^R \geq \Pi^{TM}$, and for $r \geq 0.35$ $\Pi^N > \Pi^{TM} > \Pi^R$.

Figure 2f,g show the changes in individual profits of actors in different game scenarios. As a common observation, the leader's profit in all the games goes down as the return rate increases. The leader has to provide a fixed profit (defined by parameter K) to the follower to retain him in the contract [45,55]. Based upon the follower's investment, the profit varies in all the games. For example, textile manufacturer's profit in the Stackelberg's retailer game increases with the increase in return rate, whereas the retailer's profit in the Stackelberg's textile manufacturer game initially decreases and then increases.

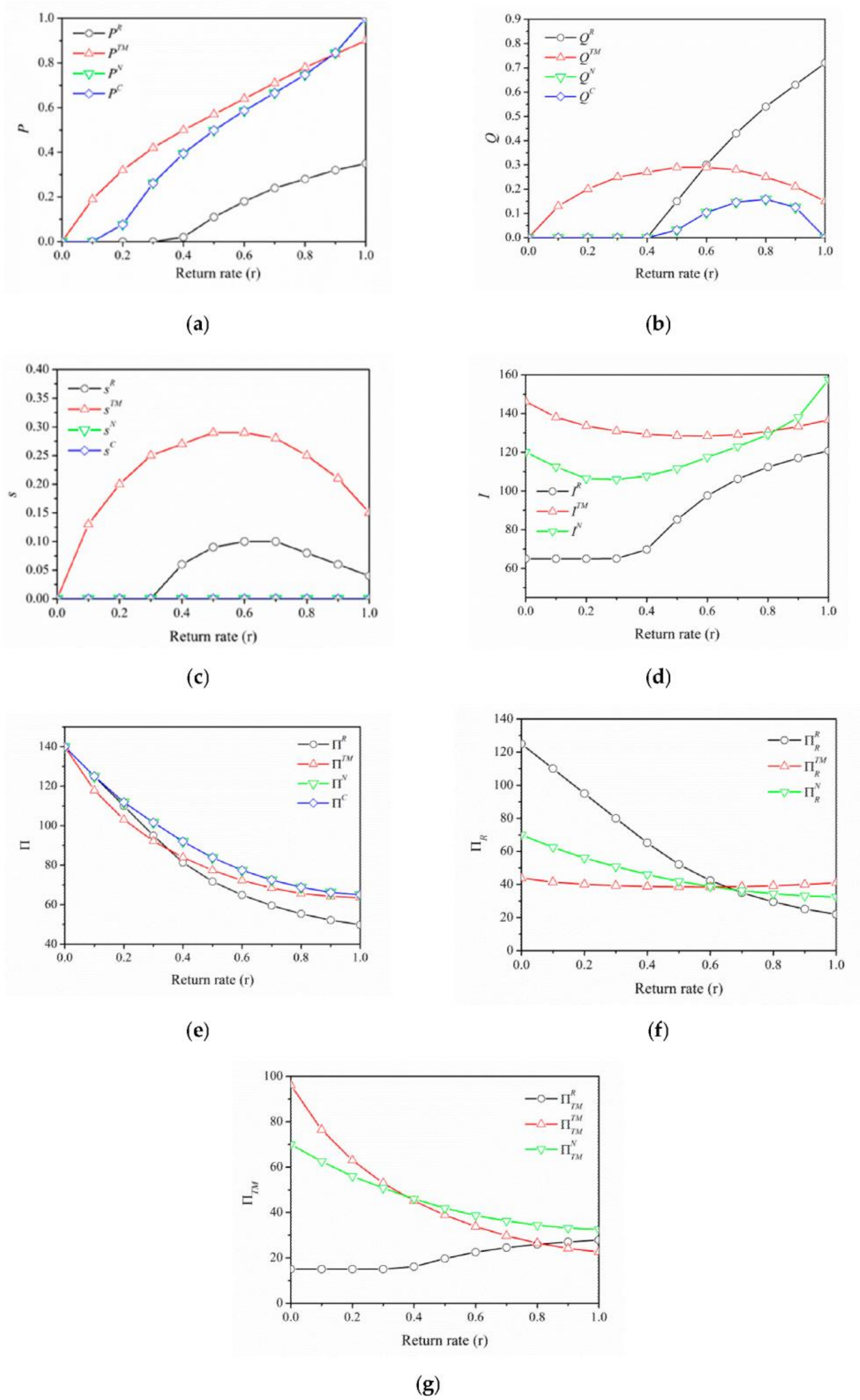

Figure 2. Variation of textile manufacturer and retailer controlled variables with variations in return rate (r) in different game scenarios. Here the superscripts R, TM, N and C represent the parameters pertaining to Stackelberg's retailer game, Stackelberg's textile manufacturer game, Nash game and cooperative game models, respectively. (**a**) shows the parameter P; (**b**) shows the parameter Q; (**c**) shows the parameter s; (**d**) shows the parameter I; (**e**) shows the parameter Π; (**f**) shows the parameter Π_R; (**g**) shows the parameter Π_{TM}.

Figure 3 shows the variation of profit under different non-cooperating game scenarios. There is a region for the retailer to switch to the Nash game from a retailer-dominated game as shown by the shaded region in Figure 3a, i.e., $r > 0.67$. Similarly, for the textile manufacturer-dominated game, it is profitable for the manufacturer to go into the Nash game with the retailer for $0.33 \leq r \leq 0.6$ (shown by shaded region in Figure 3b). Changing from a non-cooperative game to a cooperative game is always possible since $\Pi^C \geq \max\left(\Pi^R, \Pi^{TM}, \Pi^N\right)$. Actors in a cooperation game work like strategic partners, working toward a common goal [45,56]. Therefore agreement among the actors is an important aspect for its success [49]. Therefore, the changing from a non-cooperative game to a cooperative game depends on a common incentive such as profit sharing and other contractual terms [52]. Looking into the profit scenarios of each player individually, the retailer (as a leader in Stackelberg's game) would like to lead the game as long as he is getting a high profit [52,54]. Since $\Delta\Pi = \Pi^C - \Pi^R \geq 0 \forall r$ (Figure 4a) therefore the retailer has the possibility to change the game from Stackelberg's retailer to cooperating game as long as he gains a higher profit, i.e., $\Pi_R^C \geq \Pi_R^R$.

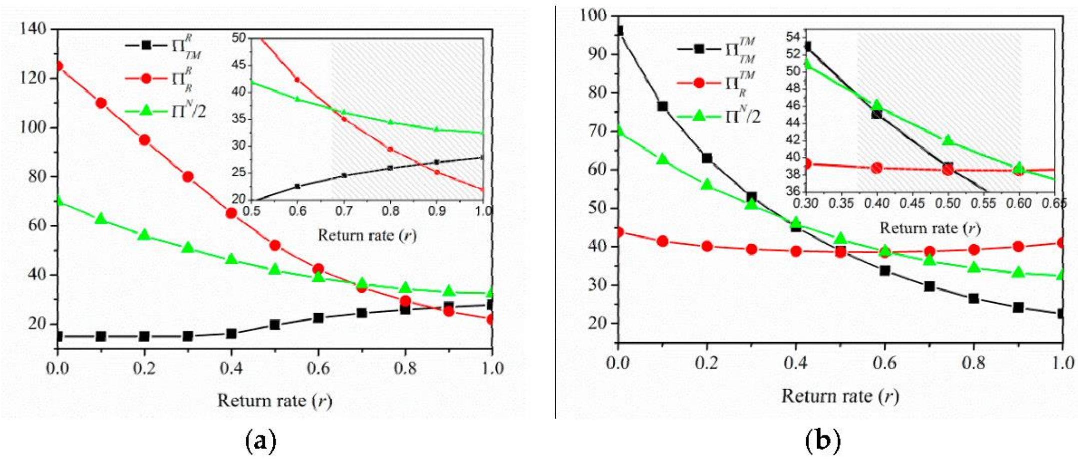

Figure 3. Competition among non-cooperative games (**a**) the Stackelberg's retailer game and Nash game; (**b**) the Stackelberg's textile manufacturer game and Nash game. The shaded region shows the favourable region for the Nash game over the respective Stackelberg's games.

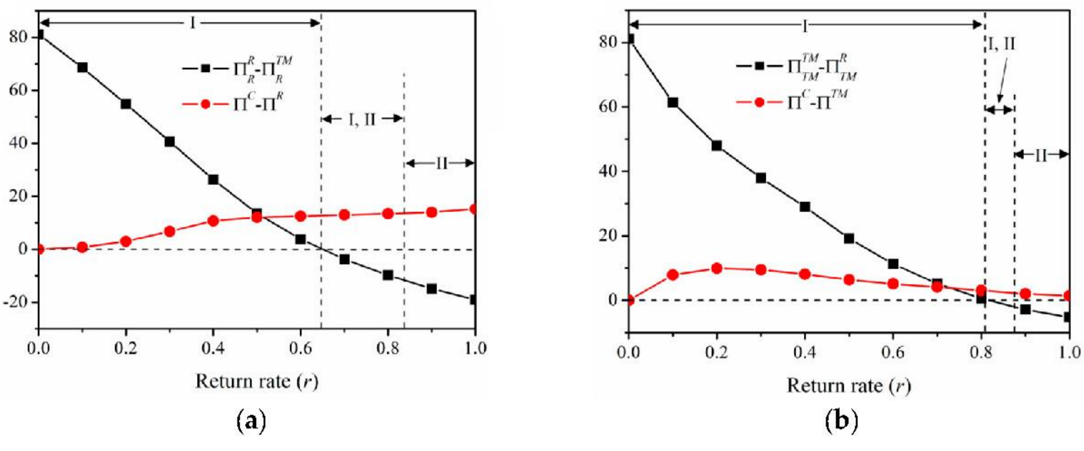

Figure 4. Competition among (**a**) the Stackelberg's retailer game and cooperative game; (**b**) the Stackelberg's textile manufacturer game and cooperative game. Region I represents the favourable region for the leader in the game to go in cooperation with the follower and II represents the favourable region for leader to go on follower's position.

For this scenario, both actors should agree to a profit division such that $\Pi_R^C = \Pi_R^R + \gamma\Delta\Pi$ and $\Pi_{TM}^C = \Pi_{TM}^R + (1-\gamma)\Delta\Pi$. However, the retailer as a leader would prefer to switch to the follower position when he gains more profit as a follower [54]. For instance, when $r > 0.65$, retailer as a follower earns more profit than as a leader, because $\Pi_R^R - \Pi_R^{TM} < 0 \forall r > 0.65$. Therefore, there are two profit-maximizing ways, one is either to switch to a cooperating game or to switch to a follower game. Depending upon the bargaining power [52], i.e., γ retailer can maintain his profit equal to or more than that in Stackelberg's textile manufacturer game for $0.65 < r \leq 0.83$. For $r > 0.83$, $\Delta\Pi = \Pi^C - \Pi^B < 0$, therefore, the only option left for the retailer to maximize his profit is switch to a game as a follower. In fact, for $0.65 < r \leq 0.81$, $\Pi_{TM}^{TM} - \Pi_{TM}^R > 0$ therefore the textile manufacturer would agree to be the leader in the game as his profit increases. Different game regions are denoted by I (Cooperative) and II (follower in Stackelberg's game) in Figure 4a.

Similarly, for the Stackelberg's textile manufacturer game, cooperative is profitable for $r \leq 0.81$, cooperative or follower in Stackelberg's textile manufacturer game for $0.81 < r \leq 0.87$ and follower in Stackelberg's textile manufacturer game $r > 0.87$. Comparing the two scenarios (Figure 4a,b), for $r > 0.81$ none of the actors wants to lead the game. Therefore, the only option left for both is forced cooperation, where both share the profit or loss equally.

In the abovementioned game models, the return rate was assumed to be an exogenous function. However, it can be compared with a changing business environment. For instance, with the easy accessibility of the Internet, a customer can educate himself with the product return policies or share a product defect on social media that can attract the attention of other users who bought the same product and hence encourage its return. Therefore, the changed business environment seen in terms of high return rate may force the organizations to rethink their business strategies as demonstrated by the appropriateness of different alliances (horizontal/vertical with leader/follower).

6. Conclusions

In this paper, we have discussed the supply chain strategies for quality inspections incorporating the effect of customer return policy using different game models. The textile manufacturer invests in the product quality whereas retailer invests in the random quality inspection and traceability. The maximum supply chain profit was obtained when both actors cooperate in the supply chain. Further, the proposed work shows that the change of roles in non-cooperative game strategies is possible under special circumstances which increase the profits of both actors.

The present work assumes that complete information about each other is available to both the actors. By excluding this assumption, future research can be focused on asymmetric information where incomplete information is available. Furthermore, the effect of product quality, traceability information, and variable penalty cost can be included in the market demand for the future work. The role of chaos arising from uncertainties caused by factors such as market demand and trend changes can be explored using Parraondo's Paradox game [57].

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