A Mapping Study of the Current Literature on Digitalization and Industry 4.0 Technologies Utilization for Sustainability and Circular Economy in Textile Industries

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A mapping study of the current literature on digitalization and industry 4.0 technologies utilization for sustainability and circular economy in textile industries

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Abstract. Fast fashion has one of the highest negative impacts on the environment. Huge amount of water and energy is consumed in all processes of raw material extraction, fiber manufacturing, weaving, dyeing, washing to the end of use, recycling and burning fibers and clothes waste. During the past decade, researchers and policy makers have discussed circular economy (CE) solutions and business models aiming to achieve sustainability goals. CE solutions have gained textile industries, regulators and scholars' attention as we are moving towards a digital world, many experts argued that Industry 4.0 technologies can accelerate industrial transition towards circularity. Digital technologies help transfer real-time material and product's condition, availability, accessibility and resources data and boost the CE transition in textiles and apparel industries. Product design development, product prototyping and recycling the materials can be done in higher efficiency by utilizing industry 4.0 technologies. Authors conducted a mapping study of the current academic literature on digitalization-based solutions and revolution in textiles industries towards circular economy. The study looked for publications articulating different implementations of digital technologies in circularity of textile industry. Huge gap was found in academic literature in need of further investigation and research to support the topic.

Keywords: Digital transformation, Circular economy, Textile industry, Circularity, Sustainability, Systematic mapping study, Digitalization, Industry 4.0

1 Digitalizationin Textile Industries

Global "re-industrialization" has made negative impacts into the environment [1]. For example, Ellen MacArthur Foundation (2017) [2] claims that under 1% of materials in clothes production is recycled. According to European Parliament [3], 2-10% of environmental impact in Europe is due to apparel industry. Same time, digitalization is transforming traditional industry companies towards new business models [4], Digital design and manufacturing has given us new opportunities for mass customization [5] and Industry 4.0 solutions allow as enhance circularity in different industries, including textiles [6]. In fact, industry 4.0 solutions and digital transformation have been major change accelerators during the last decade in various industries. Industry 4.0 leads to virtualization, modularization and optimization [7] of production and supply chain, achieving flexibility and personalization of production [8]. Digital technologies &

platform allow easier collaboration and gainsharing [9], data collection [58, 60] and help in the co-worker interactions and allows e.g. fashion producers to easily exchange knowledge in the on-site production business models [10]. Therefore, new technologies can help solving environmental problems generated by traditionally operating textile and fashion industry. E.g. smart manufacturing transition pushes textile industries from market-driven to the ready-to-wear models and adds interactivity between the consumers and companies. Smart connected products reframe the entire eco-system of fashion company by creating cyber-physical systems with case specific sensors and enhanced data-analysis. Technologies like wireless Radio frequency identification (RFID) [11] and embedded sensors offer basics for data collecting and storage from equipment operation status and maintenance information to help industrial development like plant self-configuration and self-optimization [12] Industry 4.0 technologies such as (smart) sensors, IoT, edge computing and AI allows wide scale data collection from garments to reveal real consuming and use patterns of the smart fashion products. When this information is shared across the entire horizontal supply chain, from raw material to the landfill waste dump step, the whole collaborative network can formalize its operations [59] and gain clear benefits. In overall, none of these technologies should not be developed in "vacuum", one should take the user experience, product reliability and efficiency and high-quality of cross integration into account for real disruptive technology solution and success. Decent technologies, developed with consumer in mind make it possible to produce eco-system of "smart factories", "smart networks" and "smart products". In such eco-systems, the improved data transformation on information about markets and end-users' demand helps in the complexity on decision making for the companies.

2 Sustainability and Circularity Trends in Textile Industries

Huge amounts of water, energy and chemicals are consumed in for textile manufacturing, especially as large volumes of non-renewable resources are extracted for small amount of fabric production. If newest digitalization enhanced design tools and ecologically friendly designs for textile industry processes would be applied, then the fashion industry would take major turn towards new business models with sustainable economy in mind. Regarding to the mentioned sustainability aspects, the Circular Economy (CE) concept has been part of global debates in the past decade, especially as a solution for climate change problems. The main goals of CE are to close the loops of materials, reducing carbon emissions and limiting the use of scarce virgin resources, instead of linear "take-make-dispose" model [57]. In fact, CE has contributed significantly on general industrial development by a purposeful designed and interconnected system towards closed-loop models [14]. In the context of the textile industry, by Smits et al. [15], textile industries transformation strategies towards CE, can be based on: 1) material flows based circular strategies (waste to resource), 2) Servitization (reduction of ownership of tangible items) and 3) more efficiency-based resource usage.

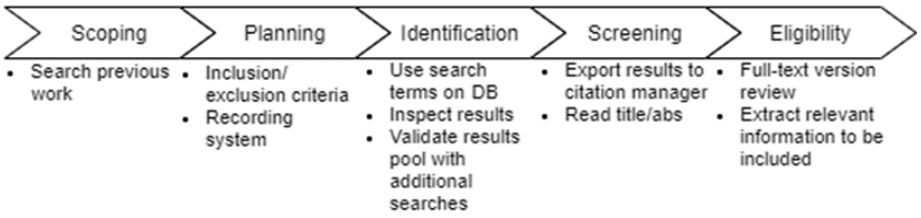
However, Nascimento et al. [16] mention that implementing circular models can bring several challenges for the industries due to high costs and required changes. This

is partly disputed by Antikainen et al. [17] discussing possibilities of novel technologies such as artificial intelligence, IoT, Big Data, etc. to accelerate the transition towards circularity. In this regard, Zhong et al [18] defined the integration of Industry 4.0 and CE as follows: design (smart solutions), enhanced maintenance (monitoring and decision-making), control (analytics, prediction and data-based modelling), scheduling (warehouse and transport activities), monitoring (technology-based information sharing). According to Ghoreishi and Happonen [19, 20], the Industry 4.0 will provide real-time data for product design to help the decision making in the production process. In addition, lifelong product monitoring will help in maintenance requirement predictions and to keep the costs down by utilizing in time maintenance models. For a more comprehensive understanding of the subject, the research conducted a mapping study to answer to question: what is the current literature on the role of digital tools in textile industries regarding to the sustainability development and the existing gaps?

3 Literature review on mapping of the academic publications on digitalization enabled sustainability

A systematic literature review [21, 22] was carried out to preliminarily map the literature in the context of textile industry development and ICT, automatization, digital / digital transformation related solutions. In this process, [23] basic systematic literature review steps were followed, to be able to systematically achieve the screening phase of the research, as presented in following figure 1.

Fig. 1. General model for systematic literature review, adapted from [23].



The scoping phase included review of previous studies for keywords from publications discussing textile industry improvement with newest technology-based solutions [19, 20, 24]. In the planning stage Scopus database, English for language as study selection rule and studies published in 2010 or earlier was confirmed as exclusion criteria due to the novelty of the topic. In addition, for the academic publications, only journals, conference publications, books and proceedings were to be considered. E.g. reports from national institutions, web pages and magazine articles were left out from the study. In the Identification phase, the research was collected from Scopus database, with the following keyword combinations (focusing on title, abstract and keywords):

- ("industry" OR "oragani*" OR "business") AND
- ("textile" OR "fashion" OR "fabric" OR "cloth") AND

- ("technolog*" OR "digital*" OR "automati*" OR "artificial intelligence") AND
- ("recycling" OR "circular economy" OR "sustainability" OR "waste")

With the set keywords, we present the following base findings (Table 1).

Table 1. Preliminary results from Scopus database, before applying of filtering rules.

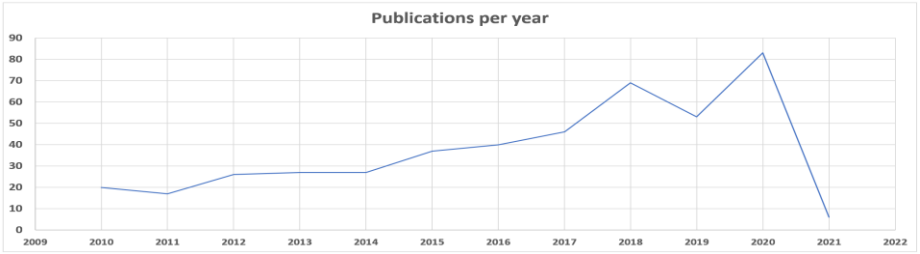
Keywords	Scopus (Title, Abstract, Keywords)		
	Documents	In english	Journal + Conference & Book and Book chapters
("industry" OR "oragani*" OR "business") **AND** ("textile" OR "fashion" OR "fabric" OR "cloth")	85 032	71 054	66 170
("industry" OR "oragani*" OR "business") **AND** ("technolog*" OR "digital*" OR "automati*" OR "artificial intelligence")	616 729	578 048	519 232
("industry" OR "oragani*" OR "business") **AND** ("recycling" OR "circular economy" OR "sustainability" OR "waste")	173 183	161 307	145 722
("textile" OR "fashion" OR "fabric" OR "cloth") **AND** ("technolog*" OR "digital*" OR "automati*" OR "artificial intelligence")	73 823	64 600	60 212
("textile" OR "fashion" OR "fabric" OR "cloth") **AND** ("recycling" OR "circular economy" OR "sustainability" OR "waste")	21 358	18 783	17 499
("technolog*" OR "digital*" OR "automati*" OR "artificial intelligence") **AND** ("recycling" OR "circular economy" OR "sustainability" OR "waste")	162 963	149 212	132 609
("industry" OR "oragani*" OR "business") **AND** ("textile" OR "fashion" OR "fabric" OR "cloth") **AND** ("technolog*" OR "digital*" OR "automati*" OR "artificial intelligence")	18 101	15 645	14 476
("industry" OR "oragani*" OR "business") **AND** ("textile" OR "fashion" OR "fabric" OR "cloth") **AND** ("recycling" OR "circular economy" OR "sustainability" OR "waste")	9 502	8 558	7 962
("industry" OR "oragani*" OR "business") **AND** ("recycling" OR "circular economy" OR "sustainability" OR "waste") **AND** ("technolog*" OR "digital*" OR "automati*" OR "artificial intelligence")	39 207	36 585	32 039
("textile" OR "fashion" OR "fabric" OR "cloth") **AND** ("recycling" OR "circular economy" OR "sustainability" OR "waste") **AND** ("technolog*" OR "digital*" OR "automati*" OR "artificial intelligence")	3 770	3 366	2 982
("industry" OR "fashion" OR "oragani*" OR "busines") **AND** ("textile" OR "fabric" OR "cloth" OR "fiber" OR "garment" OR "yarn") **AND** ("technolog*" OR "digital*" OR "automati*" OR "robot*" OR "machine*" OR "artificial intelligence") **AND** ("recycling" OR "circular economy" OR "sustainability" OR "waste" OR "up cycling" OR "salvage" OR "recover")	1 848	1 692	1 507

Proceed from the identification to screening phase, general overview was done for the found 1507 studies, screening out old and obviously non-related studies. Studies related e.g. to food, metal and paper industry and other similar research areas were excluded, as illustrated in the following visualization (Figure 2), which led to 451 studies.

Fig. 2. Base filtering and removal of old and non-related research field publications

For general overview of publishing years distribution of the 451 manually to be filtered 451 found articles, following visualizations (figure 3) was generated, to study the overall cross-sectional amount of publications per year. In this phase, it was clear that different authors were contributing more and more in this general context.

Fig. 3. Amount of publications per year for the 451 articles to be manually overviewed.



These 451 articles were manually screened, utilizing a 3-step filtering process, ending to eligibility selection. Three steps were: 1) to study the titles, 2) if needed to study the article abstract and if unclear, step 3) was to scan the paper content to judge the eligibility. The whole process with step by step result is visualized in following Figure 4.

Fig. 4. Screening and eligibility analysis.

TITLE (Round 1)	
No	398
Yes	12
?	41
Total	451

ABSTRACT (Round 2)	
No	33
Yes	7
?	1
1st	410
Total	451

FULL TEXT (Round 3)	
No	0
Yes	1
?	0
1st + 2nd	450
Total	451

Summary	
No	431
Yes	20
?	0
Total	451

The screening and eligibility step on article titles revealed most of the 451 articles to be unsuitable for the review. Main rejection reason was a focus on block chains and industrial supply chains, rather than sustainability and circularity solutions. Merely 10% of the articles continued to abstract analysis, positively resulting lot of article in the eligible list. In general, the abstracts and keywords did include lot of review specific words, but not that much actual research related context, as 95% of the articles had to be excluded in the manual content-based review. Based on results, authors wondered they missed something, e.g. due to the used keywords and/or their combinations. A form of snowballing like content extension strategy [25] was issued for additional keywords and area-specific terminology form the found 20 studies, looking for their keywords and main topics for search to Scopus database, with following keywords:

- industry AND
- ("textile" OR "apparel" OR "fashion") AND
- ("circular economy" OR "sustainability" OR "Recycling" OR "Upcycling" OR "waste management") AND
- ("IoT" OR "Artificial intelligence" OR "digital*" OR "Industry 4.0" OR "smart")

The new keyword string resulted the total of 88 new unique articles, which were processed in the same way as authors did with the 451 articles. Subsequently, new keywords did reveal 15 potential additional studies with 8 duplicates and 7 new unique contributions, compared to previously findings. Preliminary analysis for the huge difference between the selected articles and articles processed in manual steps (between the two separate processing rounds), seem to be related to the used keyword "oragani*",

“waste”, "fabric" and "cloth". In Overall, for any future research in the topic, we recommend cross checking the combinations for fully inclusive keyword sets.

4 Analyzing the found literature

For the found 27 unique studies the basic structure of research in this topic area was mapped based on yearly publishing amounts. The yearly publishing numbers analysis was made to understand the change in contributions to the area within the last 10 years.

Fig. 5. Development of contributions as publications for the topic area, years 2010 – 2021

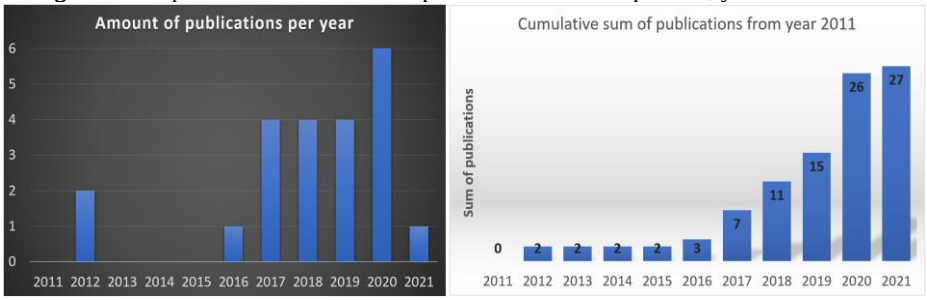
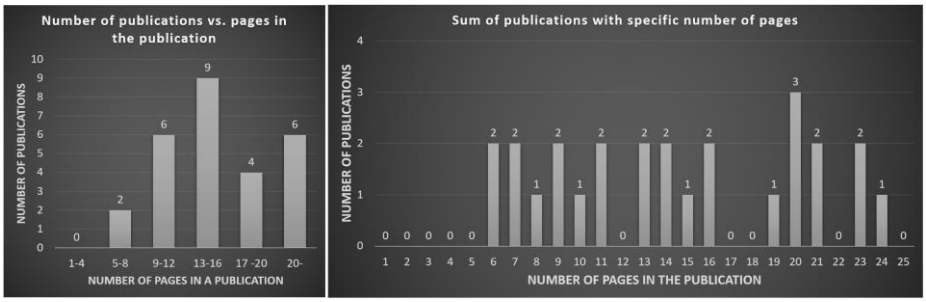


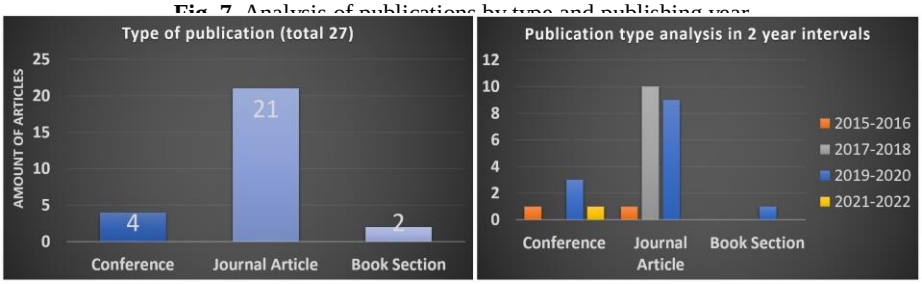
Fig. 6. Number of pages present per publication



The topic has gained significant academic attention from 2017 onwards, with a steadily growth around 4 publications per year, with spike in numbers in year 2020. Ultimately, the analysis reveals that there is a gap in this area of research and low number of contributions currently, especially considering the high environmental impacts of the textile industry. Furthermore, to understand the size / depth / knowledge scale of these publications in general, the number of pages in the publication was analyzed.

By the figure 6, it is evident that the 27 publications from years 2012 to 2021 could be divided to 3 clearly separate length groups. 1st group for the shortest papers from 6 to 11 pages (a typical length for longish conference papers). 2nd group for mid length papers is 13 to 16 pages (typical for shorter journal publications) and 3rd group for publications with length of 19 to 24 pages. The length of the publications did not mainly reveal anything unexpected, similar to the publication type analysis did (figure 7).

Fig. 7. Analysis of publications by type and publishing year



Publication type and publishing year analysis indicate high preference towards journal publications. From 27 articles, only 4 were conferences proceedings and 2 (published in 2012 and 2019) were of a book section. The Majority of the publications were between 2017and 2020, with the mentioned high preference for the journals.

Table 2. Citation analysis for the screened 27 studies

			Citation count		
ID	Title	Year	GS	Scopus	WoS (All)
27	Blockchain enhanced emission trading framework in fashion apparel manufacturing industry	2018	56	36	24
28	Green production planning and control for the textile industry by using mathematical programming and industry 4.0 techniques	2018	22	17	17
29	Circular fashion supply chain through textile-to-textile recycling	2019	15	10	7
30	Urban prototypes: Growing local circular cloth economies	2019	17	10	7
31	Blockchain framework for textile supply chain management: Improving transparency, traceability, and quality	2018	19	10	0
32	Sustainability and collaborative apparel consumption: putting the digital 'sharing' economy under the microscope	2017	12	9	0
33	A system of systems framework for sustainable fashion supply chain management in the big data era	2016	14	9	9
34	A collaborative cloud service platform for realizing sustainable make-to-order apparel supply chain	2017	9	6	6
35	Sustainability benefits of RFID technology in the apparel industry	2019	8	5	4
36	Design Thinking for Textiles: let's make it meaningful	2017	11	5	4
37	Towards sustainable textile and apparel industry: Exploring the role of business intelligence systems in the era of industry 4.0	2020	5	3	3
38	Sustainable planning strategies in supply chain systems: proposal and applications with a real case study in fashion	2020	5	3	3
39	A new sustainable product development model in apparel based on 3D technologies for virtual proper fit	2016	6	3	3
40	Digital innovation for sustainable apparel systems: Experiences based on projects in textile value chain development	2018	4	2	2
41	Content-Based Recommendations for Sustainable Wardrobes Using Linked Open Data	2018	3	2	0
42	Trends in textile markets and their implications for textile products and processes	2012	10	2	2
43	Big data analytics and sustainable textile manufacturing: Decision-making about the applications of biotechnologies in developing countries	2020	1	2	1
44	Sustainable value stream mapping and technologies of Industry 4.0 in manufacturing process reconfiguration: A case study in an apparel company	2018	4	2	0
45	Sustainability through online renting clothing: Circular fashion fueled by instagram micro-celebrities	2021	1	1	1
46	Unfabricate: Designing Smart Textiles for Disassembly	2020	0	1	0
47	Circular economy for clothes using web and mobile technologies-A systematic review and a taxonomy proposal	2020	1	1	1
48	Impact of emerging technologies for sustainable fashion, textile and design	2019	5	1	0
49	Machine vision estimates the polyester content in recyclable waste textiles	2020	1	1	1
50	Blockchain-enabled circular supply chain management: A system architecture for fast fashion	2020	0	0	0
51	The Impact of Digital Transformation on Sustainability in Fashion Retail	2020	0	0	0
52	Application of Digital Enterprise Technology (DET) for Green Made-to-Measure in Korean Luxury Fashion Industry	2017	0	0	0
53	Mastering fashion supply chain management and new product development in the digital age	2017	3	0	0

To identify how this preference has related to citation counts and appreciation of other academics, to the authors conducted the evaluation of received reference analysis for the found publications. In this analysis, the received citation count per publication was compared against multiple databases. The goal of the analysis was to map most references articles, which received higher amount of referencing.

Considering the 27 found unique studies received reference analysis (as shown in table 2), only two publications were with high amount of references, in all of the three reviewed typical reference count indexing databases. In general, these two are actually quite new publications (from 2018), which most likely indicates their high value and contribution to this topic area, as seen by the academic peers. Based on Scopus

references 7 out of 27 papers (over 25%) have received around 10 or more citations. This sort of higher citation count, in so large population on the found paper set, is somewhat uncommon finding. Given the scarcity of publications on this topic (low number of contributing papers), it could be the case, that the small number of authors, contributing into this area, are enjoying higher than average amount of references received. And finally, for Google scholar [26], 40% of the found 27 papers, had already received 8 or more citations. Also, for this reference indexing related finding, we have similar scarce contributions related assumption.

Following the citation analysis, the publishing channels were also reviewed. Analysis reveal only one journal including more than one reviewed study. In the journal Sustainability, essentially 4 from the 27 studies were present (references of for studies here). Other sustainability and textile industry related were presented too, but none of them had published multiple area specific publications e.g. *Book: Advanced Fashion Technology and Operations Management, Conference: International Conference on Sustainable Design and Manufacturing and journals: International Journal of Fashion Design, Technology and Education, Journal of Cleaner Production, Journal of Fashion Marketing and Management, Research Journal of Textile and Apparel, Sustainable Management of Luxury, The Design Journal, The Global Textile and Clothing Industry*.

Lastly, we analyzed the contributing authors, to see if any of the authors would have been present in multiple publications. In the analysis, 75 authors were found and 74 were unique contributors to the 27 studies. Only author who was contribution to two publications was Tsan-Ming Choi with contributions to [33] and [38].

5 Discussion and Conclusion

Considering the found 27 unique studies from textile and fashion industries, digitalization and circularity and sustainability research areas cross section fields, it is quite evident there is a tall order for large amount of new additional academic research contributions. As over all results of the mapping study, following can be stated:

- Clear research gap (lack of scientific literature)
- Academic contributions are mainly available only since year 2017
- Further research is suggested for other major academic databases, e.g. Web of Sciences and IEEE to cross check possible additional literature
- Future research could map the most used research methods in this research field and map the research results on their specific development style/goal focus pools.

Based on publishing years of the found 27 studies, our work did show that the area of research in sustainability, circularity and digitalization in context of textiles, clothes and fast fashion has recently gained attentions from academic scholars. In addition, the results identify that the attentions have been recently attracted to the roles of digital technologies in textile industry, especially in supply chain management. However, there is a huge lack in the area of digitalization and circularity of textiles, even when the Industry 4.0 technologies is well known to have positive impact of companies' profitability [54] and sustainability [55]. Moreover, the analysis showed that while the topic

and the relevant studies are gaining the attentions of the academic journal publishers as a pacific field, a minority has been presented by conferences and books. Consequently, it indicates that although there is high quality research in this field, the quantity of the research is still scarce. Around 25% of the found studies had collected reasonable well references, even when these publications are only few years in age. In conclusion, one can say the field of research is highly novel and worth for future research for example to explore how different textiles utilize digitalization in their circular business models, how fleet level information [56] could help digital platforms usage in fast fashion industry and how these technologies can help in sharing knowledge and circular solutions between different actors of textile industry ecosystem worldwide.

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