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Selection criteria for planning cold food chain traceability technology enabling industry 4.0

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Abstract

Failure to deliver safe and high-quality food not only causes costly food crises and foodborne illnesses, but also impairs consumer confidence and the performance of cold food chains. Industry 4.0 transformation in food traceability systems i.e., the transition from manual paper-based record keeping to automatic identification and sensor technologies, holds the potential to enable improved data transmission and self-monitoring to reduce food quality issues. Selection of these technologies to meet a specific need requires a measurement on how they perform across a range of criteria. An overview of traceability technology performance rating for criteria enabling industry 4.0 in cold food chain is absent in the literature. This article presents a summary of the traceability technology criteria relevant to cold food chain industry 4.0 transformation through iterative literature review and expert validation. The selection criteria are then combined into a quantitative technology performance matrix that can help users to determine which technology is the most beneficial for a given supply chain scenario.

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1. Introduction

Systematic management of operations and temperature is necessary throughout all stages of cold food chains (CFCs) to assure the quality and safety of fresh produce [1,2]. Inefficient CFCs can affect the shelf life and desirability of food products by causing safety and quality issues e.g., pathogenic contamination, dehydration, excessive ripening and discoloration [3].

Food traceability shows enormous potential in preventing food quality and safety issues [4]. Traceability is the ability to follow the movement of a food product through specified stage(s) of supply chain and involves continuous collection of information about the product lot, or traceable resource unit (TRU) [5,6]. Traceability systems combine data through various techniques/technologies, facilitating real time visibility of the product intrinsic condition, accurate inventory counting; communication of temperature history; and quality-based food distribution [7,8,9,10].

The fourth industrial revolution (or industry 4.0) drives replacement of manual paper-based traceability record keeping with automatic identification (Auto-Id) and sensing technologies. Auto-Id technologies such as barcode and radio frequency identification (RFID) enables higher data carrying capacity, reading speed and accuracy [11]. Sensing technologies e.g., wireless sensor network (WSN) and smart packaging indicators support real time product safety and quality monitoring [7,9].

Food traceability system transformation requires optimum technology selection involving cost-benefit analysis early in the design phase [4,12,13,14]. Inappropriate selection leads to additional costs for the organizations concerned, impairing performance, and utilizing unnecessary resources [13]. Therefore, it is necessary to explicitly define a CFC scenario and consider the innate characteristics of the available technologies during any selection process [15]. A normative approach underpinned by quantitative trade-off among cost-benefit criteria would help decision makers to select the most feasible technology matching an intended CFC requirement [13].

The contribution this research makes is to coalesce the traceability technology criteria enabling industry 4.0 transformation in CFCs that is absent in the literature and builds on the work explored in Islam et al. [13]. The technology criteria data gathered here are transformed into a technology performance matrix, using a triangular fuzzy scale. The matrix can support decision makers to optimize technology planning in CFCs. Section 2 discusses traceability technologies and their selection criteria, section 3 describes the development of the technology performance matrix and its use, finally section 4 and section 5 provide the Discussion and Conclusion of the article.

2. Traceability technologies and selection criteria

An iterative search of relevant academic and grey literature, including company reports, datasheets, webpages, and e-commerce websites followed by experts' interviews have been conducted to identify the commonly used cold chain traceability technologies and capture their key selection criteria enabling industry 4.0. The study has considered total 16 different technologies commonly used for identification and environment monitoring in CFCs.

Paper-based recording is not an industry 4.0 technology, instead an existing traceability technique used by many organizations [6], considered here as a determinant of benefit derived from other technologies. Barcodes consists of scanners and symbology with mainly two distinct variants: One-dimensional (1D) codes encoding information into the form of parallel lines (e.g., Code 128, Code 39, EAN-13) and two-dimensional (2D) codes encrypting in the form of matrices of geometric patterns (e.g., Quick response code or QR code) [13,16].

RFID requires three necessary hardware: an RFID tag, a reader, and a supervising computer [13]. RFID has multiple variations differing in how the tag communicates with the reader: passive, semi-passive, and active. Passive tags lack a power source and can only send information when energized by the readers electromagnetic field. Active and semi-passive tags can transfer data to the reader, using their own battery [15] and accommodate a wider range of sensors and GPS [17]. RFID passive tags can further be divided based on their memory programmability into two categories: read-only and read-write. According to our e-market [18,19] survey, read-only tags normally include 64-96b PROM (programmable read-only memory) that contains only the tag identifier (TID), permanently embedded by the tag manufacturer which cannot be changed, but can be read numerous times [20,21]. In contrast, read-write RFIDs contain EEPROM (electronically erasable and programmable read-only memory) which users can use to add product data typically up to 1000 000 times [20].

The passive RFIDs also differ by their transmission frequency which are: low frequency (LF) at 125/134 KHz, high frequency (HF) at 13.56 MHz and ultra-high frequency (UHF) at 860-960 MHz [17]. LF passive RFIDs typically operate under a short reading range (i.e., 1-10 cm) with a low data transmission rate of 8 kbit/s [22,23]. HF and UHF RFIDs can operate up to 1 m and 9 m reading range with 105.9 kb/s and 40-640 kb/s data rates respectively [21,22,24]. Some HF and UHF read-write RFID tags are embedded with low power sensors for recording temperature which reduces their reading range [17]. In addition, we consider Near field communication (NFC) that operates in 13.56 MHz and supports 105.9 kb/s data rates [25]. NFC tags do not need a dedicated reader; and can be read by any smartphone with NFC capability [13].

Among environment sensing technologies, we consider WSN and smart packaging indicator. WSNs can be built of nodes each of which consists of radio transceiver, microcontroller, memory capacity, energy source, and various sensors [26]. WSN offers a high-speed contactless reading appropriate for temperature recording in a CFC, but not identification [13]. Smart packaging indicators are sensors that provide qualitative information e.g., electric or colorimetric response or quantitative data e.g., time temperature indicators (TTIs) [9].

To select the best possible solution from the technologies discussed above for a specific CFC scenario, we use 17 selection criteria. The detail of the technology comparison based on these criteria are presented in detail in Islam et al. [13] and are briefly discussed in the context of industry 4.0 transformation below:

2.1. Cost effectiveness

One of the biggest disadvantages of paper-based documentation is the associated cost and environmental impact associated with paper, printers and other office supplies [27]. Barcode labels contain large amount of information presenting media savings of ten to twenty-five percent replacing paper forms [28]. HF RFID tags are lower in cost than LF tags due to simpler antenna design [17,22]. UHF readers are usually costlier than HF readers though UHF tags are more economical [22].

2.2. Waterproof capability

A technology's capacity to work in a CFC is influenced by its ability to be water resistant. Presence of water may be a barrier to scanning 1D and 2D barcodes which require a clear line of sight and a clean optic [28]. LF and HF passive RFID tags are unaffected as are active RFID, WSN and TTIs even in the presence of water, but passive and semi passive tags operating at a UHF range show a performance downturn if attached to high water content foods [4,7,29].

2.3. Flexibility

Flexibility enables a data carrier to be printable, lightweight and wearable i.e., easy to attach to a product [13]; key for communicating to consumers at the point of sale. Barcode labels are printable, lightweight, wearable providing the most flexibility [28]. Whereas RFID tags are heavier and less flexible; actives and semi passives are the heaviest due to onboard batteries while UHFs are the lightest [22].

2.4. Accuracy

Data accuracy is essential for CFCs and poor data accuracy lead to traceability errors, poor stock control and spoilage [30]. Manual data collection offers lowest accuracy [31] while barcode reading can be 80% accurate due to requirements for line-of-sight, human intervention, and clean environment [28]. RFID technologies provide the highest data accuracy [17]; WSNs and Smart packaging indicators both provide data accuracy with an error of ±0.5 ℃ for temperature data [7].

2.5. Reading range

Reading range is the greatest distance between a node (or tag) and a reader (or gateway) that enables error free data reading [29]. Three main variations that influence reading range are: line-of-sight reading, close-contact reading, and contactless reading. The choice of the technology depends on the requirements for read range in a given CFC scenario [29]. For example, contactless reading is primarily used for moving items such as, pallets carried on forklifts while close-contact reading is used when data security is essential such as e-payments [3,17]. In RFID variants, only LFs offer close contact reading [32] while others including WSN offer contactless reading capacity [14].

2.6. Data transfer speed

Paper records and smart packaging indicators in CFC require manual data transfer and handling which reduces data transfer speed [7,14]. Barcode technologies offer higher data transfer speed than manual paper forms, however they are highly dependent upon manual handling, line-of-sight and close contact reading [17]. RFID technologies provide better data transfer speed than barcodes [23]. HF and UHF passive RFIDs offer contactless data read rate at 105.9 kb/sec and 40-640 kb/s respectively [21,30]. Active RFID provides the highest read speed with on-board transmitters and batteries [17] while WSN offers contactless data transfer at 250 kb/s [33].

2.7. Multi-tag readability

Multi-tag readability enables simultaneous reading of multiple tags and usually applies to Auto-id technologies. Multi-tag readability is enabled by executing various anti-collision algorithms for RFID tags and readers [17]. HF, NFC, UHF, semi-passive and active RFIDs generally have anti-collision properties though for LF RFIDs this is limited [17].

2.8. Identification capacity

Identification capacity is the ability of a technology to identify a product that varies by the granularity offered by it [13]. Granularity is the level of product identification detail captured by a technology that is defined by its memory capacity [34]. For example, 1D barcode technology can carry only product SKU identification [13], while 2D barcodes and RFIDs with higher memory capacity usually contain item level identification [28,35].

2.9. Tag writing cycle

This criterion indicates the degree to which the technology’s memory can be reprogrammed with new data [13] that varies across no writing cycle (Read-only RFIDs [21]), single writing cycle (barcodes [15]), and multiple writing cycles (Read-write RFIDs of all types) and defines whether additional product information (e.g., processing parameters) can be written and edited during the product cycle [15].

2.10. Memory capacity

Memory capacity as highlighted earlier governs the data volume that can be stored. Memory capacity can be increased where technology has read-write functionality (e.g., RFIDs or NFC) though higher memory capacity causes extra price and requires faster data transfer to ensure quick operations throughout supply chains [36].

2.11. Environmental parameters recording

Depending on continuity of power receiving, passive RFIDs can provide either on-off temperature reading or time-temperature history as a product moves through the supply chain [17,37]. Semi-passive and active RFID, with on board batteries can always support time-temperature history records while WSNs can only provide discrete temperature reading in real time unless tailored to provide history records [14,38].

2.12. Real time location recording

Only active and semi passive RFIDs, with on board batteries, can accommodate GPS to communicate real-time location data [4]. This capacity is also available for WSN technologies [39].

2.13. Real time alert

Active and semi passive RFIDs can accommodate real-time alert systems due to their continuous on-board power supply [17]. WSN can also incorporate real-time environmental or food specific alert systems [7]. Smart packaging indicators can identify potential quality problems through emitting electric and/or colorimetric signals [9].

2.14. Data carrier durability

Passive RFIDs, inert in harsh environment (e.g., dust, moisture), can operate as long as 20 years [40]. Active and semi-passive RFIDs are also resistant to harsh environments, but onboard batteries limit their lifetime to 2 to 7 years [17]. Manual paper forms are the most vulnerable and barcodes can lose operability by being soiled or scratched [16].

2.15. World-wide Standard

Standards are highly important when a product moves between two CFC links, so that its accompanying information is understood and accepted by all parties involved. For barcode technology, EAN/UPC standards are popularly used for retail products. ISO 18000 series defines technical specifications of RFIDs for item management in supply chain while ISO/IEC 14443 are used for HF RFID and NFC cards [17]. WSNs are built on IEEE 802.15.4 Zigbee protocol and data structure standards e.g., XML [26,41]; however, TTIs require no data standard [4].

2.16. Data security

Passive RFIDs are subject to security risks e.g., data accessing and modification [16]. Manual paper forms are highly vulnerable to data breaches, whereas barcodes with some encryption capacity provide more security but they and smart packaging indicators can be subject to reading, cloning or modification as the data is visible [4,16]. Information recorded in RFIDs is not physically visible [42] and read-write RFIDs and WSNs can be embedded with password and cryptographic protection [17,43].

2.17. Minimum hardware requirements for readability

Minimum hardware requirements for readability i.e., the reader required that affects its usability. TTIs can provide instant shelf-life information and temperature history to infield operators and customers [13]. QR codes (or 2D barcodes) can easily be read by phones, but active, semi-passive and UHF passive RFID require stationary or heavy readers while LF and HF readers can be lighter [13].

3. Technology performance matrix

The criteria data gathered has been converted into a matrix (shown in Figure 1) to demonstrate the performance rating of considered technologies across the criteria. An 8-point fuzzy rating scale (shown in Table 1) is used for this conversion that approximates the subjective, incomplete, continous or intermittent technology performance data gathered from literature and expert interviews (for detail see Islam et al. [13]). The quantitative measurements corresponding to these qualitative values have been illustrated with numerals and data bars in a technology performance matrix in Figure 1. The technology performance matrix can further be used in technology selection process in a given CFC scenario.

Table 1. Technology performance rating fuzzy scale

Linguistic term	Fuzzy number
Certainly not/ Negligible/Not applicable	(0.0, 0.0, 0.0)
Lowest	(0.0, 0.1, 0.2)
Low	(0.1, 0.2, 0.3)
Medium low	(0.2, 0.3, 0.4)
Fair	(0.3, 0.5, 0.7)
Medium high	(0.5, 0.7, 0.8)
High	(0.7, 0.8, 0.9)
Highest	(0.8, 0.9, 1.0)

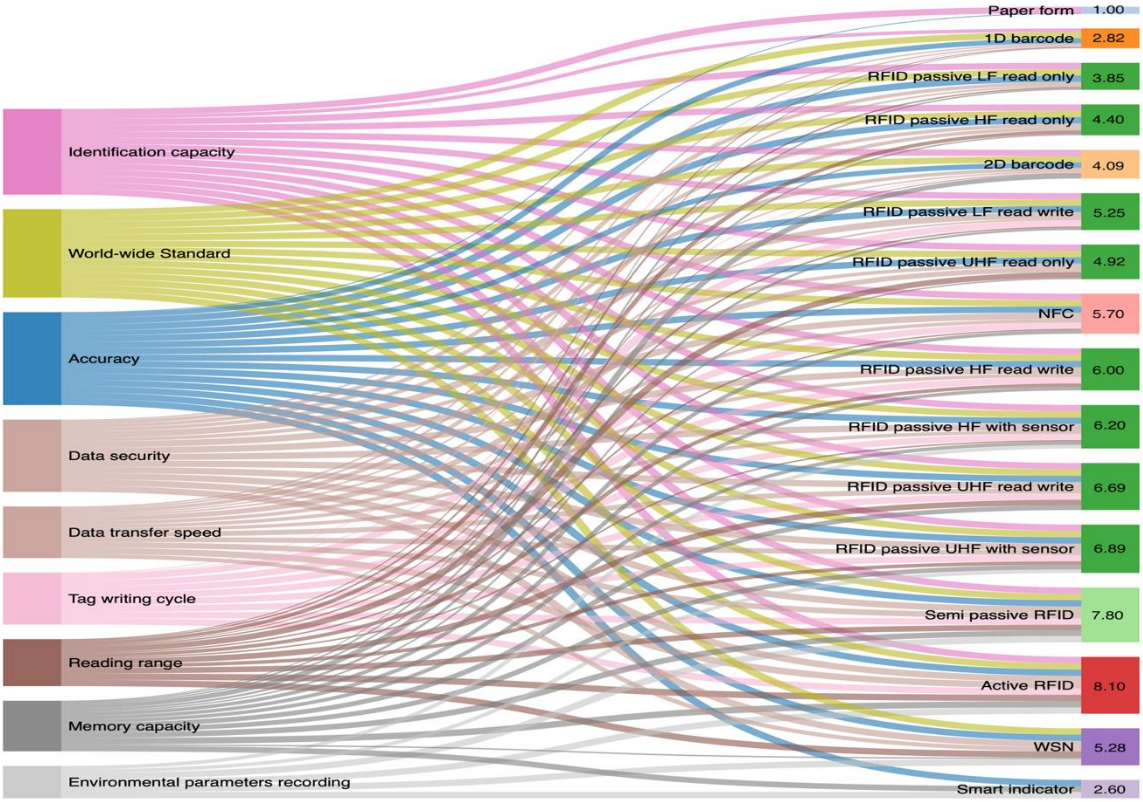
Technology / Criteria	Paper form	1D barcode	2D barcode	RFID passive LF read only	RFID passive LF read write	RFID passive HF read only	RFID passive HF read write	RFID passive HF with sensor	RFID passive UHF read only	RFID passive UHF read write	RFID passive UHF with sensor	Semi passive RFID	Active RFID	NFC	WSN	Smart indicator
Cost effectiveness	0.57	0.9	0.9	0.67	0.67	0.67	0.67	0.67	0.3	0.3	0.3	0.2	0	0.73	0	0.2
Waterproof capability	0	0.3	0.3	0.9	0.9	0.9	0.9	0.9	0.2	0.2	0.2	0.2	0.9	0.9	0.9	0.9
Flexibility	0.1	0.9	0.9	0.5	0.5	0.8	0.8	0.8	0.9	0.9	0.9	0.2	0	0.8	0	0.9
Accuracy of information	0.1	0.72	0.72	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
Reading range	0	0.1	0.1	0.2	0.2	0.5	0.5	0.2	0.8	0.8	0.5	0.8	0.9	0.2	0.9	0
Data transfer speed	0	0.2	0.2	0.25	0.25	0.5	0.5	0.5	0.72	0.72	0.72	0.8	0.9	0.5	0.58	0
Multiple tags readability	0	0	0	0	0.2	0.5	0.5	0.5	0.73	0.73	0.73	0.73	0.9	0.5	0	0
Identification capacity	0.9	0.5	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0	0
Tag writing cycle	0	0.1	0.1	0	0.9	0	0.9	0.9	0	0.9	0.9	0.9	0.9	0.9	0	0
Memory capacity	0	0.1	0.67	0.2	0.3	0.2	0.5	0.5	0.2	0.67	0.67	0.8	0.9	0.5	0.2	0.8
Environmental parameters recording	0	0	0	0	0	0	0	0.5	0	0	0.5	0.9	0.9	0	0.9	0.9
Real time location recording	0	0	0	0	0	0	0	0	0	0	0	0.9	0.9	0	0.9	0
Real time alert	0	0	0	0	0	0	0	0	0	0	0	0.9	0.9	0	0.9	0.9
Durability of data carrier	0.1	0.1	0.1	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.57	0.57	0.9	0.57	0.1
World-wide Standard	0	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0
Data security	0	0.2	0.5	0.5	0.9	0.5	0.9	0.9	0.5	0.9	0.9	0.9	0.9	0.9	0.9	0
Minimum hardware requiremnt	0.9	0.74	0.8	0.3	0.3	0.3	0.3	0.3	0.1	0.1	0.1	0.1	0	0.74	0	0.8

Figure 1. Technology performance matrix

3.1. Use of technology performance matrix

The proposed matrix (Figure 1) can be used in selecting the most appropriate traceability technologies that can support industry 4.0 transformation in industries through automation and improved data transmission. Decision makers can use the technology values from the matrix and use a quantitative approach to select a technology based on the chosen criteria set for a given CFC scenario. To demonstrate the matrix use, two simple examples have been illustrated with weighted sum method. In the first example, let us consider some CFC actors aiming to monitor real time temperature of fresh salmon (fish) that is palleted and transported by road and air between countries. Throughout this journey the product goes through various temperature influencing the product shelf-life.

To enable real-time pallet ambient temperature monitoring, automatic identification of the pallet and associated product units and recording of the ambient temperature are required. The technical criteria chosen for a pallet automatic identification are: ***identification capacity*** and ***tag reading range***; while to enable product identification, a tag attaching the pallet needs to store the carried products' identifications requiring two more criteria: ***memory size*** and ***tag writing cycle***. The criteria chosen to support real time temperature recording include ***real-time environmental parameters recording*** and ***data transfer speed***. Some additional criteria are also selected which are: ***information accurac***y for correct information transmission; ***worldwide standard*** for acquiring standard data understood by multi country CFC partners; and ***data security*** for preventing security risks throughout the



transportation.

Figure 1. Technology ranking from selected criteria for real time pallet temperature monitoring by supply chain actors

For the total nine parameters selected above in this scenario, we have considered equal weightage (i.e., 1) that derives active RFID as the highest scoring technology with weighted sum method. The technology ranking based on the selected criteria for this example has been shown through a Sankey diagram in Figure 2. Here, the nine nodes at the left edge illustrate the nine selected criteria, whereas the technologies considered in this paper is shown via sixteen nodes at the right edge. Each flow from a criterion (left) to a technology(right) presents the performance rating of the technology based on that criterion. Among all the node totals (at the right edge) active RFID is found as the highest technology with a score of 8.10 using the performance values of Figure 1.

In the second example, a consumer wants to trace the sustainability information i.e., energy consumption and carbon footprint recorded throughout the CFC of a cheese portion she buys from a store through using her smartphone. Enabling the customer to access information through a packaging label attached to a low value consumer item, the label must be light weight, low value and easily readable by the phone carried by the customer.

To satisfy these requirements, ***cost***, ***identification capacity***, ***flexibility***, ***minimum hardware requirement for the reader***, ***information accuracy***, ***writable memory size***, ***worldwide standard*** and ***data security*** are important. We have again considered equal weightage (i.e., 1) for the selected criteria that derives 2D barcode or QR code as the highest scoring technology. The technology ranking for this example has again been shown through a Sankey diagram in Figure 3, where eight nodes at the left illustrating the eight selected criteria provides the scores for the technologies at the right edge with 2D barcode (QR code) to be the highest with a score of 6.29.

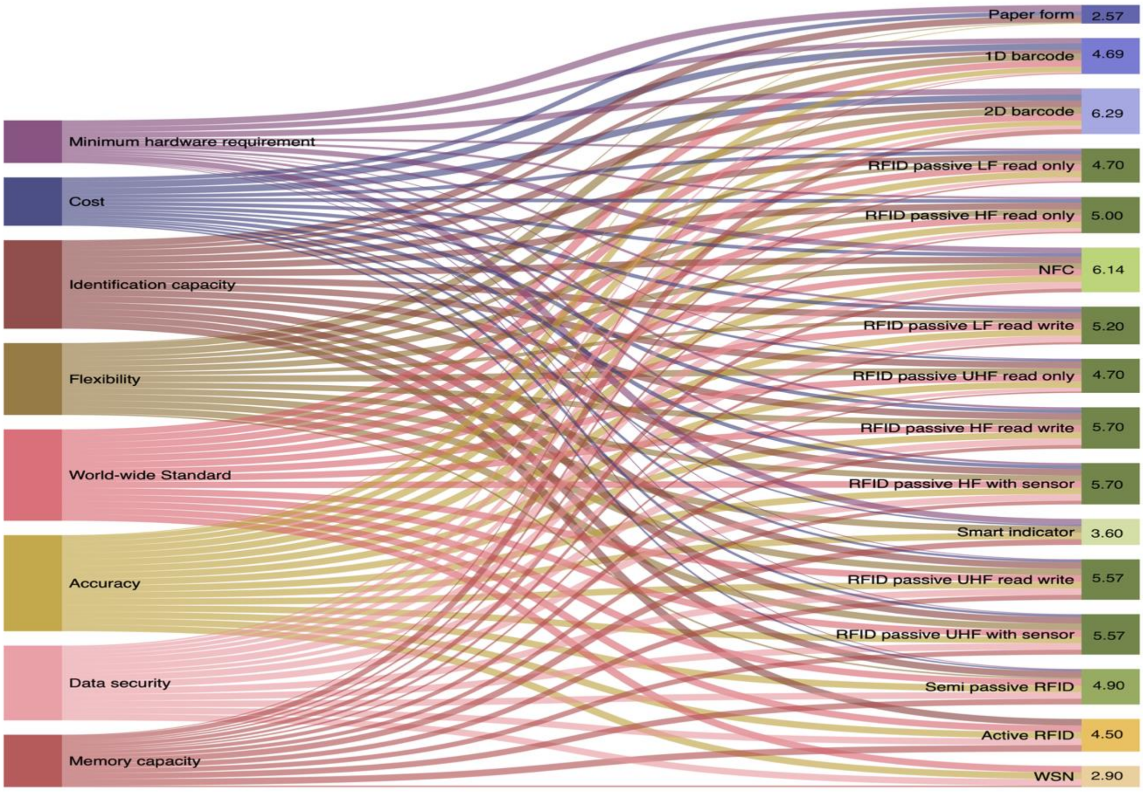


Figure 2. Technology ranking from selected criteria for communicating sustainability information to customers

4. Discussion

Appropriate selection of traceability technologies enabling industry 4.0 transformation for CFC is a complex decision problem requiring combinatorial consideration of multiple criteria. This article aims to consolidate these criteria for planning CFC traceability technologies enabling industry 4.0 that was absent in the literature. Using iterative literature review and expert interviews, the paper discusses sixteen technologies using 17 criteria using the subjective, objective, and incomplete technology data and combines them into a quantitative technology performance matrix. This study briefly presents the industry 4.0 perspective of the technologies building on Islam et al. [13] that discusses their sustainability context. The proposed matrix will help to quantitatively choose the most beneficial technology for a given scenario. To demonstrate the use of the matrix, two simple high and low-cost CFC examples are used with equal weightage method. Different sets of criteria chosen for the first and second scenarios provide two different preferable solutions: active RFID and QR code respectively. The methodology to use the proposed matrix can be found in more detail in Islam et al. [13]. Effectiveness of various multi-criteria decision making and mathematical programming methods e.g., PROMETHEE, VIKOR, goal programming and heuristic algorithms could also be tested with the proposed matrix to develop a complete efficient technology selection approach. Along with the criteria of identification and quality monitoring technologies considered in this study, criteria for data integration or communication technology e.g., blockchain improving consumer confidence could be included in future studies.

5. Conclusion

In this study, performance data of some widely used CFC traceability technologies along the criteria enabling industry 4.0 have been gathered and expressed through a quantitative matrix. Expected users of the proposed matrix are managers and technology experts in large, small, or medium enterprises who intend to identify a suitable traceability solution for industry 4.0 transformation enabling improved automation, product safety and logistics.

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