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Journal of Cleaner Production 384 (2023) 135538

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

A proposed universal definition of a Digital Product Passport Ecosystem (DPPE): Worldviews, discrete capabilities, stakeholder requirements and concerns

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ARTICLE INFO

Handling Editor: Mingzhou Jin

Keywords:
Product passport
Circular economy
Systems approach
Ecosystems
Digitalisation
Data

ABSTRACT

This paper contributes new knowledge and understanding about the role that Product Passports might play in advancing sustainable business practices towards a Circular Economy. The significance of this research is the proposed universal definition of a Digital Product Passport Ecosystem (DPPE) for international policy, industrial and technical communities. The novelty of this research lies in the systems thinking approach, coupled with systems engineering, to define and model a DPPE as a System of Systems to derive a definition. Stakeholder perspectives and requirements concerning Product Passports were synthesised using data and analysis from the European Commission's (EC) open consultation on the Sustainable Products Initiative (SPI). Nine high-level capabilities of a DPPE have been identified, and each is explored by mapping a list of information requirements discussed within the consultation. It is shown that different Product Passport applications benefit (or detriment) different stakeholder groups.

Findings suggest that DPPE solutions must be systemic, providing interoperability across multiple product life cycles, organisations, supply chains, and value chains in order to operate across international borders: thus realising benefits for world (circular) economies and the planet. Furthermore, it is proposed that if stakeholders utilise a universal definition of a DPPE in conjunction with a set of agreed ethical principles to underpin legislation, there would be fewer contradictions and ambiguity between stakeholders regarding the purpose of a Product Passport and the reasons for sharing data. Finally, the authors conclude that more research is needed on incentives for producers to share data and integrate their existing production systems with the broader ecosystem architectures to allow for maximum interoperability with minimal duplication. In addition, future research should determine specific DPP information requirements on a product-by-product basis, along with opportunities that a DPPE will enable towards industrial symbiosis.

1. Introduction

Product Passports have been proposed and advocated as a policy concept by the United Kingdom (UK) Government in its waste and resource strategy (HM Government, 2018) and explored more rigorously by the European Commission (EC) in both product-agnostic (draft) product sustainability regulations (2022) (European Commission, 2022a) and product-specific battery regulations (European Commission, 2020a). Product Passports are generally seen as a mechanism to influence consumer behaviour in relation to sustainable purchasing and responsible product ownership by making apparent sustainability aspects of a product life cycle (Munaro and Tavares, 2021), and by measuring and closing material, energy, and resource loops (Jabbour, 2019; Langley, 2022). Furthermore, Product Passports are often framed as a solution to "the lack of consistent and precise information flow about resources, products, and processes" (Walden et al., 2021) and for life cycle assessments acting as 'track and trace' instruments for unique and pooled product information (Adisorn et al., 2021; Römph and Cramer, 2020). Fundamentally, they are seen as enablers of circular business models (Jabbour, 2019; Tokazhanov et al., 2022).

Although the concept is just emerging in policy circles, there are many real-world implementations of a variety of Product Passport type

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https://doi.org/10.1016/j.jclepro.2022.135538
Received 10 August 2022; Received in revised form 14 November 2022; Accepted 4 December 2022
Available online 10 December 2022

systems across many industry sectors, both in voluntary and regulatory contexts (Adisorn et al., 2021; Walden et al., 2021). See Appendix Afor a non-exhaustive list generated as part of this research. A variety of naming conventions and technologies are adopted, including Material Passports (BAMB, 2020), Cradle-to-Cradle® passports (Maersk, 2011), Eco-labels, Smart labelling, Asset Administration Shells (or Digital Twins) (Adisorn et al., 2021), and the EC's adoption of the term Digital Product Passports (DPP). While all could be considered examples of types of Product Passports, there is a significant difference in scope and application because each type of Product Passport system was designed to solve different problems. Therefore, they collect and manipulate different data types for various end goals, even if many of the same terms are used. Researchers agree that there is a lack of understanding about what specific data should be included within a Product Passport for a given application (Adisorn et al., 2021; Berger et al., 2022).

The assortment of ways to describe the purpose of a Product Passport not only conflates understanding of the benefits between stakeholders but, more significantly, puts constraints on the ability to specify technical and semantic standards for implementation or information contained within them. This variation is sub-optimal in a global regulatory context. Indeed, given the cross-border and international distribution of many products, the same Product Passport may need to serve the objectives of multiple regulatory regimes. This study determines the extent of a common understanding between stakeholders of what a Product Passport system is, the purpose and focus of such a system, and how it should work to make technical recommendations for developing a universal data model, platform and technologies. In addition, the research tests the hypothesis (and the EC's assumption) that a Digital Product Passport (DPP) is one technical system and that regulatory stakeholder requirements are the priority.

This research demonstrates that the EC's fundamental assumption is wrong; a DPP is a complex System of Systems (SoS). A SoS is characterised by the operational and managerial independence of constituent systems (Maier, 1998), and the authors propose the term DPP Ecosystem (DPPE) is used to describe this network of organisations and technologies. From detailed analysis, the research shows the DPPE requires nine discrete capabilities at the SoS level, which will need to be delivered by multiple constituent independent technical systems and disparate organisations. The integration of these systems should be architected for legal, organisation, semantic and technical interoperability. From this holistic systems analysis, the authors argue that a DPPE should be framed as a socio-technical system, engineered using a values-based process that prioritises design for systemic change. DPPE solutions must be systemic, providing interoperability across multiple product life cycles, organisations, supply chains, and value chains, fulfilling the UK's and EC's vision and operating across international borders, thus realising benefits for world (circular) economies and the planet. It is proposed that if stakeholders utilised a universal definition of a DPPE in conjunction with a set of agreed ethical principles to underpin the legislation, there would be fewer contradictions and ambiguity between stakeholders regarding the purpose of a DPP and the reasons for sharing data. Finally, the authors conclude that more research is needed on incentives for producers to share data and integrate their existing production systems with the broader ecosystem architectures to allow for maximum interoperability with minimal duplication. In addition, research to determine specific DPP information requirements on a product-by-product basis, along with opportunities that a DPPE will enable towards industrial symbiosis (Neves et al., 2019).

The novelty of this research lies in its holistic systems approach. However, while recent academic papers provide a valuable contribution to the conceptual development of DPPs, they are primarily reductionist in their approach, breaking the ecosystem and information requirements down into the needs of different actors, different product elements, or different lifecycle phases. A selection of recent papers outlining either top-down or, more commonly, bottom-up approaches to the realisation and specification of Digital Product Passports is shown in Appendix B. Reductionist approaches introduce unnecessary boundaries to circular economy objectives that are measured across the whole ecosystem. Furthermore, when this reductionist approach focuses on a functional subset (such as a focus solely on manufacture or on policy), biases are introduced that frustrate later expansion of concepts across the whole ecosystem, as architectures have been developed without the critical foresight for a more comprehensive capability set.

The remainder of this paper is structured as follows. First, the EC's legislative context (section 2) and related policy impact evaluation process was used as a basis for this research. Next, the research design and systems methods are described (section 3), showing the process by which stakeholder data was extracted from different phases of the public consultation. From the analysis, a series of world views about the purpose of a DPP system (section 4.1) and root definitions were derived for nine distinct functional viewpoints on DPPs (section 4.2). Each viewpoint is explored by mapping a list of DPP system capabilities and information requirements articulated by stakeholders (section 4.3). It is shown that different DPP applications benefit (or detriment) different stakeholder groups (section 4.4), and thus the barriers and enablers to implementation for each application can be characterised. From this systems analysis, recommendations are made (section 5), discussing the completeness of the EC's proposed SPI regulation and the likelihood that DPPs may enable greater industrial symbiosis in their current form (section 5.2). Finally, the paper concludes with areas of future research and a proposed universal definition of a DPPE (section 6).

2. Background

The EC's Sustainable Products Initiative (SPI) responds to the objectives of the European Union Green Deal (European Commission, 2019) and Circular Economy Action Plan (CEAP) (European Commission, 2020b). It aims to make products fit for a climate-neutral, resource-efficient circular economy. The SPI is a legislative-oriented proposal that intends to widen the scope of the EcoDesign Directive beyond energy-related products. The initiative focuses on perceived 'high-impact' value chains, including electronics & ICT equipment, textiles, furniture, steel, cement, and chemicals. Still, outcomes from the initiative are expected to apply to all types of products (that the EC defines as both goods and services). By leveraging the emerging potential for product information digitalisation, including "solutions such as digital passports and tagging", the EC hopes to improve sustainability-related concerns, including waste reduction, resource efficiency, environmental impact, product durability and repairability, premature obsolescence, hazardous chemicals, and recycling and recycled content.

On September 14, 2020, the Commission published its SPI roadmap for new and revised legislation to solicit "views on the Commission's understanding of the problem and possible solutions and to make available any relevant information that they may have, including on possible impacts of the different options" through a public consultation (European Commission, 2020c) via an 'Inception Impact Assessment' (IIA) (European Commission, 2020d). Three consultation phases have followed to "ensure that the views from different organisations and stakeholder types [are] presented and considered" (European Commission, 2022b), with a fourth consultation on the draft regulatory text ongoing at the time of writing, a process described in Appendix C.

The SPI is a legislative requirement for any regulated product placed on the EU market. The legislation has global significance for worldwide supply chains; thus, respondents to the policy consultation included international stakeholders such as Amazon and eBay. The breadth of stakeholder perspectives within the consultation processes offers a platform upon which a diverse analysis of viewpoints can be extracted.

3. Methodology

This study adopts a mixed-methods systems approach, beginning with Soft Systems Methodology (Checkland and Poulter, 2007) and thematic analysis, then developed using Systems Engineering, specifically, a combination of requirements engineering and system modelling techniques. System Engineering is "a transdisciplinary and integrative approach to enable the successful realisation, use, and retirement of engineered systems, using systems principles and concepts, and scientific, technological, and management methods." (INCOSE, n.d.)

A four-stage research process (phases A to D) was followed that paralleled the consultation activities of the EC (Fig. 1). The rationale behind each stage of the process is set out in Table 1.

3.1. Data collection and sampling

Data collection and sampling were conducted to extract only the passport-related information from a much larger dataset. In phase 1 of the EC consultation process, stakeholders provided feedback in two forms: (1) in a free text response field within the EC's initial data collection process and (2) within any attached documentation. Additionally, metadata was submitted (or generated by the system), including unique ID, submission date, name of the submitter, organisation type, organisation name, organisation size, and country of origin. Three records (F1149883, F1233210, F1234362) were found to be duplicate (free text and attached documentation) responses from the same organisation but with missing metadata. These duplicates were removed from the dataset, meaning there were 190 unique respondents. In total, 71 respondents (n = 71) were found to reference 'passport' in either their free-text response or the attached documentation. A complete list of these organisations can be seen in Appendix D. These were extracted to form the sample dataset for further analysis. Of these, 11 records were missing organisation names and types. In ten of these cases (F554580, F584020, F598079, F797976, F807361, F892370, F907598, F1221639, F1234362, F1235244, excl. F1170319), the name and nature of the organisation was clear from the response text (or attached files) and was confirmed by the authors using publicly available company information. Two organisations identified as 'trade unions' (F1110583, F959443) and one recognised as a 'company/business organisation' (F1235211) were business trade associations. One organisation identified as a 'company/business organisation' (F1151835) was an NGO.

3.2. Approach to respondent coding

The EC has adopted multiple terms for similar stakeholder and actor groups within its consultation documentation. These terms were mapped within a circularity lifecycle to rationalise for greater synthesis (Fig. 2) and categorised as either stakeholders of products or stakeholders of regulation. Table 2 shows the generalised stakeholder definitions used throughout this paper to refer to the many types of stakeholders who took part in the consultation.

4. Results

4.1. Respondent worldviews of the purpose of a DPP

CATWOE is a technique used in soft systems methodology to model human activity systems and to expose a variety of actors' (A) worldviews (W) (Checkland and Poulter, 2007). For example, if DPPs act as the transforming process (T), then customers (C) are those who are affected by the transformation, owners (O) are those who could stop or block the process, and the Environment (E) are aspects that constrain the transformation. Stakeholder comments were analysed to extract perspectives on the purpose of a DPP and the worldview (or assumptions) underpinning the success of such a system. The analysis resulted in 15 distinct

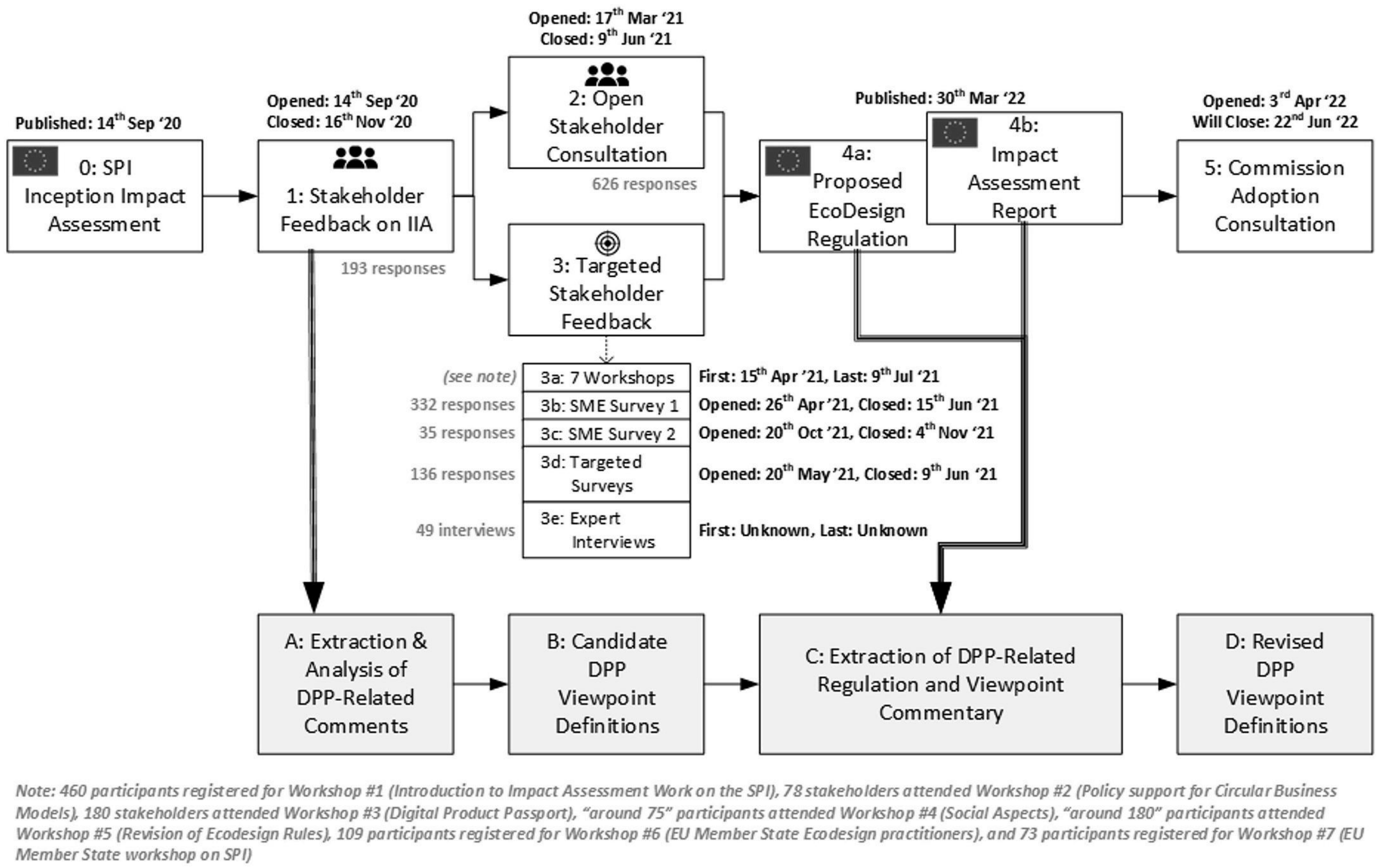


Fig. 1. The integration between the research process of this paper and the consultation activities of the EC.

Table 1
Research approach.

Research Phase	Summative Description
A: Extraction & Analysis of DPP-Related Comments (on the SPI's Inception Impact Assessment) – Raw Data from individual respondents	The SPI IAA (European Commission, 2020d) positioned DPPs as a potential solution to improve product sustainability and circularity, but the concept was not articulated in any detail at this stage. Given the absence of a widely understood conceptualisation for DPPs, a qualitative thematic analysis was used on stakeholder feedback on the IIA (1, Fig. 1) to explore the variety of stakeholder opinions on the purpose and form of a DPP. Coding was conducted without any preconceived themes or frameworks.
B: Development of stakeholder worldviews on the purpose of a DPP	Interpreting the extracted dataset was conducted using *systems thinking* techniques concerned with understanding and intervening in complex problem situations based on the principles and concepts of the systems paradigm. It enables a big picture understanding of a system of interest from viewpoints outside a defined system of interest (Hitchins, 2003) (being the EC's DPP). Using *CATWOE,* part of the Soft Systems Method (SSM) (Checkland and Poulter, 2007), 15 different worldviews were identified.
C: Extraction of DPP-related information from the EC's proposed regulation and Impact Assessment report	The EC's report (and draft regulation) (4a & 4 b, Fig. 1) provides a broad characterisation of the DPP problem space and intended DPP solution; however, it fails to make explicit the discrete purposes for which a DPP should exist. While individual respondent-level feedback from phases 2 and 3 (Fig. 1) was unavailable, a wide range of summary findings (and implicit benefits) are included in the ECs phase 4 literature. These were extracted to create a complementary dataset characterising both problem-space applications and possible solutions. Coding was based on the worldviews identified in phase B (Fig. 1).
D: Revision of the candidate DPP viewpoint definitions	By associating opinions, benefits and capabilities extracted in phase C with the worldviews developed in phase B, the robustness of the 15 perspectives could be tested, and whether the segregation was correct and valid. Through this process, the 15 worldviews were rationalised down to nine final DPP perspectives (section 3.1), as it became clear that some previously differentiated viewpoints existed within common clusters of functional capability.

worldviews, shown in Table 3, broken down by % of respondents who shared that worldview. Stakeholder categories were used to indicate who the blockers within each worldview would be, and a non-exhaustive list of constraints was generated for each. Further analysis of stakeholder concerns is reported in section 4.4.

From the analysis, respondents view DPPs predominantly as a mechanism to first effect behaviour change in businesses, then consumers. This finding reflects the premise for the SPI, that regulation will positively encourage sustainable business practice through mandatory information disclosure and enable consumers to make more sustainable product decisions. However, the variety of worldviews about the purpose of a DPP suggests that many stakeholders can foresee several 'bigger picture' holistic benefits for society and economies as a consequence of collecting and collating information about a product throughout its lifecycle. Furthermore, this variety hints at multiple systems working together to realise the full benefits of the legislation. Therefore, to begin to specify what a Digital Product Passport must and should do, it was necessary to functionally break down the DPP 'ecosystem' to define the core functions of sub-systems or constituent systems.

4.2. Nine functional viewpoints of a digital product passport ecosystem

A functional viewpoint is a way of describing a system's purpose at a high level. Nine discrete functional ecosystem viewpoints on DPPs were developed (Table 4) with root definitions, using the 15 worldviews as a starting point. A root definition is created in a sentence-like structure to describe the operational goal (what) and functionality (how) with stakeholder high-level requirements (why). The root definitions are constructed thus, "A DPP is a system for [a specific operational purpose] that [delivers an overall capability] by [fulfilling a functional requirement] in order to [meet stakeholder needs]". Each viewpoint has been generated from a multi-stakeholder perspective.

4.3. Capability requirements for a digital product passport ecosystem

Stakeholder discussion of capability often takes a solution-oriented view (*how will the system do* it) rather than a problem-oriented one (*why does the system need to do it*). The solution-domain view manifests as statements regarding the nature of the information to be collected and how the system might function. Each constituent system definition's "by.." component (Table 4) was further expanded and characterised.

Figs. 3–11 show information and system requirements (or capabilities) required by stakeholders for the DPP depicted as hierarchies of requirements within grouped themes. Most interestingly, the authors have differentiated the requirements articulated during the consultation but not included in the final draft legislation. These are shown using dashed and dotted borders around the requirement statements in each figure.

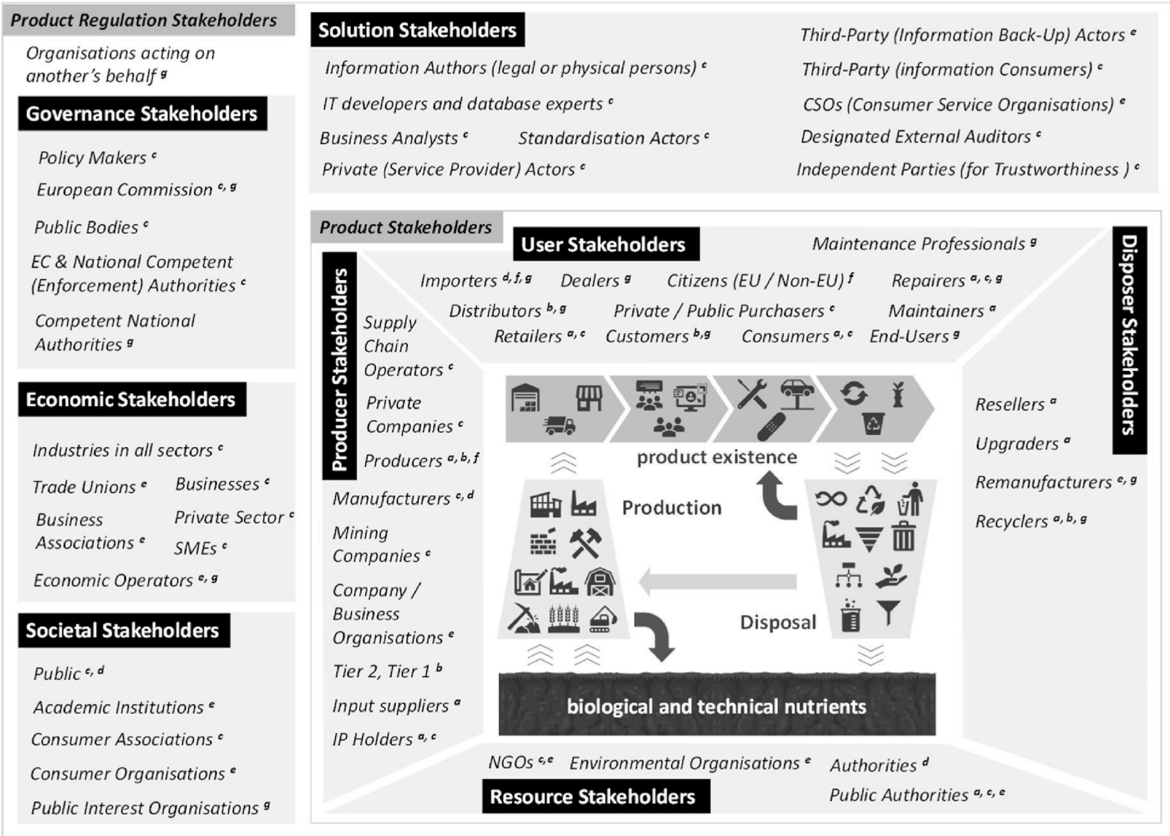
4.3.1. A system for identification and information exchange between actors (viewpoint A)

This viewpoint (Fig. 3) addresses how a chosen product ecosystem is modelled and how information exchange across the ecosystem is standardised. Information modelling includes describing things uniquely, using commonly understood approaches, with human and machine-readable information and rules for information exchange between actors. Viewpoint A requires the unique identification of organisations (that the EU DPP terms 'economic operators' and refers to manufacturers, importers, and others), in relation to a role and industry, for example, automotive or farming. This viewpoint also requires the unique identification of products and product types, classified by controlled vocabularies (or taxonomies) in relation to a category or class of product so that regulations, rules, and requirements are positively associated with that given product type.

Specific standards and taxonomies are not explicit in the draft legislation, but some stakeholders make suggestions, for example, the EU Customs Tariff Database (TARIC) (European Commission, n.d.). Other information requirements related to read and write access rules, and the technical requirements concerning access speed and interoperability, referring to open standards. Unique 'data carrier' IDs are required, distinct from unique product identifiers. The term data carrier here describes a scannable label on the product, like a QR barcode, which would link to the data in the DPP and associated information, such as pre-sales information for buyers.

4.3.2. A system for evaluating comparable aspects of products (viewpoint B)

This viewpoint (Fig. 4) facilitates the comparison of a range of product options (within a given type of product) at any procurement stage. This system requires information points to distinguish between



(a) Annex 18, Table 99 (b) Annex 18, Figure 1 (c) Annex 18, 'Potential stakeholders' benefits, pg 592-596 (d) Annex 18, 'Roles', Table 101
(e) Annex 18, pg 617-621 (f) Feedback Organisations (to Impact Assessment, Open Public Consultation) (g) COM(2022)142 Ch.III

Fig. 2. A variety of stakeholder names used within the EC consultation literature mapped to analysis categories.

Table 2
Generalised stakeholder definitions used in this paper.

Stakeholder Type	Description
Stakeholders of Products	
Resource	Stakeholders that represent the interests of the environment and environmental resources but are not involved in the active consumption of those resources.
Producer	Stakeholders that transform raw material resources into finished useable products.
User	Stakeholders that sell, acquire, use, and maintain products are not involved in creating and manufacturing those products.
Disposer	Stakeholders that handle a product once it has been disposed of either return that product to use or decide the best way to derive additional value from it.
Stakeholders of Product Regulation	
Societal	Stakeholders with predominantly a social interest in the regulation of products.
Economic	Stakeholders with predominantly an economic interest in the regulation of products.
Governance	Stakeholders with predominantly a governance interest in the regulation of products.
Solution	Stakeholders that have an active operational role in the design, utilisation, and disposal, of product passport system solution but do not have a stake in the product lifecycle.

each product's benefits, capabilities, features, and performance (model, batch, or item, as appropriate) within that range. That range is likely to be defined by the product type identification described in viewpoint A (see Fig. 3). This view also requires information searching within and between product information sets. This viewpoint is predominantly for the benefit of retailers and buyers/consumers. Note that performance scores include sustainability claims or impact scores based on a range of suggested assessment methods and metrics but not explicitly specified in the proposed legislation.

4.3.3. *A system for demonstrating responsible business practices (viewpoint C)*

This viewpoint (Fig. 5) evidences the different sustainability claims (be they regulatory, marketing, or otherwise) of various organisations within a supply chain: those operators responsible for a commitment back to some form of underlying evidence, possibly with some external verification. In this viewpoint, the entire range of product commitments (performance claims, green claims, regulatory and standards compliance) are traceable to the operators responsible for those claims and the underlying evidence required to support those claims. At its most transparent, this system could link individual claims within inter-stakeholder communications, for example, product website information claiming compliance with a standard, back to the responsible operator that can validate that claim. This functionality requires tracing responsibility for compliance across specific operators in the supply chain and the level of aggregation to which that responsibility is demonstrated; it can ascertain whether a claim has been made against a particular product, a set of products, or a company-wide policy.

4.3.4. *A system for the oversight of industrial circularity performance (viewpoint D)*

This viewpoint (Fig. 6) is necessary to monitor, oversee, and harmonise the analysis of different product sectors and define good progress towards circularity across an industry or industries. This viewpoint characterises the shift from a linear to a circular production and consumption pattern and is recognised, but not yet explicitly defined, by the EC: "Identification of the most relevant and valuable data

Table 3
Stakeholder worldviews on the purpose of a DPP, with blockers and constraints in fulfilling that purpose.

%	DPP Purpose	Worldview (Assumptions)	Blockers	Constraints
44	To enable sustainable consumer decision-making	Consumers will make better product choices if provided with comparable sustainability information at the point of sale.	User stakeholders, particularly consumers	Lack of consensus on what sustainability information to include for comparison purposes.
41	To demonstrate a sustainable business practice	Regulation will positively encourage sustainable business practices through mandatory information disclosure	Producers and economic stakeholders	Intellectual property and commercial interests; interoperable technical systems; data quality; identification of actors along the value chain
30	To explain how to handle/ operate the product	Better quality product handling information will change user and disposer behaviour.	Producers	Lack of capability and inclination of users and disposers.
18	To demonstrate sustainable product design values	A product's entire circularity impact can be assessed and communicated simply to consumers.	Producers	All products can be assessed using the same criteria; Access to skills and knowledge to design products sustainably.
18	To demonstrate sustainable processes and policy	Information made public via a DPP will provide a mechanism for quality assurance which ensures greater public trust in products and producers.	Producers, governance stakeholders	Quantifying consumer trust is complex.
17	To facilitate collaborative multi-stakeholder sustainability efforts	Standardised sustainability information shared between economic actors will result in more significant collective efforts.	Producers, users (particularly value-chain actors)	Competitive business models; lock-in to closed-loop consortiums.
17	To monitor value extraction from resources	Information on the recyclability of materials will enable more materials to be recycled at end-of-life.	Disposer, producer	Current waste management provision and capacity; forecasting waste availability; viability of circular business models
15	To document the whole life cycle of the product	Capturing the entirety of real-time events with a product lifecycle will provide better transparency of information related to sustainability.	Users	Privacy; data ownership; data quality; commercial interests; interoperable technical systems
14	To itemise the resources contained within a product	Information about a product's material composition and sources can be easily determined.	Producers	Intellectual property and commercial interests
14	To classify the source of resources used within a product	Product declarations of hazardous substances and recycled content will encourage using non-toxic and recyclable materials in production.	Producers	Lack of consensus on the information required per product type.
13	To explain how to reuse, dismantle, and dispose of the product	Detailed guides to product disposal will enable better, safer and more efficient waste management.	Disposer	Limited provision and capacity to recycle a wide variety of materials and resources.
13	To monitor resource use and (total) availability	Tracking materials of concern within the economy will benefit all markets.	Governance stakeholders	The complexity of information systems, timeliness and data accuracy; political will.
13	To describe a product's performance against criteria	Complex sustainability data requires rationalising into criteria that consumers readily understand.	Producers	Translating complex data into summary insights; industry-wide agreement on criteria.
11	To classify a product's ecological footprint	Product information about its ecological footprint will educate users and encourage them to consume less.	Producers, users, particularly consumers	The quantifying of an ecological footprint in various contexts and use-based situations.
11	To explain how to maintain, repair, and refurbish the product	Users having access to quality operational information will maximise the product's longevity.	Producers, users, particularly consumers	Consumers' willingness to make-do and mend or purchase second-hand products.

will take place in consultation between the Commission, stakeholders and authorities, driven by the SPI sustainability and circularity objectives" (European Commission, 2022b, p. 589). This requirement infers a system that can document, compare, and assess how different operators and types of products compare against other lifecycle models with different performance metrics. These metrics inform the decision criteria for good product procurement (viewpoint B). For governing organisations, this is the system that would, for example, show where investments are needed to improve industry performance and enable policy evaluation of the effects of the SPI.

4.3.5. A system for evaluating product design performance (viewpoint E)

This viewpoint (Fig. 7) traces the different performance characteristics of the product in design, manufacture, and use. The notion of circularity and sustainability principles between purpose D and purpose E should not be confused; D focuses on the performance of industries, while E focuses on the performance of products. The identified metrics are mainly discussed from the perspective of the production phase of a product lifecycle; however, retesting those metrics later in the lifecycle should not be discounted. Some metrics also imply split abstraction,

Table 4
"What is a Digital Product Passport?" Nine synthesised discrete functional viewpoints as root definitions.

Viewpoint	A DPP is a …	That …	By …	In order to …
(A) ID & Information exchange	System for identification and information exchange between actors	Increases the value of product-related data	Providing a mechanism for uniquely identifying, describing, and exchanging product and actor data	• Enable downstream product lifecycle activities. • Increase the efficiency of information sharing between enterprises.
(B) Product comparison	System for evaluating comparable products	Ensures adequate and reliable sustainability information is available	Providing a comparable set of attributes of uniquely identifiable product designs	• Enable sustainable consumer decision-making • Enable green public procurement activities • Facilitate tailored product comparison and advice services
(C) Business transparency	System for demonstrating responsible business practices	Increases the incentive to create sustainable products	Requiring evidence to support the claims made by actors	• Demonstrate compliance with standards, rules, and regulations • Demonstrate sustainable decision-making and the avoidance of greenwashing • Better response to supply-chain risks
(D) Measuring industry performance	System for the oversight of Industrial circularity performance	Facilitates a transition towards a sustainable, circular economy	Defining the metrics for sustainability and circularity across product lifecycles	• Target investment and innovation at the most opportune areas for improvement • Measure the impact of sustainable business models
(E) Product design	System for evaluating product design performance	Encourages manufacturers to create and maintain sustainable products	Defining essential sustainability and circularity performance requirements for a given product type	• Encourage products that are more reusable, repairable, upgradeable, recyclable, etc.
"What is a Digital Product Passport?" Nine synthesised discrete viewpoints and root definitions of PPE capability				
Viewpoint	A DPP is a …	That …	By …	In order to …
(F) Product-life tracking	System for tracking product origin, possession, and event history	Increases transparency of post-sale product life	Capturing evidence of a transparent chain of custody of the product, its parts, and associated events.	• Demonstrate product authenticity and fight counterfeits • Guarantee second-hand product quality and improve the capability for second-life applications • Provide post-sale manufacturer (warrantied & unwarranted) services & support, including product recall • Use post-sale customer feedback to improve product designs
(G) Product operation	System for communicating operational information about a product	Increases the useful lifespan of products and ensures maximum value recovery at end-of-life	Providing information necessary to maintain the product's useful life and how to dispose of the product optimally.	• Improve user product handling • Improve product maintenance capability • Improve availability and cost of spare parts and repair services • Encourage successful uptake of closed-loop product recovery schemes and other product recycling initiatives
(H) Product impact assessment	System for whole-life assessment of a product's impact	It makes the total impact of a product transparent	Requiring a whole-life assessment against social and environmental impact performance metrics	• Encourage a reduction in the most-impactful products
(I) Material & part identification	System for identifying materials & resources in products	Enables traceability of a product's material composition	Identifying hazardous, problematic, and valuable materials contained within a product	• Improve material reclamation • Penalise and reward manufacturers based on the types of materials included • Trace stock and flow

being measurable at both product and part levels, and possibly requiring unique identification of the functional and physical decomposition of a product (viewpoint I) and an interlinking of DPP (data carrier) unique IDs (viewpoint A). Finally, the product performance factors reflect metrics for each product (or part within a product); claims that can be evidenced through viewpoint C, used to generate performance scores for comparison purposes for buyers in viewpoint B, relating to lifecycle models described in viewpoint D.

4.3.6. A system for tracking product origin, possession, and event history (viewpoint F)

This viewpoint (Fig. 8) traces events, including possession or ownership of a product from the moment it acquires a DPP until the end of a product's life. This viewpoint requires the ability to uniquely identify each steward (viewpoint A) of a product across its lifespan (tracing ownership and possession) and the work done by each possessor on the product (tracing product manipulation or adaptation). Notably, the EU DPP proposal only considers possession until a product is dismantled. However, this could be extended into the waste-management phase of a product to deliver full circular product traceability at an auditable level. At its most traceable, the possession traceability recorded here is the granular form of the abstracted enterprise roles described in viewpoint A (provided that roles are also defined for the product in use, such as customers, maintainers, refurbishers, and recyclers). After viewpoint D, this viewpoint is the least defined in the draft legislation. However, it is potentially the most complex system, as rules on recording and accessing data about product events throughout its life are required in the DPP.

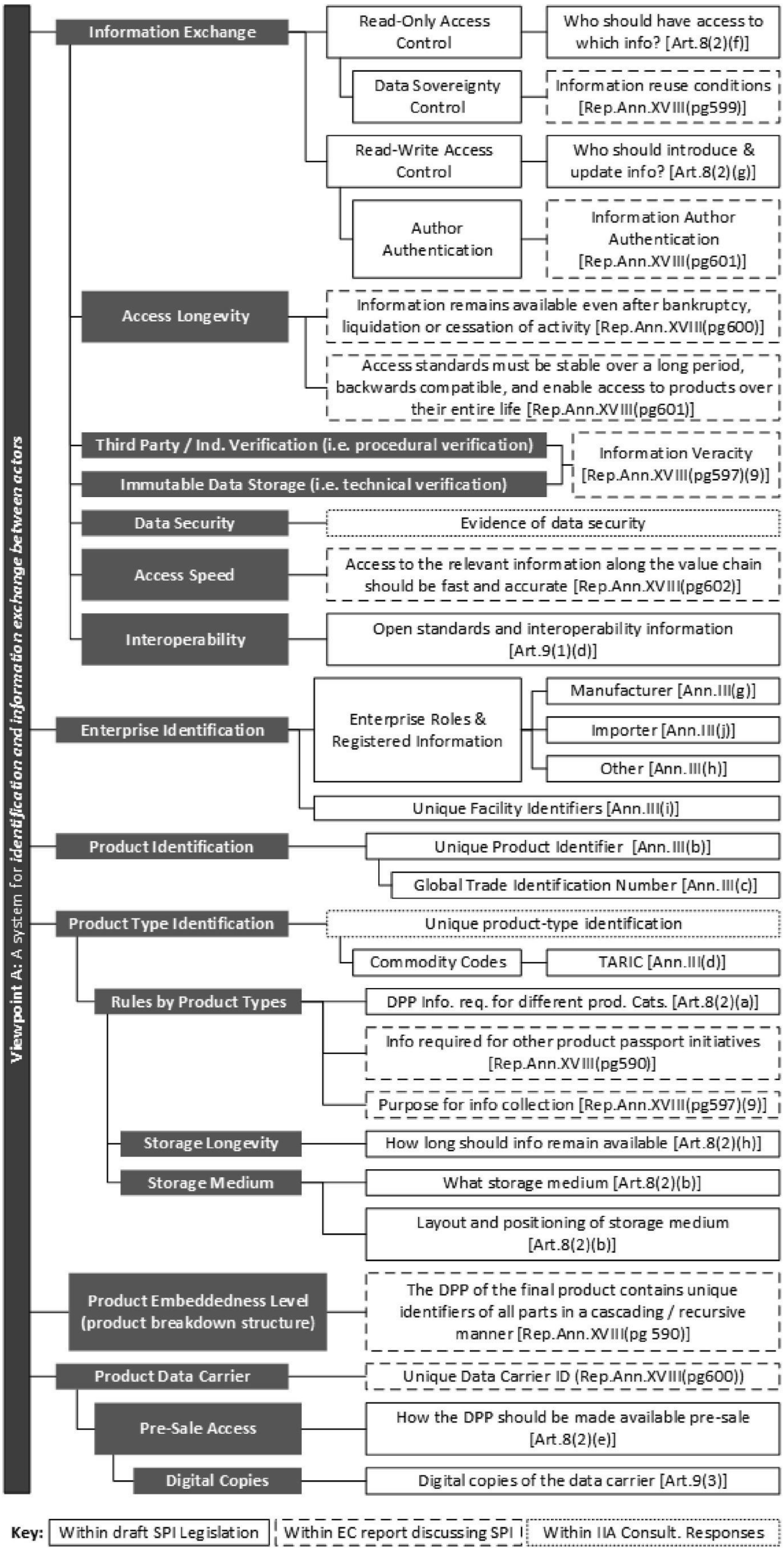


Fig. 3. System capability and information requirements within viewpoint A.

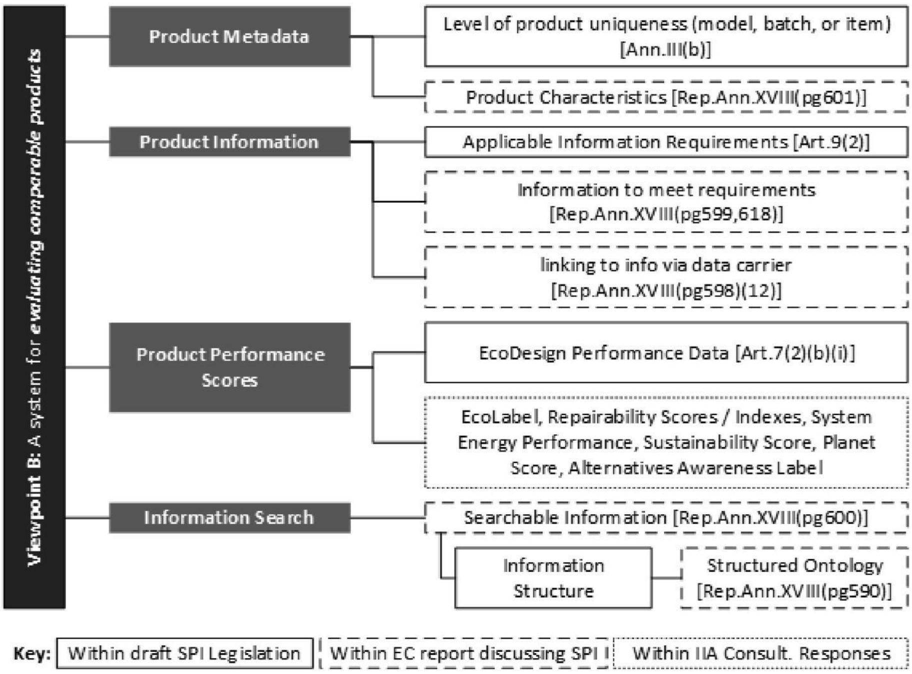


Fig. 4. System capability and information requirements within viewpoint B.

4.3.7. A system for communicating operational information about a product (viewpoint G)

This viewpoint (Fig. 9) provides manufacturer information on the operational aspects of a product; how they have designed a product to be used, upgraded, maintained, disposed of or recycled. In addition, integration and association with the product breakdown structure are also required due to the possibility of changing and replacing product parts during its life (viewpoint A).

4.3.8. A system for the evaluation of environmental impact (viewpoint H)

This viewpoint (Fig. 10) provides the traceable relationship between the activity of different economic operators and their impact on the planet, being the topic of Lifecycle Assessments (LCA). Based on critical assumptions, LCA is traditionally performed at a fixed point in the product life cycle. However, the DPP's proposed cascading/recursive capability suggests that those within product supply chains could feed their local assessment information directly via the DPP. This viewpoint can be split into two main capabilities; the ability to characterise the scope of assessment and, thus, the ability to inform how to integrate multiple assessments and characterise the impacts (both environmental and social) modelled within such assessments.

4.3.9. A system for identifying materials & resources in products (viewpoint I)

This viewpoint (Fig. 11) identifies materials and resources used within (and used in creating) a product to enable traceability. This viewpoint concerns resources, whether raw materials or more complex components, parts, substances, and mixtures. Most of the DPP's focus is on the capability to describe resources contained within a product (at the level defined by the product breakdown structure in viewpoint A) and how much of that product is made up of reused and reusable components. However, there is also the requirement to describe the production resources, those used in the manufacture of the product. If unique material identifiers are used, this will leverage additional capability to trace material resources within the economy and better manage material waste.

4.4. Stakeholder perspectives on functional viewpoints

Stakeholder sentiment was extracted and collated against each viewpoint to understand better the consensus for support of DPPs, concerns and foreseeable issues.

4.4.1. Perspectives on a system for information exchange between actors (A)

DPPs can generate new value for *economic* stakeholders within a given product ecosystem, which may not benefit all enterprises. A system that enables data sharing throughout the value chain along the product lifecycle shifts value away from *producers*, who are unsurprisingly concerned about the low, competitive advantage and the sensitivity of intellectual property, and the value of data, encouraging data hoarding. *Users and disposers*, by contrast, are worried about the cost and competitiveness of repairing and reusing products versus the cost of buying new, with the value shift operating in their favour, excepting retailers, who anticipate limited direct benefit for consumers. *Governance* stakeholders see a positive opportunity for increased circular activity. If implemented correctly, DPP systems can offer trading efficiencies (marketing costs, compliance costs, trade barriers) and technical efficiencies (investment costs, stranded assets, coherency of implementation) for *economic and producer* stakeholders. Creating an additional administrative burden with costs likely to pass on to consumers.

The requirement to provide information on a product within a DPP was "very well accepted across all stakeholder groups" (European Commission, 2022b, p. 88). With increased data sharing, *resource* and *governance* stakeholders hope to benefit from products' reduced environmental and social impact. Information controls are called for to address the commercial sensitivity of IP. *Economic* stakeholders are willing to make some data available, even without direct benefit, if the public interest objectives and utility are clear. A diverse set of stakeholders should be consulted, including SMEs, IP Rights Holders, EU Verification Bodies, IT Developers and Database Experts. Stakeholders already involved in the digitalisation of information along value chains recommended a technically decentralised/distributed system, given "it would be very difficult to manage a centralised database with such a wide scope" (European Commission, 2022c, p. 596). Those *solution*

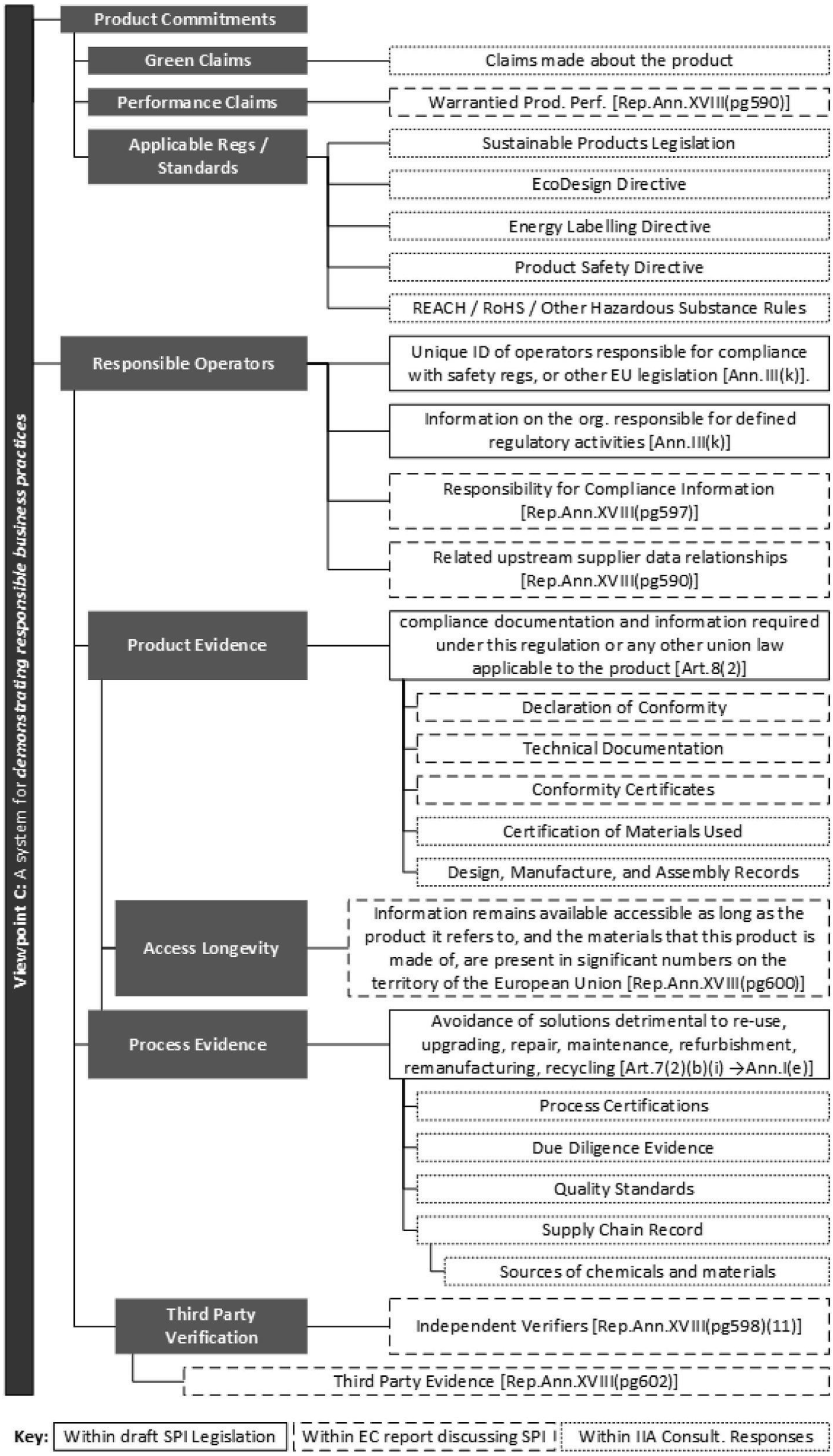


Fig. 5. System capability and information requirements within viewpoint C.

stakeholders also recommend that EU DPP needs an international perspective because the value chain will cover partners outside the EU; therefore, the DPP should be based on open-source systems and ensure interoperability and access for everybody (ibid). The greatest challenge identified in implementing the DPP is related to the complexity of the value chains (ibid).

4.4.2. *Perspectives on a system for product comparison (B)*

Stakeholders generally agree that there is a lack of adequate and reliable product sustainability information and that *user, societal,*

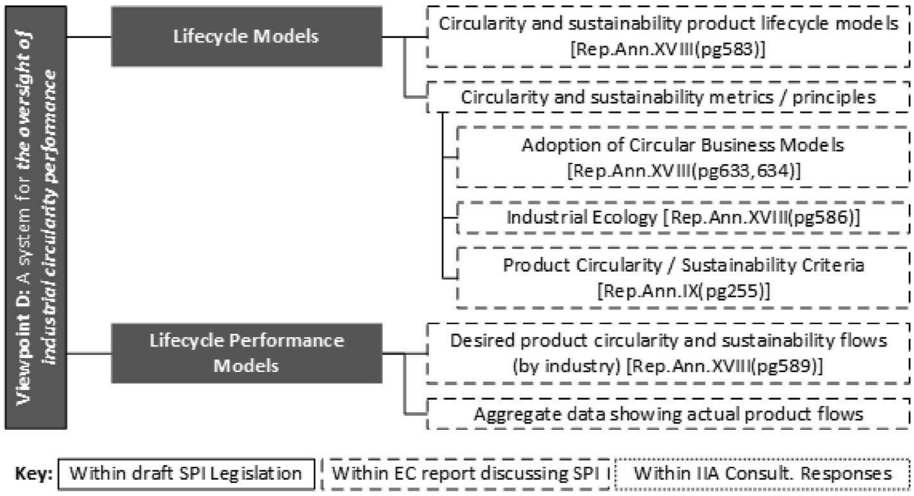


Fig. 6. System capability and information requirements within viewpoint D.

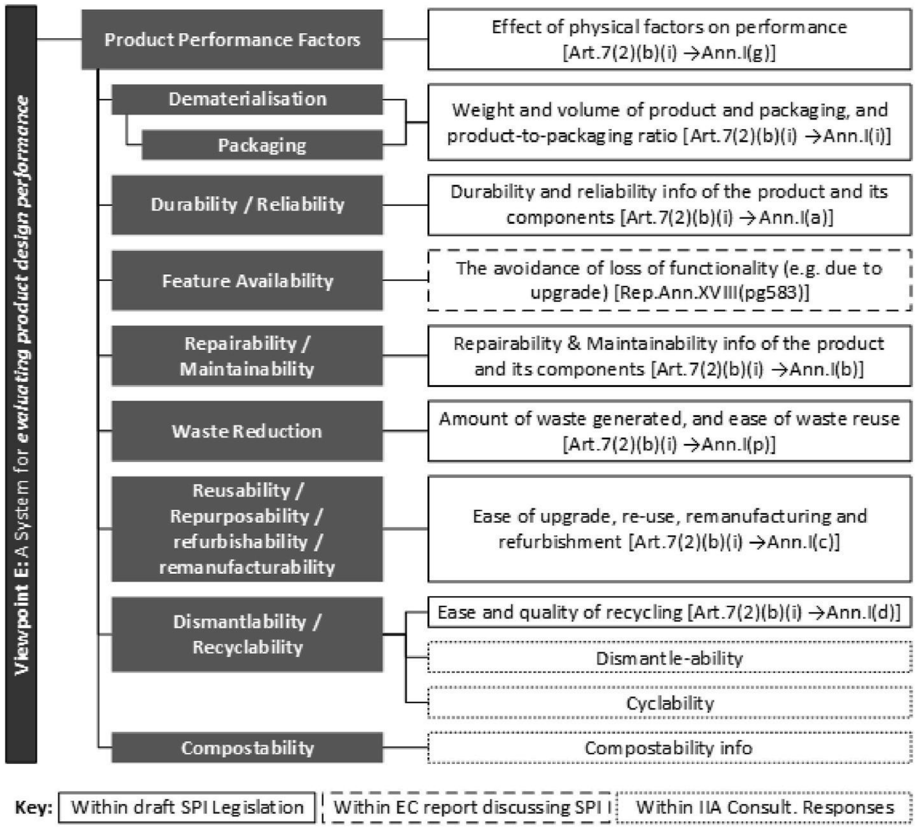


Fig. 7. System capability and information requirements within viewpoint E.

governance, and *resource* stakeholders could be better informed. A system that enables consumers to make better decisions by comparing products will generally benefit *users,* but a proliferation of information may also confuse them. All stakeholders generally supported the setting of performance classes. However, there was a lack of support from *economic* stakeholders for repairability scores. *Governance* and *economic* stakeholders will benefit from this system by enabling Greener Public Procurement (GPP) activities. However, *governance* stakeholders highlight that a lack of adequately trained personnel may limit effective procurement policies.

As this system enables comparison between products of a specific type, a "strong need for uniform requirements regarding the nature of the data collected" was noted. However, different sectors and products require different types of information, with *producers* calling for sector-specific approaches. It is implicit that the DPP system will overcome the limited packaging space for information communication on products.

4.4.3. Perspectives on a system for business transparency (C)

Stakeholders generally describe a commercial and regulatory landscape that does not encourage sustainable decision-making. The lack of coherence between regulatory initiatives is flagged. However, *governance* stakeholders expect that the SPI regulation should address this fact. An expansion in regulation and oversight was generally accepted, but for different reasons. *Governance, users* and *resource* stakeholders

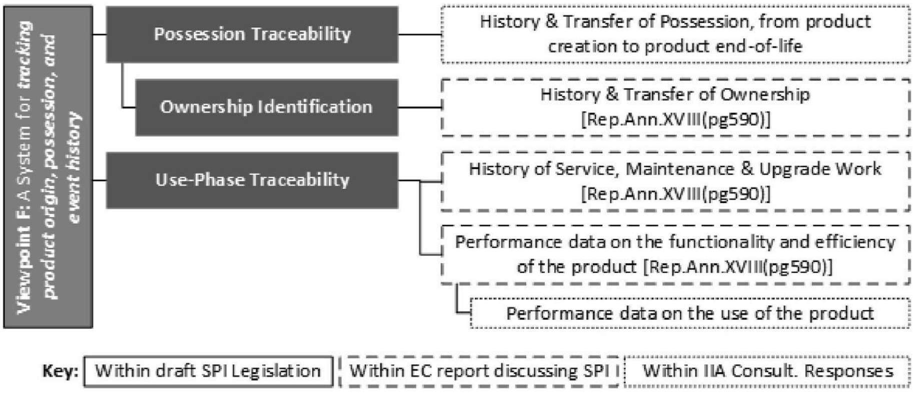


Fig. 8. System capability and information requirements within viewpoint F.

think voluntary approaches to product sustainability do not work, contrasting the general opinion of *economic* and *producer* stakeholders. However, mandating sustainability would provide a more level playing field for conscientious *economic* stakeholders and overcome a concern that not enough consumers are willing to pay more for sustainable products. This system enables *economic* stakeholders to demonstrate compliance and appropriate due diligence. It is generally well accepted, although regarding providing information on the social conditions along the value chain, only 31% of *producers* (business associations) agreed, compared to most *resource* stakeholders (88% of NGOs and 100% of environmental organisations) (European Commission, 2022b, p. 88). DPPs could provide greater transparency for *users*; however, this sentiment conflicts with IP concerns from *producers*. *Economic* and *governance* stakeholders caution that governance resource constraints could hinder progress and enforcement, although DPPs could enable faster screening methods for non-compliance. This system has the capability for businesses to demonstrate sustainable practices over and above regulatory obligation, providing *users* and *societal* stakeholders with trusted information and the avoidance of greenwashing.

This system is also concerned with how evidence is delivered. Support for mandatory third-party certification or inspection comes from *social* and *governance.* However, *economic* stakeholders do not support this due to the cost of verifying claims along the value chain (a concern specifically highlighted by NGOs).

4.4.4. Perspectives on a system for measuring industry performance (D)

Stakeholders generally agree that product lifecycles could be more circular and support the intent of the SPI in taking a holistic approach to measuring industries' progress towards sustainability. *Governance* stakeholders see the benefits of reduced emissions and improved circularity efficiencies across all sectors. *Societal* stakeholders see the benefits of increased product lifespan, consumer empowerment and access to more sustainable products. *Resource* stakeholders see an improvement in feasible, holistic, circular pathways and the ability to address overconsumption, while p*roducers* see the benefits of consolidated data. This system aims to aid *governance* stakeholders' decision-making concerning targeted investment and innovation where there is the most potential for the public good and environmental sustainability. *Economic* stakeholders*, producers* and *disposers* see the benefit of that investment. *Resource* stakeholders describe the benefit of increased technological innovation. The promotion of more sustainable business models allows *economic* stakeholders to increase the value that can be extracted from their materials and products. For *producers*, this is via the adoption of Circular Business Models (CBMs) that enable new services to be provided while *users* benefit from lower costs and increased product guarantees. However, a lack of circularity knowledge and skills may hinder development.

The system's capability to have defined sustainability metrics is well supported by stakeholders, with calls for clarity on how circularity and sustainability are measured. *Economic* stakeholders would benefit from developing better indicators and applying a systemic, interoperable approach. *Producers* support gathering data on reuse, sorting, recycling and CBMs, while *resource* stakeholders support the collection of product expected lifespans.

4.4.5. Perspectives on a system for evaluating product design (E)

Stakeholders generally agree that products could be designed to be more sustainable. Both *governance* and *resource* stakeholders agree that "products are more and more complex and difficult to recycle" (European Commission, 2022b, p. 90). The goal of this system is to encourage a shift in design thinking addressing a universally agreed-upon consumer opinion that "products are not currently designed to be easily repaired or upgraded" (European Commission, 2022b, pp. 89–90). However, how this is assessed in practice sees less agreement. Within responses from *economic and resource* stakeholders, 32% of business associations (vs 88% of NGOs and 91% of Environmental Organisations) supported the focus on "actions to be taken by producers to improve durability, re-useability, upgradability and reparability" (European Commission, 2022b, p. 88). Still, only 18% (vs 38% NGOs, 36% Env. Org.) supported "producers/importers to publish information on how they have prioritised materials that are safe and sustainable-by-design and have substituted chemicals of concern with safer ones whenever possible" (ibid). However, SMEs suspect that early negative impacts will be offset by "reduced material use and expenditure; increased customer loyalty; better access to the market for greener products; reputational benefits etc." (European Commission, 2022b, p. 96).

4.4.6. Perspectives on a system for product-life tracking (F)

For *economic* stakeholders and *producers*, product origin information brings better supply chain knowledge through increased transparency, and *societal* stakeholders achieve increased trust. This system aims to enable *economic* stakeholders and *producers* to combat counterfeiting, levelling the playing field against unscrupulous suppliers. At the same time, *users* benefit from increased confidence in the authenticity and ability to resell. A guarantee of second-hand product quality seeks to discourage planned obsolescence, a feature *resource* stakeholders argue products are designed to do, while *economic* stakeholders disagree. Similarly, *economic* stakeholders argue that second-hand product quality is difficult to assess, while *resource* stakeholders disagree. *Economic* stakeholders are more optimistic about the capability to dynamically evaluate the performance of products and ensure a managed second-life product application. This system allows *economic* stakeholders and *producers* to provide post-sale services to *users* and administer warranties and recalls. Post-sale customer feedback works opposite, providing users' data back to *producers* and *economic* stakeholders, allowing them to improve their product offerings. Similarly, the system enables greater supply-chain oversight for *producers* and *economic* stakeholders' *ability to assess and respond to risk.*

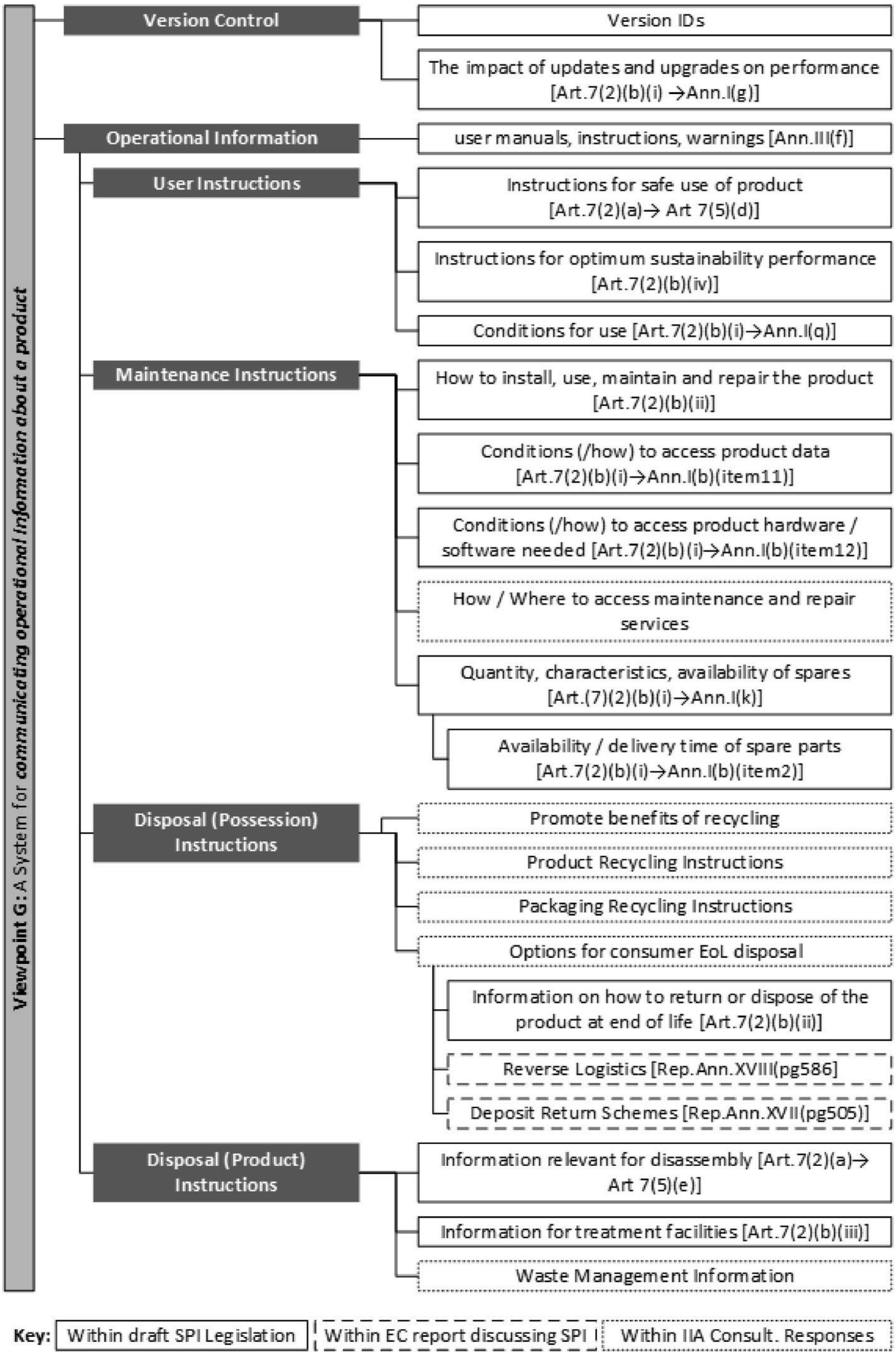


Fig. 9. System capability and information requirements within viewpoint G.

4.4.7. *Perspectives on a system for product operation (G)*

Perspective G encompasses all operational information to extend a product's service life and optimal disposal. A system that improves user product handling is generally well-supported by all groups, supplying *users* with the information they need to best operate, maintain and safely service the product (be they consumers or maintenance-focused organisations). However, the exact information to be provided is less clear, and metrics such as availability of spares and expected product lifetime are considered hard to assess by expert stakeholders. A system that improves the availability and cost of spare parts is targeted at spares availability. Some *user* stakeholders express that they may benefit from the ability to remanufacture spare parts of products no longer supported by Original Equipment Manufacturers (OEM). Still, again *producers* feel that IP rights are an issue. A system that encourages successful uptake of recycling schemes through better access to product information benefits *producers* by recovering resources for remanufacturing. *Disposers* benefit from the operationalisation of recovery schemes. However, it is noted in expert interviews that these are only successful if the relevant infrastructure is built and operating effectively.

4.4.8. *Perspectives on a system for product impact assessment (H)*

All stakeholders agree that products do not sufficiently address their environmental impact. For *governance* stakeholders, a product impact assessment system aims to encourage a reduction in the most impactful products. The aim is to decouple economic growth from climate, biodiversity, and pollution impacts. While for *economic* stakeholders and

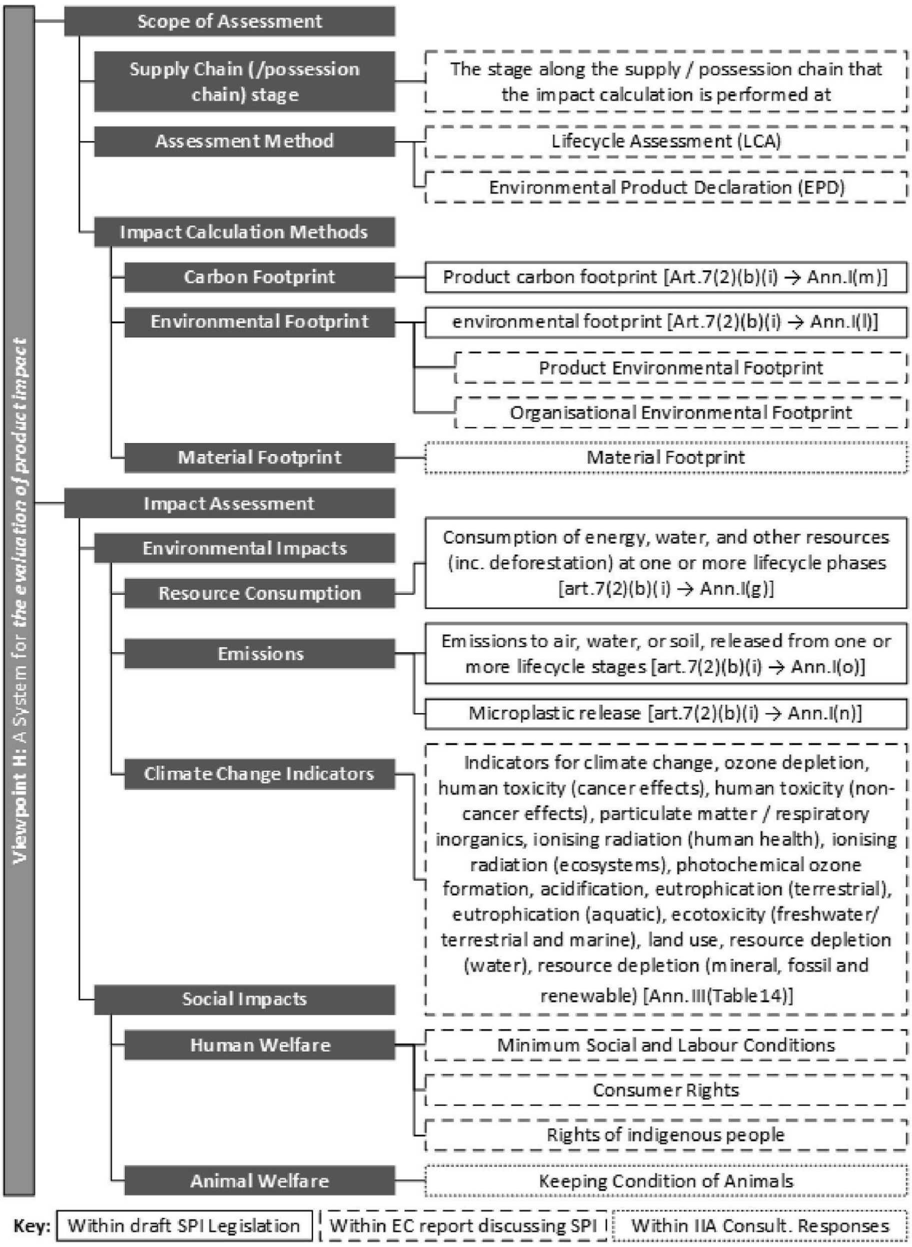


Fig. 10. System capability and information requirements within viewpoint H.

producers, product impact assessment aims to reduce greenhouse gas emissions, improve working conditions, and reduce environmental crime. *Economic* stakeholders consider environmental and social information a high effort for low advantage, with some benefit to *users* but an increased benefit to *resource* stakeholders. Nevertheless, all stakeholder groups supported the requirement to provide information about a product's environmental performance. In contrast, social performance information saw significantly more support from *resource* and *governance* stakeholders than *economic* stakeholders, with stakeholder opinion split on whether addressing social aspects is feasible.

Product and Organisational Environmental Footprint Assessments (PEF/OEF) are considered appropriate by many *resource* stakeholders and, to a lesser extent, by other stakeholders. Most stakeholders support a lifecycle assessment approach. However, the EC has surmised that a greater range of aspects must be identified "to properly execute financial and environmental calculations on the product's impacts" (European Commission, 2022c, p. 598).

4.4.9. *Perspectives on a system for material resource management (I)*

DPPs facilitate monitoring and oversight of the flow of materials within their jurisdiction through increased knowledge of the materials contained within products. However, the provision of this type of information has significantly less support from *economic* stakeholders than from *resource* stakeholders. For *governance* stakeholders, improving material reclamation will result in greater strategic autonomy, while the DPP will simplify waste management reporting. *Disposers* will be able to identify valuable resources better and automate their sorting and separation processes. A system that penalises and rewards manufacturers enables rules on hazardous/critical materials and minimum recycled content levels in products. *Governance, resource* and *user* stakeholders support banning materials that inhibit recyclability. *Economic* stakeholders saw some negative short-term impact of minimum recyclability requirements but generally considered these offset over time and saw the benefit of phasing out harmful materials.

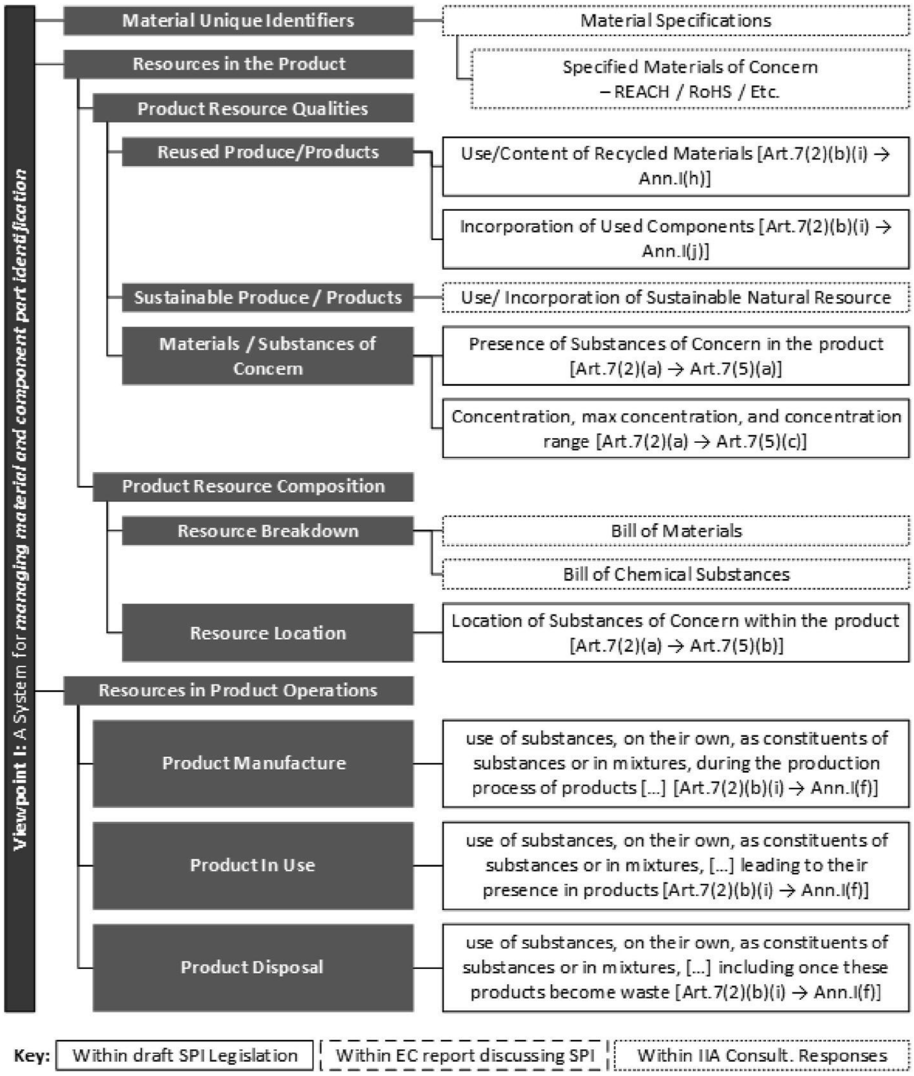


Fig. 11. System capability and information requirements within viewpoint I.

5. Discussion and recommendations

The EC's Regulatory Scrutiny Board has met twice during the SPI consultation to provide feedback and opinion on the proposal. The Board's overall view at the first meeting in September 2021 was negative (European Commission, 2022d), and the revised proposal in December 2021 was positive with reservations. Three of the Board's main recommendations are key considerations in moving forward, (1) DPP objectives made more explicit, (2) keeping admin costs for businesses to the minimum necessary, and (3) requirements must be generated on a product-by-product basis.

5.1. DPP's objectives made more explicit

The Scrutiny Board's December requirement to make DPPs objectives more explicit, has resulted in a leap from a description of the DPP concept and legislative goals to 'solutionism' of the technical purpose of a DPP and how the system might be implemented – Annex 18 of the Impact Assessment (European Commission, 2022c). Inevitably, the technological solution is beginning to be specified from this regulatory stance without the context of existing technologies and passport systems already being used by various industries (see Appendix A), or from expert technical involvement. Furthermore, this focus on the delivery instrument fails to properly consider the appropriate role and scope of the DPP system that requires behaviour change in consumers and businesses: responding to the Scrutiny Board's commentary with 'the system can do XYZ, so its role and scope is XYZ', rather than 'we need a system to fulfil ABC roles within the wider scope of SPI, and thus its capability needs to be DEF'. A systems engineering approach aims to articulate *why* product passports should do *what* they do: the antithesis of the EU's current strategy.

Unsurprisingly, the EC perceives the DPP system as a techno-social mechanism for compliance (viewpoint C - Business Transparency) and sees the DPP solution through this lens. As such, the objectives of regulatory governance (to provide specific evidence demonstrating compliance) are conflated with the purpose of the regulation, that is, to influence changes in behaviour within the regulated ecosystems, suggesting that this should be considered a socio-technical system. However, product Eco-design is only one part of a 'sustainable product' solution. The EC needs to articulate the context and scope in which their product sustainability principles (termed 'product parameters' in Annex I of the regulations) fit into a broader set of sustainability objectives or ethical principles and, more importantly, to determine what these are. Figs. 3–11 show that while the information points highlighted contribute to some sustainability objectives, they are not a complete set of overarching sustainability goals. A clear sustainability framework, underpinned by ethical principles in which information requirements can be set, would enable a more comprehensive and shared vision of sustainability between economic actors. This clarity would also future-proof legislation, setting the horizontal sustainability objectives against principles rather than specific information points (set out in vertical legislation) that could be expanded and updated over time without the need to update the horizontal framework.

Recommendation #1 – The overarching sustainability goals or ethical principles that underpin the legislation and the Digital Product Passport Ecosystem should be articulated.

Recommendation #2 – A Digital Product Passport Ecosystem should be seen as a socio-technical system; therefore, a values-based systems engineering requirements process (IEEE, 2021) should be adopted that prioritises design for systemic change.

One of the key outputs of this research is the identification of 9 discrete ecosystem capabilities that make up a Digital Product Passport Ecosystem, along with specific definitions for each (Table 4). Therefore, current thinking needs to change from a DPP being a single wholly directed or managed compliance system to a more complex Digital Product Passport Ecosystem (DPPE) that requires architecting as such. It is worth noting that not only is the Ecosystem a SoS, but each constituent system is also a SoS comprised of multiple actors, organisations, processes, and technical systems that need to interoperate to achieve the overarching capability. It is recommended that the EC's European Interoperability Framework (EIF) principles are followed (National Interoperability Framework Observatory, 2022) that cover aspects of legal, organisational, semantic as well as technical interoperability. Once it is acknowledged that the ecosystem needs to be engineered to deliver nine capabilities, decisions can be made on how best to design, develop and manage the SoS to achieve these. A decision on the type of SoS is also needed; either directed, acknowledged, collaborative or virtual ('ISO/IEC/IEEE International Standard – Systems and software engineering – System of systems (SoS) considerations in life cycle stages of a system', 2019).

Recommendation #3 – The Digital Product Passport Ecosystem is a complex System of Systems that should be architected for legal, organisational, semantic and technical interoperability to deliver the nine ecosystem capabilities and achieve the overarching sustainability goals.

Systems Engineering requires two types of systems checks or tests: systems verification (did we build the system right?) and validation (did we build the right system?). Technical systems verification can be easily done if system requirements are specified. However, validation is more complex as it requires testing against original stakeholder or capability objectives. From policy conception to systems implementation, the EC needs to plan how and when to evaluate whether any DPP system meets its policy and fundamental sustainability objectives. Mechanisms for DPP validation could be aligned to functional viewpoint D – A system for the oversight of Industrial circularity performance - but additional opportunities exist to evaluate policy objectives immediately. Realist Evaluation is a theory-driven approach to generate evidence of 'what works, for whom in which contexts, and why' (Pawson, 2013) and can be used in ex-ante policy impact evaluation for complex initiatives. The stakeholder assumptions, derived from the authors' CATWOE analysis (Table 3), are the assumptions that underpin the success of the legislation, and these can be tested to see in which contexts they are correct and where they are less likely to work due to constraints.

Recommendation #4 – The stakeholder policy assumptions generated through this research should be used as candidate theories within a Policy Impact Realist Evaluation of the SPI legislation and future DPPE stakeholder validation activities.

5.2. Incentives for businesses towards adoption and keeping costs down

From the CATWOE analysis, the overwhelming assumptions are that regulation will positively encourage sustainable business practices. Consequently, consumers will make better product choices if provided with comparable sustainability information at the point of sale – even if the cost of implementing these changes is passed on to the consumer in the short term. The circular economy has been framed as a strategy that reconciles continued economic growth in a world with finite resources (Korhonen et al., 2018). Most of these discrete systems within the DPPE rely on the *producers* to do more (spend more) for their business and products to be regulated with sustainability in mind. However, some significant barriers and issues must be overcome to incentivise investment in changing business practices and data sharing with competitors and new economic operators building new business models along the value chain. A view supported by existing research (Adisorn et al., 2021).

For the *producers,* interactions with a system purely for compliance will only ever frame it as an administrative burden. To minimise such burden, the EC should not see product passports as a new system but rather as an interface to existing systems and a tool to improve operational efficiencies. For greatest producer success, the EC should ask what systems and processes currently exist for each top-level sustainability goal and how a DPP solution might modernise and reduce the administrative burden on economic operators. The EC acknowledge this, saying that the data architecture needs careful consideration "with the objective of achieving the highest degree of interoperability with the minimum degree of changes to existing systems." (European Commission, 2022c, p. 589).

Recommendation #5 - Future research should investigate the incentives for producer stakeholders to adopt open architectures, share more data and integrate their existing solutions within a wider ecosystem.

5.3. Specifying DPP requirements on a system-by-system and product-by-product basis

Technical and solution stakeholders state a preference for distributed/decentralised systems in the consultation. From the authors' research into existing bespoke systems that demonstrate some DPP capability (Appendix A), many utilise decentralised technologies (Blockchain) but with a centralised governance model dependent upon business needs. By distinguishing capability into the nine discrete functional viewpoints within the ecosystem, it becomes evident that different capabilities and information types require different system features. Each discrete system in the ecosystem could adopt different types of technology architecture, such as event-driven software architectures and IoT hardware for product-life tracking and desktop applications with interoperable features for life cycle assessments.

Recommendation #6 - Future research should investigate system architectures in existing DPP systems (and those that provide similar capability) to model common Enterprise Architectures and Solution Architectures for the DPPE, particularly at key integration points.

As well as generic requirements for products linked to a DPP Ecosystem capability, there is a need to accommodate the specifics of various products, where detail and complexity are required for some but not all products. There already exists a wealth of systems and approaches to asset management and tracking but dependent on the context, solutions are very different. In the case of safety-critical systems, additional granularity and context are essential, for example, tracking life-limiting parts and 'back-to-birth' traceability within the aviation industry (IATA, 2020). In this case, a specified traceability process is integral to aviation regulation that must be complied with by the OEM and the MRO (Maintenance, Repair and Overhaul) involved in the design and manufacturing, operation or repair of the individual part.

As the EC develops specific legislation for EV Batteries and Battery Passports, due to come into force ahead of the SPI, researchers (Berger et al., 2022) and commercially led project consortiums (Circular Economy Initiative, 2022) are developing specific use cases and requirements for EV Battery Passports focusing solely on the EV battery value-chain. Therefore, there is a danger of adding to ecosystem complexity if interoperability between systems is not considered in this context.

Recommendation #7 - Future research should seek to establish information and process requirements on a product-by-product basis in the context of integration within a wider PPE architecture.

5.4. A DPPE as an enabler of industrial symbiosis

Industry Symbiosis (IS), in the traditional sense, focuses on a symbiotic material or energy relationship between the waste of one industry becoming the valuable input of another (Neves et al., 2019).

Explicit association between DPPs and the prospect for material/energy symbiosis is infrequent, but some opportunities for IS are evident. At the resource level, the SPI regulation sets out the need to specify materials used in the production process and those that are waste materials from the product in/after use. If this information was freely available to other manufacturers, additional symbiotic opportunities could be identified. Viewpoint H (Fig. 10) includes a consumption record (of energy, water, and other resources). Matching these consumption needs with knowledge of waste created elsewhere (identified in Viewpoint I) could enable IS matchmaking between parties. At the product level, viewpoint F enables the tracing of product possession and manipulation. While not explicitly mentioned, it is not too far outside the current system's scope to be able to identify products that are no longer in active use by their current owners. Combining this with information from viewpoint B, those looking for new products could be connected to those who already possess them but do not need them.

Suppose the definition of IS is expanded to include mutual benefits regarding the extraction of value from data (informational symbiosis) and the supply and acquisition of operational data (operational symbiosis). In that case, a more comprehensive range of opportunities is evident. Viewpoint A describes an improved efficiency of information transfer between parties. While most supply chains already have some product information transfer mechanisms, a well-designed and interoperable PPE may enhance these interfaces for other economic operators. Given the various calls to harmonise and standardise information sharing, these synergies are not realised. Adopting an operational perspective, an open system for tracking products means that supply chains can better tackle counterfeit goods, manage post-sale issues such as warranty claims and product recalls, and respond to supply chain risks. Suppose this system can guarantee the quality of goods at any stage of life. In that case, this should maximise re-sale value for second-hand ownership and establish markets for second-life applications for products that may currently be considered waste by the current owner, like the use of electric vehicle batteries for energy storage (Zhu et al., 2021). An open system for communicating operational information about a product, if well designed, can help producers improve how their products are cared for while the users of those products see longer product lifespans. Finally, open data concerning disassembly and material extraction may act as an enabler for the shift towards increased IS (in both traditional and expanded definitions), given that IS is one way of achieving increased circularity efficiencies.

Recommendation #8 - More research is needed on opportunities for industry symbiosis and new business models built on open data along the value chain enabled by a DPPE.

6. Conclusion

The novelty of this research lies in the systems thinking approach, coupled with systems engineering, to rigorously define and model a DPPE as a System of Systems to derive a universal definition. Stakeholder perspectives and requirements concerning Product Passports were synthesised using data and analysis from the European Commission's (EC) open consultation on the Sustainable Products Initiative (SPI). It is a limitation that most responses were trade associations, NGOs, and public authorities within Europe. However, many businesses that responded are trading globally. Another limitation is that no citizens or consumer organisations commented on Product Passports, and no responses were submitted from outside Europe or North America.

In conclusion, the following universal definition of a Digital Product Passport Ecosystem is proposed using the following CATWOE structure. "*A System owned by* **O** *to do* **W** *by* **A** *by means of* **T** *given the constraints of* **E** *in order to achieve* **X** *for* **C.**"

"A Digital Product Passport Ecosystem (DPPE) is a socio-technical System of Systems, which is collaboratively owned by the producers, users, and disposers of products. A DPPE evidences sustainable business practice and product design values, encourages change in consumer and disposer behaviour, and enables greater collective efforts towards a circular economy by all product stakeholders (resource, producer, user, disposers) and economic stakeholders. It does this by defining the metrics for sustainability and circularity for a given product and across product lifecycles, which requires a whole-life assessment against social and environmental impact performance metrics, then translates these into a comparable set of attributes for uniquely identifiable product designs. The DPPE provides a mechanism for uniquely identifying, describing, and exchanging product and actor data between actors. It also requires evidence to support the claims made by actors and evidence of a clear chain of custody of the product, its parts and associated events. The DPPE provides the information necessary to identify hazardous, problematic, and valuable materials, maintain the useful life of the product, and how to dispose of it optimally. The DPPE operates within acknowledged constraints (such as commercial interests, data quality and data ownership, a variety of sustainability metrics, privacy concerns, legacy systems, cost, skills, and current capacity) to achieve the sustainability values and goals of societal stakeholders."

CRediT authorship contribution statement

Melanie R.N. King: Conceptualization, Methodology, Validation, Investigation, Supervision, Project administration, Funding acquisition, Writing - original draft, Writing - review & editing. **Paul D. Timms:** Formal analysis, Investigation, Data curation, Visualization, Writing - original draft, Writing - review & editing. **Sara Mountney:** Formal analysis, Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Supporting data analysis will be made available on university data repository

Acknowledgements

The authors are grateful for the support of the Engineering and Physical Science Research Council (EPSRC) through the UK Manufacturing Symbiosis Network Plus, who funded this research EPSRC grant ref EP/S036091/1. This study has gained full ethical approval from Loughborough University Ethics Review Sub-Committee (ID 5881).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2022.135538.

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