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CIRCULAR ECONOMY IN THE BUILT ENVIRONMENT: A FRAMEWORK FOR IMPLEMENTING DIGITAL PRODUCT PASSPORTS WITH KNOWLEDGE GRAPHS

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Abstract

The built environment is heavily dependent on wasteful linear economic models and needs to transition to the circular economy (CE). One of the key enablers of CE is Digital Product Passports (DPPs). However, determining the necessary information and selecting suitable technologies remains to be challenging in practical implementations. This research aims to present a framework for implementing DPPs using Knowledge Graphs (KGs). A literature review was conducted to identify the key components of the framework. The result shows that the key elements encompass use cases identification, data collection, modelling, integration, governance, access and querying, and maintenance and updating.

Introduction

The building and construction sector is a key area that has significant impacts on the economy and environment. This sector contributes to the economy (about 9% of the EU's Gross Domestic Product), provides direct and indirect job opportunities (18 million direct jobs at the EU) and satisfies the people's needs for buildings and facilities. Moreover, this sector is one of the main consumers of resources: about 50% of the total use of raw materials, and 36% of the global final energy use and accounts for 39% of the energy and process-related emissions and the agents of acid rain (Norouzi et al., 2021).

Scientific literature, as for instance Piscitelli et al. (2020), Górecki et al. (2019), and Benachio et al. (2020) claim that the huge amount of employed natural resources and waste production by the construction sector are consequences of a linear economy model. In contrast, they propose another economic model, that is the CE, which is based on the principles of better managing the resources.

In 2018, the Nordic Council of Ministers published a report titled, "*Circular economy in the Nordic construction sector, Identification and assessment of potential policy instruments that can accelerate a transition toward a circular economy*"[1], as result of a project that aimed to "*accelerate a transition toward a CE in the construction sector in Denmark, Finland, Norway and Sweden*". The report concludes by identifying four key tools to achieve the goal: Environmental Product Declarations (EPD), Construction Products Regulation (CPR), Building Information Modelling System (BIM), Material passports and/or building passports.

From a lifecycle perspective, the construction industry is responsible for the depletion of vast global natural resources and the gross production of landfill waste (Badi and Murtagh, 2019). Efforts to address the inefficiency of the construction lifecycle in building projects include the use of Building Information Modeling (BIM) processes (Gan et al., 2018, Jalaei and Jrade, 2015), Life Cycle Assessment (LCA) (Akanbi et al., 2018) and material passports (Honic et al., 2019).

Expanding on the scope of material passports, digital product passports (DPPs), an emerging concept for achieving digitalization of product life cycles, may present an opportunity for CE adoption and scaling (Walden et al., 2021). Numerous published scientific works seem to confirm that DPPs are enablers of CE in the construction sector, see for example Walden et al. (2021), Adisorn et al. (2021), Plociennik et al. (2022). However, the implementation seems to be still far off, as issues such as deciding which information DPPs must include, how to practically implement DPPs, how to store the data that DPPs will contain, how to balance the transparency of information with business confidentiality concerns, how to involve customers, and whether information taken from a DPP should form qualifying criteria for regulation remain unsolved (Götz et al., 2022).

Götz et al. (2022) also underline that although numerous publications discuss the importance of DPPs, there is still no universally accepted definition and it is unclear whether technological elements, such as identifiers, underlying data spaces and knowledge graphs, will be included in DPPs. The European Commission (EC) defines DPPs as an electronically accessed data set containing product-specific information. It is expected that DPPs would provide details on the origin, composition and repair/disassembly possibilities of a given product, including how its components can be recycled or disposed at end of life[2]. This paper adheres to the definition of DPPs presented by the European Commission.

Different technology alternatives are suggested to implement DPPs including Internet of Things (IoT), blockchain, digital twins and ontologies and knowledge graphs (Walden et al., 2021, Sauter et al., 2019, Götz et al., 2022). Given the comprehensiveness of DPPs, KGs are seen as suitable for implementing DPPs due to KGs'

[1] http://norden.diva-portal.org/smash/get/diva2:1188884/FULLTEXT01.pdf

[2] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52022PC0142

capability to represent, integrate, and reason with complex, heterogeneous data from multiple sources, providing scalability, expressiveness, and extensibility (Peng et al., 2023, Tian et al., 2022). The objective of this study is to formulate an approach to implement DPPs using KGs. A knowledge graph (KG) is a type of knowledge base that uses a graph-based data model for integrating data (Kejriwal, 2022). It consists of nodes that describe things, edges used to capture the relations between things, and labels with well-defined meanings. Additionally, KGs acquire and integrate information into an ontology and applies a reasoner to derive new knowledge (Ehrlinger and Wöß, 2016). This allows for improved data integration, analytics & sharing of data by linking descriptions of entities together (Kejriwal, 2022).

A literature review is conducted to introduce a framework to support the implementation of DPPs with the aim of enabling CE in the built environment. The research question for this study is, "*What are the key components of a framework to support the implementation of digital product passports using knowledge graphs?*"

Research Method

A literature review that employed a systematic search is conducted to answer the research question of this study. To gather relevant papers, the systematic search process outlined by Booth et al. (2016) was followed. The primary source of information was obtained from the Web of Science and Scopus databases, which are known for their comprehensive collections of peer-reviewed scientific papers (Mongeon and Paul-Hus, 2015, Leslie, 2013, Burnham, 2006). The search concepts are identified and combined into a search strategy based on the aim of the study. Table 1 presents the search strategy, results, field and data.

Table 1: Search strategy, search result, search field and search date

Search strategy	Search database	Search result	Search field	Search date
("knowledge graph*" OR ontolog*) AND	Scopus	19	title-abs-key	Nov 16, 2022
("product passport" OR "material passport") AND "CE" AND ("built environment" OR construction)	Web of Science	-	title-abs-key	Nov 16, 2022

As depicted in Table 1, a total of 19 papers are identified and exported to the Rayyan systematic review web application for subsequent paper inclusion and exclusion process. The following inclusion and exclusion criteria are specified for paper selection process.

Inclusion criteria: the paper must be peer-reviewed and relevant to the research question, specifically discussing the implementation of DPPs to enable CE in the built environment.

Exclusion criteria: the paper is not relevant to the research question.

The initial step in the paper selection process involved eliminating duplicate papers. It was verified that there were no duplicate papers. Next, the papers were screened for inclusion by examining the titles. No paper was excluded based on reading the titles. After reviewing the abstract of the papers, nine papers were excluded leaving ten papers for full-text analysis. A review of the retrieved papers revealed that there are a limited number of studies that discusses KGs in more depth. To address this gap, nine papers were handpicked for inclusion based on their relevance to the research question. Table 2 presents a total of nineteen papers included in the study. The PRISMA flow diagram in Figure 1 provides a graphical representation of the paper selection process.

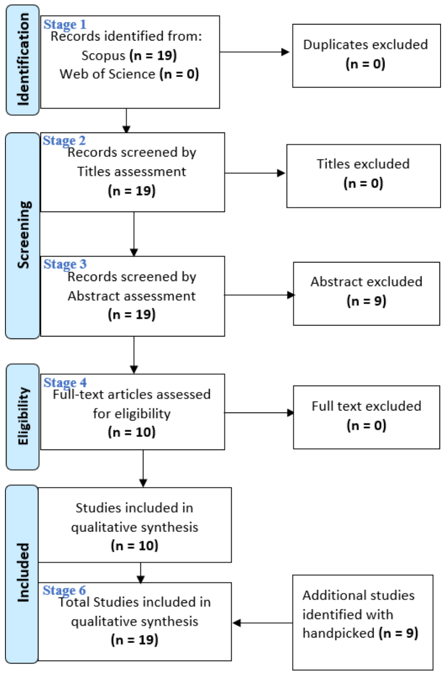

Figure 1: Paper Selection Process (PRISMA flow diagram)

According to Booth et al. (2016), there are three approaches to synthesizing data in systematic literature reviews namely aggregative, configurative, and integrative. An aggregative literature review involves combining the findings of multiple studies to summarize and examine concepts or ideas relevant to the research question (Booth et al., 2016). A configurative literature review refers to synthesizing the findings of multiple studies to create a new conceptual framework or theory (Booth et al., 2016). An integrative literature review involves synthesizing the findings of multiple studies to test a specific hypothesis (Booth et al., 2016). This study employs the configurative approach to synthesizing data, as the goal is to introduce a framework to support the implementation of DPPs using KGs. This approach involves the identification of patterns and themes within the existing body of literature, which are then utilized to formulate a new framework or theory.

Table 2: Articles Included in the Literature Review

No	Authors	Title
1	Adisorn et al. (2021)	Towards a Digital Product Passport Fit for Contributing to a Circular Economy
2	Agrawal et al. (2022)	Building Knowledge Graphs from Unstructured Texts: Applications and Impact Analyses in Cybersecurity Education
3	Albagli-Kim and Beimel (2022)	Knowledge Graph-Based Framework for Decision Making Process with Limited Interaction
4	Berglund-Brown et al. (2022)	Assessing Circular Information Flow in Industrialized Construction: a framework for evaluating data for circular construction
5	Demestichas and Daskalakis (2020)	Information and communication technology solutions for the circular economy
6	Ducuing and Reich (2023)	Data governance: Digital product passports as a case study
7	Gligoric et al. (2019)	SmartTags: IoT Product Passport for Circular Economy Based on Printed Sensors and Unique Item-Level Identifiers
8	Götz et al. (2022)	Digital product passport: the ticket to achieving a climate neutral and circular European economy?
9	Humm et al. (2022)	New directions for applied knowledge-based AI and machine learning
10	King et al. (2023)	A proposed universal definition of a Digital Product Passport Ecosystem (DPPE): Worldviews, discrete capabilities, stakeholder requirements and concerns
11	Munaro and Tavares (2021)	Materials passport's review: challenges and opportunities toward a circular economy building sector
12	Munaro et al. (2020)	Towards circular and more sustainable buildings: A systematic literature review on the circular economy in the built environment
13	Munaro et al. (2021)	Circular Business Models: Current State and Framework to Achieve Sustainable Buildings
14	Saari et al. (2022)	Digital product passport promotes sustainable manufacturing
15	Sauter et al. (2019)	CEO & CAMO ontologies: A circulation medium for materials in the construction industry
16	Schwabe et al. (2020)	Knowledge Graphs: Trust, Privacy, and Transparency from a Legal Governance Approach
17	Talla and McIlwaine (2022)	Industry 4.0 and the circular economy: using design-stage digital technology to reduce construction waste
18	Weichselbraun et al. (2022)	Building Knowledge Graphs and Recommender Systems for Suggesting Reskilling and Upskilling Options from the Web
19	Wilcke et al. (2017)	The knowledge graph as the default data model for learning on heterogeneous knowledge

Results

The literature review in this study identified important components that support the implementation of DPPs using KGs. Some of the key themes emerged during the review includes:

- Identify use cases
- Data collection
- Compliance to standards and regulations
- Data modeling and integration
- Access and querying
- Data governance
- Maintain and update

The following sections briefly describe each theme in relation to the implementation of DPPs using KGs.

Identify use cases

Identifying use cases is a crucial part in designing and implementing DPPs (Munaro and Tavares, 2021, Götz et al., 2022). This approach allows for a more focused and targeted design of DPPs, while also providing an opportunity to align the identified use cases with CE principles such as elimination of waste and pollution, full utilization of resources through efficient circulation, and regeneration of natural resources (Munaro et al., 2021, Munaro and Tavares, 2021). In order to effectively implement DPPs, it is recommended to initiate with small-scale piloting utilizing a step-by-step approach that allows for incremental development and expansion (Götz et al., 2022).

Examples of possible use cases include increasing transparency for both consumers and businesses, using end-of-life data in design phase decisions, providing information required for product repair or recycle processes to enable material circulation and decision-making in the context of CE and predictive maintenance (Munaro et al., 2021, Sauter et al., 2019, King et al., 2023). At this stage, KGs can support data exploration and visualization of large, complex and unstructured data sets, allowing to identify patterns and trends which helps in the selection of use cases (Agrawal et al., 2022).

Data Collection

The theme of data collection emerged as a crucial component for the implementation of DPPs. Studies highlight the lack of data availability in the areas of recycle, reuse, repair and remanufacture (Berglund-Brown et al., 2022, Munaro and Tavares, 2021). Additionally, there is a need for obtaining data throughout the lifespan of a product from various involved stakeholders, in order to promote the potential for reusing, recycling or remanufacturing products as well as facilitating decision-making and planning processes, as it allows individuals or organizations to answer questions such as how and when a product can by reused and by whom (Munaro and Tavares, 2021). There is also a lack of knowledge base and metrics related to the end-of-life management of products, highlighting the need for data collection efforts to fill this information gap (Munaro et al., 2020). Challenges such as these can be addressed with the concept of DPPs to contain a wide range of product data from its origin to end-of-life management. Technologies such as IoT, data analysis, AI algorithms and SmartTag have been identified as crucial for efficient collection of data on a product's lifecycle (Demestichas and Daskalakis, 2020, Gligoric et al., 2019, Humm et al., 2022). KGs and IoT can provide a unified means to collect data from heterogeneous sources in real time, which is vital for building DPPs (Le-Phuoc et al., 2016).

Compliance with standards and regulations

Compliance to standards and regulations is an important key element to support the implementation of DPPs (Adisorn et al., 2021, King et al., 2023, Ducuing and Reich, 2023). For the harmonized implementation of DPPs with the existing approach, it is suggested to utilized the already established international initiatives and standards to prevent unnecessary repetition or duplication of efforts (Götz et al., 2022). Standards are needed to ensure the consistency and interoperability of DPPs across different products and industries (Saari et al., 2022). Moreover, information related to regulations of safety, environmental protection, and labour rights should be contained in DPPs (Saari et al., 2022). The use of KGs, through the expression of requirements for DPPs, can support in addressing compliance and regulatory constraints (Humm et al., 2022). Additionally, semantic models, such as ontologies, can be used to organize and represent the collected data in a way that adheres to any standards and regulations related to DPPs (Gligoric et al., 2019, Munaro and Tavares, 2021).

Data modeling and integration

Studies have highlighted the importance of data modeling in tracking and tracing materials and components to support CE as well as create values from circular actions (Talla and McIlwaine, 2022, Munaro et al., 2021, Munaro and Tavares, 2021, Demestichas and Daskalakis, 2020).

To implement DPPs, product related data should be collected throughout the products' lifecycle. Such data come from multiple heterogenous digital systems (Saari et al., 2022). The use of KGs enables to connect knowledge, gathered from different domains in different data models and formats without altering their original forms (Wilcke et al., 2017). KGs offer flexible data modeling and integration that supports the transparency, innovation and collaboration needed among the involved stakeholders in the value chain (Munaro and Tavares, 2021, Munaro et al., 2021, Humm et al., 2022). Using ontologies and resource description framework (RDF) for linking and enriching independently owned and maintained material passports have also been proposed for data modeling (Sauter et al., 2019).

Access and querying

DPPs should offer the ability to query and access information in order to create values from circular actions (Berglund-Brown et al., 2022, Munaro et al., 2021). This aspect of DPPs can be supported by KGs, which enable to represent connections between various data sources, and integrate diverse data (Agrawal et al., 2022). In this regard, users are enabled to conduct semantic search and gain valuable insights from wide range of data (Agrawal et al., 2022). The right information will be available and stakeholders will have the ability to understand the status of products in meaningful way and can make informed decisions accordingly, such as whether products need to be reused, recycled, repaired or remanufactured (Munaro et al., 2020). Decentralized systems, wherein data is published as Linked Data, to allow users to easily access and find relevant information is suggested (Sauter et al., 2019).

Data governance

Data governance measures facilitate the effective implementation of DPPs (Ducuing and Reich, 2023). One of the main challenges when implementing DPPs is finding the balance between open access of data with data protection, requiring a well-established data governance approach that emphasise the need for data confidentiality in situations where data security is important (Ducuing and Reich, 2023, Sauter et al., 2019). Data governance ensures that all stakeholders are engaged and that data is accurate, relevant and support CE practices (Munaro et al., 2020). KGs can be used to deploy and enforce policies for data management, allowing to ensure maximize data value and security (Schwabe et al., 2020).

Maintain and update

The content of DPPs constantly evolve throughout the life span of products (Munaro and Tavares, 2021, Götz et al., 2022). This indicates the importance of maintaining and updating DPPs in order to ensure their accuracy, relevance, and alignment with CE practices (Munaro and Tavares, 2021, Gligoric et al., 2019). Additionally, the continual transformation of DPPs necessitate the need for technologies that are capable of flexibly adding new information to accommodate the dynamic nature of DPPs (Götz et al., 2022), which can be addressed by KGs (Humm et al., 2022).

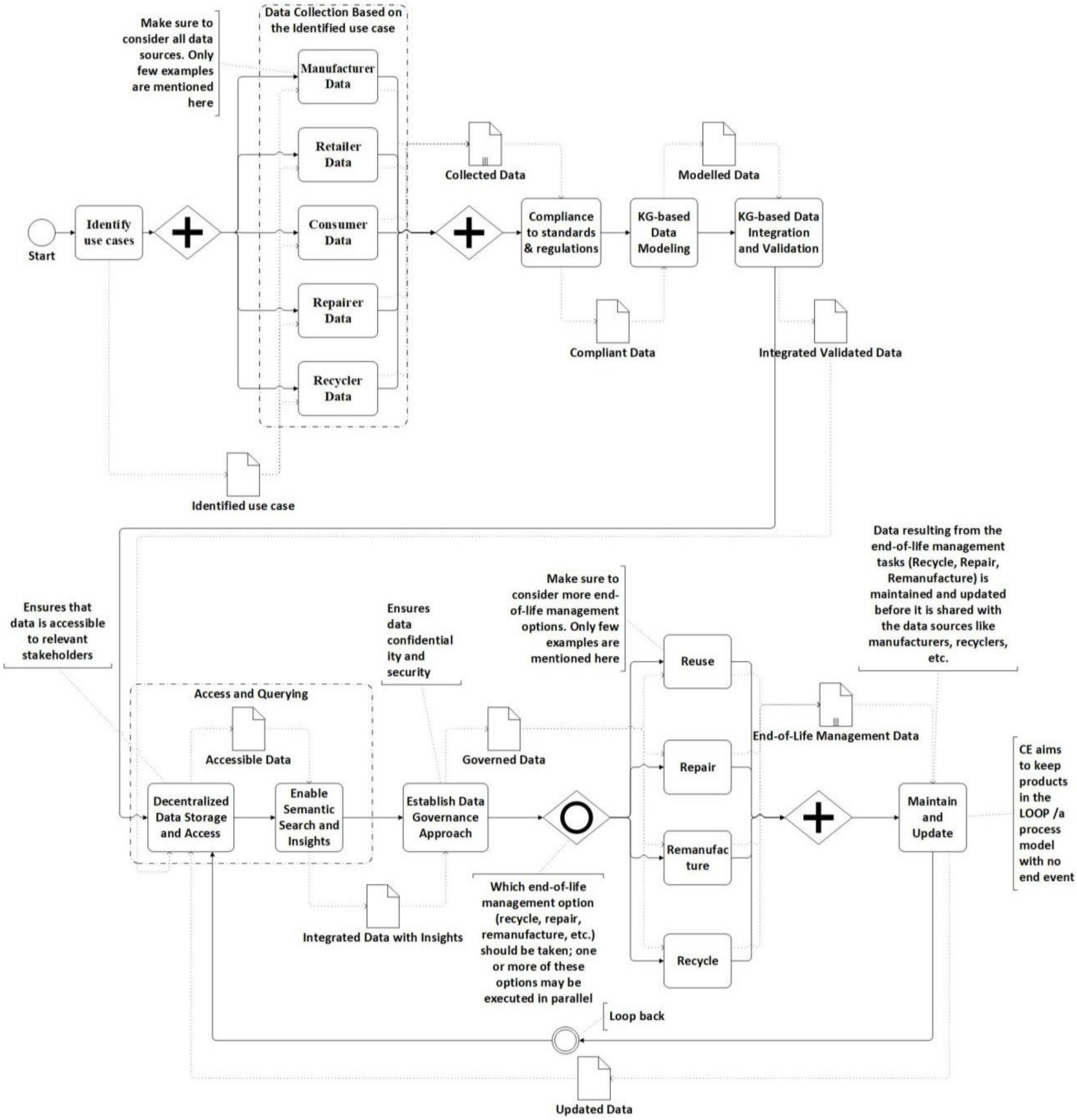

Figure 2 Conceptual Framework for Knowledge Graph-based Digital Product Passports

Overview of the Framework

The themes identified in the literature review are interpreted as key components of the framework as shown in Figure 2. The concept of Business Process Modeling and Notation is incorporated in the framework.

The framework starts with the identification of use cases. These use cases form the basis for collecting data from various actors involved in the built environment, such as manufacturers, retailors, and end-users. Compliance with standards, certifications and regulations are important elements to consider during data modeling. KGs are then used to model and integrate the data that was gathered from the actors. Access to the data modelled in KGs is facilitated through a user interface, enabling users to obtain information about the product and make informed decisions regarding repair, reuse, remanufacture, or recycling of products. Data governance measure is applied to ensure data quality and security.

KGs can support with the decision of whether to repair, remanufacture, or recycle a product by giving a comprehensive view of the product's features and its history (Albagli-Kim and Beimel, 2022, Weichselbraun et al., 2022). In this regard, DPPs implemented in KGs, can offer a thorough understanding of the product's components, materials, and functionalities as well as its previous interactions with actors enabling stakeholders to make an informed decision about the best possible course of action for the product. For example, recycling a product might be preferable over repair if it had sustained considerable damage. Similarly, remanufacturing a product that has a high level of functioning may be preferable than recycling it. Additionally, information related to the availability of spare parts, the costs associated with different courses of action, and the environmental impact of different options can be modelled in KGs, making the decision-making process efficient (Albagli-Kim and Beimel, 2022, Weichselbraun et al., 2022).

The inclusive event gateway is used to indicate that based on the information sourced from the DPP, a decision is made to either repair, reuse, remanufacture or recycle. It allows for making multiple decisions based on data available in the DPP, for example, when a product is no longer fit for its intended use, multiple courses of action may be required to maximize its value including repurposing any parts of a product that can still be functional and recycling or remanufacturing parts that are not functional, thus optimizing resource utilization, minimizing waste and keep products, components and materials circulating in the economy[3].

The status of the product, including any necessary information for repair, reuse, remanufacture, or recycling is communicated to the relevant actors responsible for implementing the chosen course of action. The DPP is then updated with the new information. In alignment with the fundamental principles of CE, which prioritizes eliminating waste and keeping products and materials in circulation, the process lacks a definitive end event but rather the process is repeated, and products remain in the loop. Data governance models will guide the overall processes.

Conclusions

This literature review proposed a framework to support the implementation of DPPs using KGs. Studies suggest that by developing such systems, relevant product related data throughout the product's lifespan can be stored and shared in an effective manner with the goal of promoting CE in the built environment. The main challenges discussed include determining what information is needed, ensuring transparency, and managing data without compromising confidentiality.

This study identified components essential for successful implementation of DPPs including identifying use cases, data collection, standards and regulatory compliance, data modeling and integration, access and querying, data governance, and maintaining and updating.

However, the study was unable to address potential challenges that organizations encounter when implementing DPPs or how they can be overcome due to scope limitations. Additionally, the framework is a preliminary work and should be further developed by incorporating feedback and lesson learned both from case studies and considering different scenarios and contexts in which DPPs are implemented. Future research focus on the practical implementation of DPPs in research case companies while improving the framework proposed in this research.

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References

Adisorn, T., Tholen, L. & Götz, T. (2021) Towards a Digital Product Passport Fit for Contributing to a Circular Economy. *Energies,* 14**,** 2289.

Agrawal, G., Deng, Y., Park, J., Liu, H. & Chen, Y.-C. (2022) Building Knowledge Graphs from Unstructured Texts: Applications and Impact Analyses in Cybersecurity Education. *Information,* 13**,** 526.

Akanbi, L. A., Oyedele, L. O., Akinade, O. O., Ajayi, A. O., Delgado, M. D., Bilal, M. & Bello, S. A. (2018) Salvaging building materials in a circular economy: A BIM-based whole-life performance estimator. *Resources, Conservation and Recycling,* 129**,** 175-186.

Albagli-Kim, S. & Beimel, D. (2022) Knowledge Graph-Based Framework for Decision Making Process with Limited Interaction. *Mathematics,* 10**,** 3981.

Badi, S. & Murtagh, N. (2019) Green supply chain management in construction: A systematic literature review and future research agenda. *Journal of cleaner production,* 223**,** 312-322.

Benachio, G. L. F., Freitas, M. D. C. D. & Tavares, S. F. (2020) Circular economy in the construction industry: A systematic literature review. *Journal of Cleaner Production,* 260.

Berglund-Brown, J., Kedir, F., Riabova, A. & Hall, D. (2022) Assessing Circular Information Flow in Industrialized Construction: a framework for evaluating data for circular construction.

Booth, A., Sutton, A. & Papaioannou, D. (2016) *Systematic approaches to a successful literature review*.

Burnham, J. F. (2006) Scopus database: a review. *Biomed Digit Libr,* 3**,** 1.

Demestichas, K. & Daskalakis, E. (2020) Information and communication technology solutions for the circular economy. *Sustainability (Switzerland),* 12**,** 1-19.

Ducuing, C. & Reich, R. H. (2023) Data governance: Digital product passports as a case study. *Competition and Regulation in Network Industries*.

[3] https://archive.ellenmacarthurfoundation.org/explore/the-circular-economy-in-detail

Ehrlinger, L. & Wöß, W. (2016) Towards a definition of knowledge graphs. SEMANTiCS (Posters, Demos, SuCCESS)

Gan, V. J., Deng, M., Tse, K. T., Chan, C. M., Lo,M. & Cheng, J. C. (2018) Holistic BIM framework for sustainable low carbon design of high-rise buildings. *Journal of Cleaner Production,* 195**,** 1091-1104.

Gligoric, N., Krco, S., Hakola, L., Vehmas, K., De, S., Moessner, K., Jansson, K., Polenz, I. & Van Kranenburg, R. (2019) SmartTags: IoT Product Passport for Circular Economy Based on Printed Sensors and Unique Item-Level Identifiers. *Sensors,* 19**,** 586.

Górecki, J., Núñez-Cacho, P., Corpas- Iglesias, F. A. & Molina, V. (2019) How to convince players in construction market? Strategies for effective implementation of circular economy in construction sector. *Cogent engineering,* 6**,** 1690760.

Götz, T., Berg, H., Jansen, M., Adisorn, T., Cembrero, D., Markkanen, S. & Chowdhury, T. (2022) Digital product passport: the ticket to achieving a climate neutral and circular European economy?

Honic, M., Kovacic, I. & Rechberger, H. (2019) Improving the recycling potential of buildings through Material Passports (MP): An Austrian case study. *Journal of Cleaner Production,* 217**,** 787-797.

Humm, B. G., Archer, P., Bense, H., Bernier, C., Goetz, C., Hoppe, T., Schumann, F., Siegel, M., Wenning, R. & Zender, A. (2022) New directions for applied knowledge- based AI and machine learning. *Informatik Spektrum*.

Jalaei, F. & Jrade, A. (2015) Integrating building information modeling (BIM) and LEED system at the conceptual design stage of sustainable buildings. Sustain Cities Soc, 18, 95–107.

Kejriwal, M. (2022) Knowledge Graphs: A Practical Review of the Research Landscape. *Information,* 13**,** 161.

King, M. R. N., Timms, P. D. & Mountney, S. (2023) A proposed universal definition of a Digital Product Passport Ecosystem (DPPE): Worldviews, discrete capabilities, stakeholder requirements and concerns. *Journal of Cleaner Production,* 384.

Le-Phuoc, D., Quoc, H. N. M., Quoc, H. N., Nhat, T. T. & Hauswirth, M. (2016) The graph of things: A step towards the live knowledge graph of connected things. *Journal of Web Semantics,* 37**,** 25-35.

Leslie, S. A. (2013) Web of Science, Scopus and Google Scholar: A content comprehensiveness comparison. *The Electronic Library,* 31**,** 727-744.

Mongeon, P. & Paul-Hus, A. (2015) The journal coverage of Web of Science, Scopus and Dimensions: A comparative analysis. *Scientometrics,* 106**,** 213-228.

Munaro, M. R., Freitas, M. D. C. D., Tavares, S. F. & Bragança, L. (2021) Circular Business Models: Current State and Framework to Achieve Sustainable Buildings. *Journal of Construction Engineering and Management,* 147.

Munaro, M. R. & Tavares, S. F. (2021) Materials passport's review: challenges and opportunities toward a circular economy building sector. *Built Environment Project and Asset Management,* 11**,** 767-782.

Munaro, M. R., Tavares, S. F. & Bragança, L. (2020) Towards circular and more sustainable buildings: A systematic literature review on the circular economy in the built environment. *Journal of Cleaner Production,* 260.

Norouzi, M., Chàfer, M., Cabeza, L. F., Jiménez, L. & Boer, D. (2021) Circular economy in the building and construction sector: A scientific evolution analysis. *Journal of Building Engineering,* 44.

Peng, C., Xia, F., Naseriparsa, M. & Osborne, F. (2023) Knowledge Graphs: Opportunities and Challenges. *Artificial Intelligence Review*.

Piscitelli, G., Ferazzoli, A., Petrillo, A., Cioffi, R., Parmentola, A. & Travaglioni, M. (2020) Circular economy models in the industry 4.0 era: A review of the last decade. *Procedia Manufacturing,* 42**,** 227-234.

Plociennik, C., Pourjafarian, M., Nazeri, A., Windholz, W., Knetsch, S., Rickert, J., Ciroth, A., Lopes, A. D. C. P., Hagedorn, T. & Vogelgesang, M. (2022) Towards a Digital Lifecycle Passport for the Circular Economy. *Procedia CIRP,* 105**,** 122-127.

Saari, L., Heilala, J., Heikkilä, T., Kääriäinen, J., Pulkkinen, A. & Rantala, T. (2022) Digital product passport promotes sustainable manufacturing: whitepaper.

Sauter, E. M., Lemmens, R. L. G. & Pauwels, P. (2019) CEO & CAMO ontologies: A circulation medium for materials in the construction industry. 1645-1652.

Schwabe, D., Laufer, C. & Casanovas, P. (2020) Knowledge Graphs: Trust, Privacy, and Transparency from a Legal Governance Approach. *Law in Context. A Socio-legal Journal,* 37**,** 24-41.

Talla, A. & Mcilwaine, S. (2022) Industry 4.0 and the circular economy: using design-stage digital technology to reduce construction waste. *Smart and Sustainable Built Environment*.

Tian, L., Zhou, X., Wu, Y.-P., Zhou, W.-T., Zhang, J.-H. & Zhang, T.-S. (2022) Knowledge graph and knowledge reasoning: A systematic review. *Journal of Electronic Science and Technology,* 20.

Walden, J., Steinbrecher, A. & Marinkovic, M. (2021) Digital Product Passports as Enabler of the Circular Economy. *Chemie Ingenieur Technik,* 93**,** 1717-1727.

Weichselbraun, A., Waldvogel, R., Fraefel, A., Van Schie, A. & Kuntschik, P. (2022) Building Knowledge Graphs and Recommender Systems for Suggesting Reskilling and Upskilling Options from the Web. *Information,* 13**,** 510.

Wilcke, X., Bloem, P. & De Boer, V. (2017) The knowledge graph as the default data model for learning on heterogeneous knowledge. *Data Science,* 1**,** 39-57.