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Context-Aware Sustainable Design: Knowledge Graph-Based Methodology for Proactive Circular Disassembly of Smart Products

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In nowadays industrial landscape, the reduction of greenhouse gas emissions has become imperative, requiring a profound revision of product design practices to reduce their environmental impact throughout their life cycle. Design for X (DfX) approaches, in particular Design for Disassembly (DfD) and Design for Circularity (DfC), offer promising solutions by integrating environmental indicators from the earliest stages of the design process. This article proposes a methodological framework aimed to create sustainable smart products. The framework takes advantage of Circular Disassembly indicators disseminated proactively and contextually within the Product Lifecycle Management (PLM), and the Manufacturing Process Management (MPM). Delving deeper into Design for Circular Disassembly (DfCD) approach, and the growing role of artificial intelligence by using a knowledge graph. By seamlessly integrating proactive environmental design indicators right from the preliminary phases of PLM, and MPM systems, the proposed framework promotes the development of a sustainable smart products, helping to reduce design errors and time-to-market. This innovative approach underlines the central role of early design decisions in promoting environmental sustainability within industry.

Keywords: *Design for X, Sustainability, Smart Product, Preliminary design, Knowledge Graph.*

I. INTRODUCTION

In the field of smart product development, attention to sustainability, particularly with regard to disassembly and the principles of the circular economy, has a significant impact [1]. Anticipating quickly and proactively, ideally right from the preliminary phases, is becoming imperative [2]. To facilitate this anticipation, the support of recommendation systems can play a crucial role, helping to anticipate Design for X (DfX) oriented sustainable indicators. Measuring the effects of DfX strategies is equally essential for assessing the impact of design on sustainability [3].

This methodological framework is in line with this perspective of anticipating and measuring the impacts of DfX. It recognizes the need to design service systems for smart products, focusing on the user. This encompasses the collection and analysis of real-time data to enable contextualization, the management of system complexity, and the creation of sustainable business models. It also emphasizes the need to continuously monitor and adapt systems to meet user needs [4]. By integrating these elements into our knowledge graph-based methodological framework, we aim to provide a proactive approach to the development of intelligent, sustainable products from the earliest stages of the design process.

The aim of this paper is to propose an innovative methodological framework exploiting a knowledge graph to guide and raise awareness among stakeholders in the development of a sustainable smart products into two contexts: design and manufacturing context. To target precisely when and why to provide information and knowledge to stakeholders. This effort is part of the circular economy perspective, covering social, environmental, and economic aspects. We highlight the crucial role of circular disassembly indicators in this framework, with a focus on Direct Product Cost, one of the three economic aspects we explore.

In the next section, we explore the literature on preliminary and proactive engineering, Design for X with the emergence of a new approach call Design for Circular Disassembly (based on the combined approach of Design for Disassembly and the Design for Circular Economy). We conclude with a look at context-sensitive recommendation systems. The next section will deal with the methodological framework, and the following chapter will exploit the framework to apply it to a case study with the knowledge graph. The final section concludes the article.

II. STATE OF THE ART

1) *Preliminary and proactive design*

Proactive design can be seen as an emerging engineering framework that integrates life-cycle knowledge and technological constraints into product development as early as possible, and manages this knowledge in an integrated and harmonious way [5]. For example, the methodology proposed by the authors [6] has been proposed so that maintainability design and functional/structural design can be carried out simultaneously. In Design for Assembly, procedures are integrated with advanced computer-aided design concepts to create an assembly-oriented design environment [7], [8]. A proactive approach to the application of the design-for-assembly interface and the enhancement of the capabilities of design experts, to extend the coverage and capabilities of geometric reasoning algorithms [9], [10]. The proactive approach anticipates future design errors in the context of the life cycle (disassembly, maintenance, etc.). Anticipation can be defined as the ability to act on the preparation of certain future effects or states in the environment. Consequently, anticipation can be seen as a dynamic action associated with a future-oriented decision-making process, requiring self-awareness in a given situation [11].

2) *Design for X and Design for Circular Disassembly*

There are methods called DfX (Design for X) which make it possible to anticipate and reduce design errors linked to a given context (design, manufacturing, etc.). Part of this methodology [12] makes it possible to anticipate the impact of a business or objective on each stage of the product life cycle. The development of DfX lays the foundations for a proactive approach, insofar as it will impact the product at an early stage in the design process, based on future situations or contexts. It is interesting to develop a new design tool that provides an accurate response to customer requirements and facilitates the internal communication of data and results within the smart product development project. However, the most important conclusion is the need to answer the question of how designers can effectively and reliably share, capitalize, and reuse knowledge by considering DfX techniques integrated into the overall product lifecycle, and how designers become context-aware and provide value-added information to improve the monitoring of operations and their performance. In this respect, knowledge management (KM) practices provide a conceptual and methodological framework for examining these issues. This requires an ontology, which is seen as a relevant method for representing knowledge in a machine-interpretable way. It is

also important to stress that the DfX approach needs to be empirically verified and validated, through significant gains which are often a gap in the DfX application [3].

Based on the DfX approach, there are several End Of Life approaches (Design for Disassembly, Design for Recycling, Design for Remanufacturing, Design for Repair...) [13] within this, a sustainability-oriented design method called (Design for Sustainability - DfS) that focuses more on the life cycle in its entirety in connection with the Life Cycle Assessment (LCA) to prepare and anticipate environmental impacts for the smart product from the design stage. It focuses on design rules to increase the lifespan of the product, process or system [14], [15]. At the end of the product's life cycle, Design for Disassembly (DfD) approach, simplifies the dismantling process, reducing the time and the costs required for disassembly, and enabling the recovery of components and materials [13]. To ensure the successful implementation of DfD techniques, designers must consider several guidelines [16], [17]: (i) consider the architecture of the product, the design of its components, the fasteners used and the type of material used; (ii) consider the end-of-life (EOL) destination of each component, i.e. whether it will be recycled, reused or landfilled with normal or special treatment; (iii) consider the cost of each component according to its end-of-life destination; (iv) consider the cost of labor for the disassembly process; (v) consider the cost of disposing of product waste remaining at each stage of the disassembly process; (vi) consider the profit resulting from each stage of the disassembly process; (vii) and consider the effect of each step in the disassembly process. The circular economy approach is then important to consider, and having a global view is very complex on all environmental issues. A new approach is beginning to emerge, in addition to the well-known constraints on disassembly, it incorporates the constraints associated with the circular economy on all three aspects: economic, social, and environmental. This is the Design For Circular Disassembly (DfCD) approach, define by its authors [18] as "the process of (re)designing products and their components for easier partial/full disassembly at their end-of-life, with the goal of improving or preserving their circular economy potential". This approach makes it possible to model the impact of product end-of-life on the disassembly process in terms of disassembly effort and circularity index. The authors tested this approach on the design of an electric kettle and found that failure to consider the product's end-of-life can lead to sub-optimal disassembly design recommendations from a circularity point of view. The aim of Design for Circular Disassembly is therefore to enable products to be designed more efficiently and sustainably, by considering

their end-of-life and promoting the reuse and recycling of materials.

3) *Context-sensitive recommendation system within the digital thread*

With the advent of artificial intelligence tools, the scientific community has become increasingly interested in using recommendation systems (such as virtual assistants) with a semantic technology (e.g. ontology and knowledge graph) to facilitate the work of designers, in the search for alternative solutions to reduce design errors and to ensure interoperability within the digital thread. According to [19] the definition of a context-sensitive cognitive design assistant "is a transparent, ubiquitous and intelligent computer program that detects relevant information that can be used to characterize a designer's situation and provide, without explicit user intervention, relevant information and/or services to the designer, the relevance depending on the designer's task".

The context-sensitive recommendation system is an approach that consists, in each context, in proposing relevant information in the appropriate context. For example, the objective of the recommendation algorithm is to extract information from the database that is relevant to the user's needs. Recommender systems often fall into two broad categories: collaborative recommendation and content-based recommendation. According to the author [19], information recommendation based on knowledge graphs is an important part of ubiquitous computing. According to the same author, the assistant that offers the user recommendations must not interfere with the user's mastery of design rules. A black-box effect can lead to designer frustration and a loss of skills. Secondly, a structured digital representation of design rules is essential for the operation of such an assistant. The functionalities of a cognitive assistant dedicated to the mastery of design rules will therefore strongly depend on the type of representation used.

To develop and propose a * model, it is important to understand the context to identify the intentions of users (designers, assembly planners, etc.) and make the best use of the tool. That's why it's important to raise awareness of smart product development [4] by being aware of design constraints in the current context. Several studies have defined context in design engineering. The authors [20] defined the context as "as a set of constraints influencing the behaviour of an embedded system in a given task". Based on their work, the analysis of several definitions of context offers a model of context that includes the following elements: elements, environment, users,

and observers. The authors discuss the nature of context structure by considering the element as a step in a problem in which the context explicitly solves that problem. The authors [21] approach the problem of context by defining it "as any information that can be used to characterize the situation of an entity, an entity being a person, a place, a physical or computational object", while context awareness or context-aware computing is described "as the use of context to provide a user with information and/or services relevant to the task at hand. Several authors define, model and propose approaches with the context: a metamodel and a design process [22], a categorization of context with five fundamental notions: relationships, individuality, time, place, and activity [23], an ontology-based contextual modelling of user activity in a business environment to provide the right information to the right person at the right time [24], the structure of multi-scale knowledge by proposing an activity-based model, with a virtual assistant that helps designers in the design context [25] to provide knowledge at each level of the design context and based on the user's activity. The use of a knowledge graph for modelling the context offers a dynamic and flexible approach to ontologies, enabling more fluid representation of relationships between concepts. This choice favors more scalable modelling, better adapted to the complexity of interconnected data, offering a richer, more contextual understanding of information [26].

III. METHODOLOGICAL FRAMEWORK

The main objective of this methodological framework is to encourage the development of sustainable smart products by integrating circular disassembly indicators from the earliest design phases. This article proposes a proactive model based on a knowledge graph that will guide decisions and adjust designs to maximize social, environmental, and economic benefits. The framework presented (Figure 1) below represents the interaction of stakeholders (product architect and assembly planner) in the digital thread, who will design and manufacture the smart product. They receive and send information via queries related to their design and manufacturing context (product structure called engineering Bill Of Material (eBOM), assembly plan, 3D model, etc.) into a knowledge base via their reciprocal information systems (PLM and MPM). The knowledge base will be maintained by a knowledge manager, who will populate the knowledge graph and create the rules and queries for the reasoning, so that other stakeholders receive circular disassembly indicators at the right time. The knowledge graph will detect data changes (here the property values), to propose up-to-date indicators.

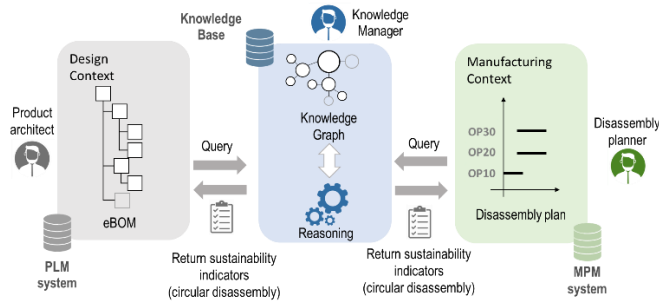


Figure 1. Framework for Circular Disassembly design in the digital thread.

The knowledge graph was built on Neo4j due to its ability to manage interconnected data, providing performance suitable for modeling complex relationships. It leverages the Labeled Property Graph (LPG), as implemented by graph database management systems, is a data model for visually and structurally representing entities (nodes) categorized by labels, linked by relationships, and enriched by key-value properties, thus providing a graphical representation for modeling complex and interconnected domains. The knowledge graph described below (Figure 2) is a global view that incorporates the different contexts of the circular economy (environmental, social, and economic), design and manufacturing contexts. Added to this are the granular details of smart product design, i.e. the physical relationships between disassembly and assembly (kinematics and technology relationships) [27], the virtual relationships of the smart product such as interactions with human-machine interfaces and the sending of data to the software embedded in the product. Added to this, are three examples of circular disassembly indicators which are respectively in contexts linked to the circular economy. Namely, in the social context, the ease of removal for the product components (to facilitate assemblies that are easy to dismantle (even at the end of the product's life) to reduce time requirements during disassembly). The indicator on compatibility in the environmental context, both of component materials (based on the type of process, e.g. the solder is difficult to dismantle provided it destroys or deforms the part) but also of embedded software (to reduce the number of software and facilitate interoperability between them). The last indicator is the direct cost of the product, which makes it possible to indicate and control the costs associated during the progress of the smart product development.

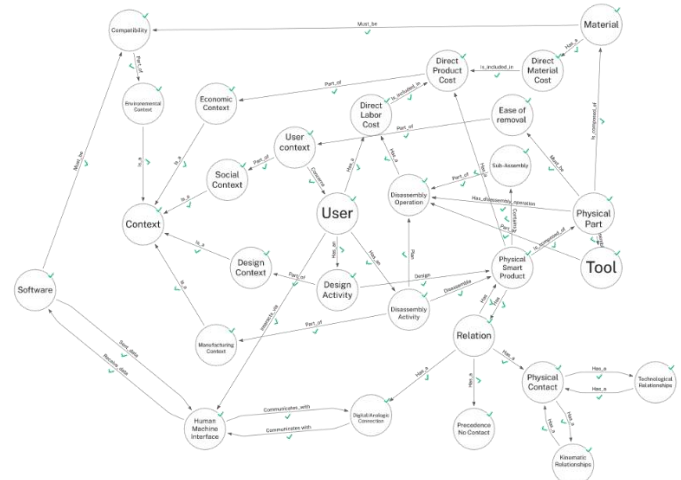


Figure 2. Knowledge graph model for the recommendation system.

The next chapter presents a use case for the development of a smart product.

IV. USE CASE

The study focuses on one indicator to show the feasibility of the use case. Focus on Direct Product Cost (DPC) as an economic indicator, it offers a preliminary trend rather than an absolute value, as at this stage the information available may be limited. However, during the design phase of the smart product, here a smart light switch.

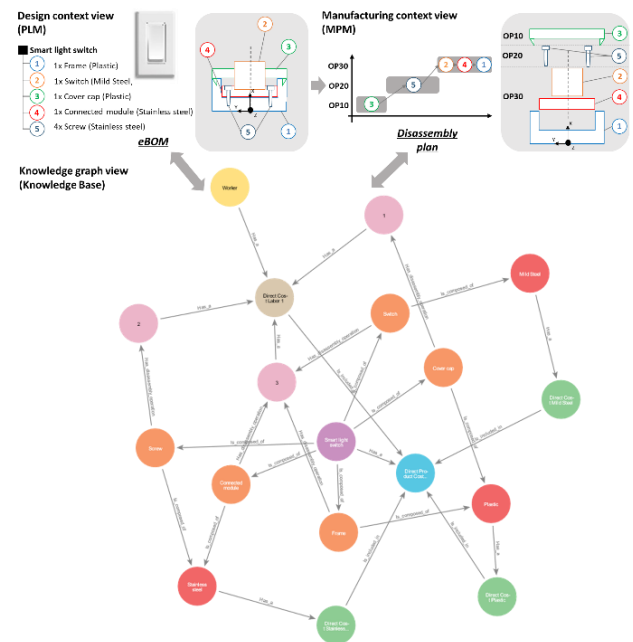


Figure 3. Case study of smart light switch with a knowledge graph view.

In the development of the smart product (Figure 3), the product architect carries out an eBOM so that the knowledge graph is populated as the data is provided and sends it indications on an estimate of the cost of the product. To subsequently provide the assembly planner with additional elements to carry out the disassembly plan, with the help of the graph. The DPC will dynamically update itself according to the data received, thanks to the interoperability of information systems and the digital thread. Cost management during the product design in manufacturing is an essential component of decision-making. In this article, we will explore how graph databases, can be used to calculate the direct costs (Figure 4). We will focus on three main aspects: Direct Material Cost (DMC), Direct Labor Cost (DLC), and finally, Direct Product Cost (DPC).

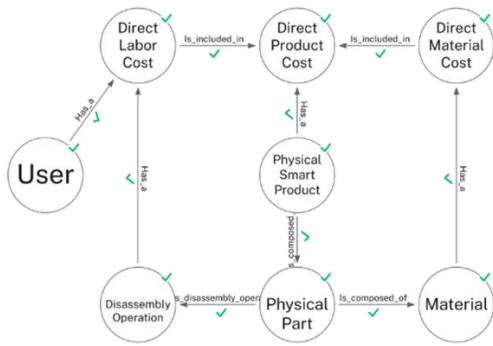


Figure 4. Extract of the Knowledge graph model focused on the uses case.

Using Neo4j to calculate production costs with the Cypher queries translate theoretical formulas into operations on the data graph, providing an in-depth view of the direct cost associated with manufacturing a product.

1) Direct Material Cost (DMC)

The theoretical formula for DMC is defined as follows:

$$DMC = \sum_i (Price\ per\ Unit_i \times Quantity_i) \quad (1)$$

This formula calculates each material by multiplying its unit price by the quantity used to manufacture the product.

2) Direct Labor Cost (DLC)

The theoretical formula for DLC is given by:

$$DLC = \sum_i (Operation\ Time_i \times Hourly\ Rate_i) \quad (1)$$

This formula estimates the total labor cost by multiplying the operation time for each task by the user's hourly rate.

3) Direct Product Cost (DPC)

DPC is the sum of DMC and DLC:

$$DPC = DMC + DLC \quad (1)$$

This is a global measure of the total direct cost of manufacturing the product.

4) Practical implementation in Neo4j

The theoretical formulas mentioned above are implemented in Neo4j using Cypher queries.

a. Calculating Direct Material Cost

In this study, a Cypher query language is used to extract specific information. In this case, material information is extracted. The following Cypher code (Figure 5) illustrates this query:

```
MATCH (n:Material) RETURN n LIMIT 25;
```

Figure 5. Query to return all values in the Material label.

MATCH is a clause used to specify a pattern. In this case, the pattern is (n:Material), which means looking for nodes with the label "Material". (n:Material) defines a variable n that represents nodes with the label "Material". RETURN n is the query that specifies the result to retrieve. In this case, to return the nodes which correspond to the previously defined pattern (those with the label "Material"). LIMIT 25, limits the number of results returned to 25. In other words, the query will return a maximum of 25 nodes matching the specified pattern. The result of the query is that there are three types of materials attached to the component, with an average price per kg for each material (Figure 6).

```
(:Material {materialName: "Plastic", materialAvgPrice(USD/kg): 3.0, materialID: 1})
(:Material {materialName: "Mild Steel", materialAvgPrice(USD/kg): 1.5, materialID: 2})
(:Material {materialName: "Stainless steel", materialAvgPrice(USD/kg): 5.0, materialID: 3})
```

Figure 6. Query result for Material values.

In the early stages of development, when the CAD model is not yet defined, estimating the cost of materials can be a challenge. A weighting approach with coefficients can be used to assign relative values to materials, offering a general trend without requiring specific details of component shape.

The following formula allows to add a weighting to the price of the material:

$$\text{Weighted Material Cost} = \text{Average Material Price} \times \text{Material Weight} \quad (1)$$

The Average Material Price represents the average cost of material per kilogram. The Material Weight is the weight assigned to each material category based on its relative relevance. This formula expresses the weighted material cost in terms of the weighting coefficients assigned to each material category. These coefficients reflect the relative importance of each category of material in the estimated final cost of materials.

```
MATCH (m:Material)
WITH m,
CASE
WHEN m.materialName = 'Plastic' THEN 0.2
WHEN m.materialName = 'Mild Steel' THEN 0.1
WHEN m.materialName = 'Stainless steel' THEN 0.3
ELSE 0.4
END AS weight
SET m.materialWeighting = m.`materialAvgPrice(USD/kg)` * weight
RETURN m.materialID, m.materialName, m.`materialAvgPrice(USD/kg)`, m.materialWeighting;
```

Figure 7. Query for Material weighting.

In this query (Figure 7), materials are weighted according to their name. Each category of material is assigned a weighting coefficient, representing its relative importance in the final cost. CASE WHEN...THEN...ELSE...END, this clause allows to define conditions for each material category and assign a specific weight to each. "weight" is the weight assigned to each category (materialName) is stored in the "weight" variable. RETURN is the query returns the material and the associated weighted cost, providing a qualitative estimate of material cost based on weighting coefficients. This approach overcomes the lack of specific details on component shape at an early stage of development, providing an indication of material cost based on relative estimates. The result (Figure 8) proposes a coefficient which weights the cost of plastic, mild steel, and stainless steel.

m.materialID	m.materialName	m.`materialAvgPrice(USD/kg)`	m.materialWeighting
1	"Plastic"	3.0	0.6000000000000001
2	"Mild Steel"	1.5	0.1500000000000000
3	"Stainless steel"	5.0	1.5

Figure 8. Query result for Material weighting values.

By breaking down the query (Figure 9), we look for "Physical Part" nodes linked to "Material" nodes by an "Is_composed_of" relationship.

```
MATCH (pp:`Physical Part`)-[:Is_composed_of]->(m:Material)
WITH SUM(m.materialWeighting * pp.partQuantity) AS directMaterialCost
MATCH (dmc:`Direct Material Cost`)
SET dmc.`totalDirectMaterialCost(USD)` = directMaterialCost
RETURN dmc.directMaterialCostID, dmc.directMaterialCostName, dmc.`totalDirectMaterialCost(USD)`;
```

Figure 9. Query for calculating the Direct Material Cost.

The calculation of the DMC is given by multiplying the average material price with weight by the quantity of each physical component. The results are stored in a "Direct Material Cost" node, where the totalDirectMaterialCost(USD) field is updated with the calculated cost. Finally, the query returns the identifier, name and total direct material cost. This approach gives a consolidated view of the direct material cost in the analysis (Figure 10).

dmc.directMaterialCostID	dmc.directMaterialCostName	dmc.`totalDirectMaterialCost(USD)`
1	"Direct Cost Plastic"	10.35
2	"Direct Cost Mild Steel"	10.35
3	"Direct Cost Stainless Steel"	10.35

Figure 10. Query result for the Direct Material Cost values.

b. Calculating Direct Labor Cost

The next step is to calculate the DLC. To do this, a search on the data in the "User" node which contains the hourly rate allows you to have an inventory. The query uses the same principle as the Figure 5. This query searches for and returns up to 25 nodes tagged as "User" in the Neo4j database (Figure 11).

```
(:User {userName: "Worker", hourlyRate: 15.0, userID: 1})
```

Figure 11. Query result for User values.

The graph must recover the data related to the disassembly operations. The first query for this remains the same as the Figure 5 and Figure 11. This query aims to identify and return nodes tagged as "Disassembly Operation". The variable n represents these nodes, offering a selection of the disassembly operations (operation time, the type of Sub-Assembly - SA (either in series or in parallel), number of operation (Figure 12).

```
(:Disassembly Operation {operationNumber: "OP 10", operationSAType: "No SA", operationID: 1, operationTime: 10.0})
(:Disassembly Operation {operationNumber: "OP 20", operationSAType: "No SA", operationID: 2, operationTime: 25.0})
(:Disassembly Operation {operationNumber: "OP 30", operationSAType: "Serial", operationID: 3, operationTime: 7.0})
```

Figure 12. Query result for Disassembly Operation values.

The following Cypher code (Figure 13) aims to introduce a weighting approach for disassembly operations by considering time variations between sub-assemblies' type in series and in parallel.

```
MATCH (do:`Disassembly Operation`)
WITH do,
CASE
WHEN do.operationSAType = 'Serial' THEN 1.5 // Longer serial disassembly time
WHEN do.operationSAType = 'Parallel' THEN 1.0
ELSE 1.0 // No weighting by default
END AS weight
SET do.operationWeighted = do.operationTime * weight
RETURN do.operationID, do.operationNumber, do.operationSAType, do.operationTime, do.operationWeighted;
```

Figure 13. Query for Disassembly Operation weighing.

This code provides a qualitative estimate of disassembly time, considering time variations between operations performed in series and in parallel. Weight is thus multiplied by the disassembly time. Considering that the series sub-assembly is theoretically longer than the parallel sub-assembly. The weighting (Figure 14) is based on operation types, enabling a disassembly time trend to be obtained at an early stage of development, when specific details may not be fully defined.

do.operationID	do.operationNumber	do.operationSAType	do.operationTime	do.operationWeighted
1	"OP 10"	"No SA"	10.0	10.0
2	"OP 20"	"No SA"	25.0	25.0
3	"OP 30"	"Serial"	7.0	10.5

Figure 14. Query result for Disassembly Operation weighing value.

Once, data on hourly rate and time of dismantling operations weighted. There remains the query which calculates DLC. It establishes relationships between users, direct labor costs, and disassembly operations (Figure 15).

```
MATCH (u:User)-[:Has_a]->(dlc:`Direct Labor Cost`)-[:Has_a]-(do:`Disassembly Operation`)
WITH SUM(do.operationWeighted * u.hourlyRate / 3600)
AS directLaborCost
MATCH (dlc:`Direct Labor Cost`)
SET dlc.`totalDirectLaborCost(USD)` = directLaborCost
RETURN dlc.directLaborCostID, dlc.directLaborCostName, dlc.`totalDirectLaborCost(USD)`;
```

Figure 15. Query for calculating Direct Labor Cost.

Using these relationships, the total direct labor cost is calculated as a function of each user's operation time and hourly rate. The results are stored in a "Direct Labor Cost" node, in the totalDirectLaborCost(USD) field (Figure 16).

dlc.directLaborCostID	dlc.directLaborCostName	dlc.`totalDirectLaborCost(USD)`
1	"Direct Cost Labor 1"	0.18958333333333333

Figure 16. Query result for Direct Labor Cost value.

c. Calculating Direct Product Cost

After calculating the DMC and DLC queries, the aim of the following query (Figure 17) is to calculate the DPC by linking the direct material and labor costs to the DPC.

```
MATCH (dmc:`Direct Material Cost`)-[:Is_included_in]->(dpc:`Direct Product Cost`)-[:Is_included_in]-(dlc:`Direct Labor Cost`)
SET dpc.`directTotalCost(USD)` = dmc.`totalDirectMaterialCost(USD)` + dlc.`totalDirectLaborCost(USD)`
RETURN dpc.directProductCostID, dpc.directCostName, dpc.`directTotalCost(USD)`, dpc.`directMaterialCost(USD)`, dpc.`directLaborCost(USD)`;
```

Figure 17. Query for calculating Direct Product Cost.

The sum of direct Material and Labor costs is then stored in the "Direct Product Cost" node. The query returns the values (Figure 18), and an overview of the costs is displayed. Thus, making stakeholders aware of the impact of their design and manufacturing of the smart product.

dpc.directProductCostID	dpc.directCostName	dpc.`directTotalCost(USD)`	dpc.`directMaterialCost(USD)`	dpc.`directLaborCost(USD)`
1	"Direct Product Cost A"	20.189583333333335	32.5	0.175

Figure 18. Query result for Direct Product Cost values.

In this case study, the DPC indicator is one element in a broader set of circular indicators. In our methodological framework, we also include indicators linked to the environmental aspect, such as material and software compatibility, and social indicators, such as ease of component disassembly. These indicators are essential to assess the full impact of a smart product on circularity and disassembly, beyond the economic dimension alone.

V. CONCLUSION

Our approach recognizes that, in the preliminary phases, the information available is limited. DPC therefore offers an initial trend, evolving as new data is integrated into the knowledge graph. This evolution is made possible by the interoperability of

information systems, which ensures digital continuity throughout the life cycle of the smart product. This methodological framework proposes an innovative approach to guiding the development of a sustainable smart products by integrating circular disassembly indicators right from the design phase. By focusing on DPC and including it in a broader context of social and environmental indicators, our model aims to measure and avoid potential drifts when dismantling a product. Interoperability and digital thread are at the heart of this paradigm, enabling the model to be adapted dynamically as information becomes available. This framework thus offers a proactive approach to building more sustainable products.

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