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Designing an optimal modular-based product family under intellectual property and sustainability considerations

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With the rapid development of new technology and the growing global competition in industry, it is essential for companies to protect their sensitive product designs and technologies. To ensure that their systems are not exploited by potential patent infringers, original equipment manufacturers often apply physical attributes and/or reduce commonality within a product family to prevent easy reusing and recovering. Yet, these design strategies are key barriers to the sustainable recovery and recycling of products. To address these trade-offs, this paper proposes a stepwise methodology to identify the sustainable optimal product family architecture design while protecting intellectual property on sensitive parts or modules. The developed approach notably allows the selection of suitable and sustainable candidates to share among products, taking into account the cost-benefit of commonality within the product family. To demonstrate and test the proposed methodology, a case study is performed with a printer-product family. Environmental savings resulting from the new modular-based architecture obtained for this product family are quantified and discussed.

Nomenclature

K	Index set of product variant within product family, $k \in K$
θ	Criterion for determining the degree of commonality
δ	Target for the environmental saving
X^k	Clustering matrix for each product k
Y^k	Binary decision vector for shared candidates for each product k
$I_{i,j}$	DSM for component interaction of component i and j
$L_{i,j}$	DSM for life cycle similarity of component i and j
$M_{i,j}$	DSM for material similarity of component i and j
EP_j^k	Environmental impact saving of j component in product k
CIM_j^k	Cost impact metric for component j in product k
BIM_j^k	Benefit impact metric for component j in product k

1 INTRODUCTION

The rapid development of technology and global competition have led many original equipment manufacturers (OEMs) to invest substantially in research and development (R&D) [1]. With increasing their R&D investment costs, it has become essential for OEMs to protect sensitive designs and technologies that drive their distinctive features and profitability from potential users or undesirable agents. Besides, for products targeting aftermarket (e.g., printer cartridges, automobile parts), parts with high resale rates or high profits should be prevented from being recycled and resold by third-party remanufacturers. In this context, protecting intellectual property (i.e., sensitive components and technologies) is becoming an essential challenge for OEMs. Intellectual property (IP) is "a bundle of rights that protects applications of ideas and information that have commercial value" [2]. IP is a broad concept involving many types of intellectual property rights such as design patents, trademarks, copyrighted material, etc. In our context, for simplicity, IP refers to a set of components that contain important information (or technologies) and/or high potential values that can be utilized in the future.

To prevent third parties from replicating their state-of-the-art designs and components, some OEMs use specific design strategies to protect their IP rather than designing for sustainability. In particular, OEMs have responded to preventing third-parties from recycling and remanufacturing their high valuable products or components without proper authorization. For instance, OEMs can use physical attributes that make it difficult (or impossible) to disassemble and reassemble their products to prevent them from being reused [3, 4]. For product family designs, divergent com-

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monality strategies that do not share sensitive components are used to decrease the efficiency of reuse [4–6]. Unfortunately, these design strategies are in contradiction with sustainable design principles. These strategies usually lead to an ineffective recovery as well as a single use of the product, resulting in a waste of resources and energy. In addition, some countries exist movements to promote refurbishing (or remanufacturing) of patented products. Some laws prohibit products from OEMs that use designs that prevent reusing or remanufacturing are not used by state agencies [1,7]. Therefore, integrating both protection on sensitive components and sustainability in product design presents an important challenge for industries that are willing to adopt a sustainable and secured approach in new product development.

To tackle this issue, modular product architecture design with the simultaneous consideration of IP and sustainability can be applied. The modular architecture is designed to have many internal couplings within a module while also having less external couplings between modules [8]. The modular product architecture design has been known to offer many benefits to both manufacturers and consumers, including flexibility to the design, addressing various customer needs, and contributing to sustainable design [8–11]. A few researchers also suggested IP modular architecture design as a way to protect IP [4,5]. To the best of our knowledge, the integration of environmental sustainability, supported by life cycle assessment, in the modular design of products under IP security consideration within an integrated optimization model does not exist in the design engineering literature.

The paper proposes a novel methodology, including an optimization model to identify sustainable product family architecture design while protecting their security (i.e., IP-related parts and/or modules) based on matrix-based tools. The proposed step-by-step approach aims to the optimization of individual product design and selection of suitable and sustainable parts and/or modules that can be shared among products considering the cost-benefit of commonality within the product family in the context of product security and sustainability. The rest of the paper is organized as follows. Section 2 reviews relevant prior work/literature on this topic. Section 3 depicts a mathematical model for sustainable product architecture design and selecting shared modules, while considering IP protection. Section 4 illustrates the optimization model through a case study on printers. Finally, conclusions and future research are discussed in section 5.

2 LITERATURE REVIEW

Product architecture refers to the "comprehensive representations of a set of characteristics, such as the number and type of components, the number of interfaces between components, and the fundamental structure of the product" [12]. Adequate product architecture is critical not only in the optimal design of individual products but also in the process of determining shared components or modules between product variants within a product family [5,13,14]. Defining product platform architecture is indeed a pivotal challenge to design and develop product variants, with an adequate modularity (and component commonality) level that fits with the demand of diverse market segments [15]. This section reviews and discusses the contributions and limitations of prior works addressing optimal product architecture and modular design strategies, in the light of sustainability and product security constraints.

2.1 Product family design strategies for product security and sustainability

The concept of product family design relies on designing "a set of products that share one or more common elements (e.g., components, modules, and subsystems)" [16] in order to satisfy several market segments (customized product variants for different/targeted groups of customers) while minimizing cost for the OEM [17,18]. Jiao et al. [19] provided a decision framework to support product family design and platform-based product development, considering both front-end and back-end issues of the engineering design and development process. While their framework includes and links various topics concerning product portfolio like platform-based product family design, manufacturing, production, or supply chain management, sustainability aspects are not explicitly considered and quantified.

Since, while some researchers proposed methodologies to address the simultaneous consideration of new and remanufactured products in product family design [20,21], previous studies of sustainable product family design generally assumed that products within the product family have the same product architecture. Even though the product family performs similar or identical functions, it often uses different components or architectures. To bridge part of this gap, Rojas and Kim [5] assumed that products could have different architectures within the product family and proposed a methodology to identify an optimal product architecture and component sharing decisions amongst product family with security consideration. For IP-related parts, it is assumed that they are in a proper module and that this module could not be shared amongst the product family (i.e., following a divergent commonality strategy). However, one key limitation of this previous study is that it only considered the risk of redesigning the product family to determine commonality , but not the economic value or ecological benefits that could arise when shared. Given that commonality is a new attribute of the product family that can lead to economies of scale that could have a positive impact on reducing environmental impact [14], decisions on commonality should be made in consideration of the entire life cycle of the product.

2.2 Modular-based design for product security and sustainability

With increasing regulations for tackling global warming and achieving carbon mitigation targets, sustainable product design appears as a relevant solution to support manufacturers in reducing the carbon footprint of their products [22–24]. Sustainable product design is to make efforts to reduce the environmental impact by considering the entire life cycle of the product from the stages of product development, manu-

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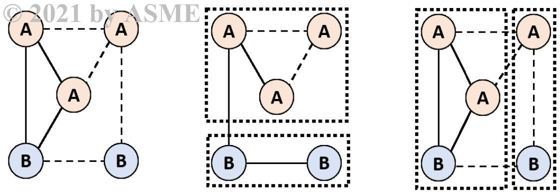


(a) (b) (c)

Note: Components A, B are under distinct IP status.
Solid lines and dash lines refer to high and low interconnections between components, respectively.

Fig. 1. (a) A simple example of product prior to modularization (b) Modularity based on IP status [4] (c) Modularity based on component interconnections

facturing, and use to the end-of-life stage [24, 25]. Among the several methodologies for sustainable design, the optimization of module-based product configurations is a typical methodology that helps manufacturers reduce the carbon footprint of their products while maintaining an attractive product range for a wide range of customer categories. Modular product design aims to subdivide "complicated products and systems into components and considers them individually instead of as an amalgamated whole" [26]. Importantly, modular product platforms can provide substantial cost and time savings while allowing manufacturers to offer a broader range of products to reach diverse market segments [27]. Analyzing more than 100 studies on how modular product design and sustainability factors are intertwined, Ma and Kremer [28] highlighted the contribution of a modular-based approach for designing environmentally sustainable and economically profitable products.

In fact, the identification and specification of suitable product family platforms through modular product design can provide substantial benefits for producers, such as to: increase manufacturing and remanufacturing efficiency and effectiveness, reduce inventory cost, save distribution time, and satisfy the demand for mass customization [29–31]. Kim and Moon [11] recently developed a methodology to identify an "eco-modular" architecture by proposing sustainable modular drivers. In this line, Yang et al. [18] proposed a module-based product configuration method by considering both economical and carbon emission-related environmental impacts in product design and manufacturing. Interestingly, their numerical results have shown that such an approach can provide effective decision support for low-carbon and modular manufacturing. However, this study does not integrate the aspect of intellectual property on sensitive or secured components when defining the appropriate modules.

Henkel et al. [4] introduced the concept of IP modularity, which aims to protect and capture value in an open innovation model based on real design cases. According to their proposed "IP module" concept, to protect IP value in product design, it is necessary to identify the degree of IP each part has and to separate with other components or modules. For instance, components A and B are under distinct IP status, as shown in Fig. 1. The type of line connected between each component indicates whether the interaction between the two parts is high or low. According to the IP modularity presented by Henkel et al. [4], the product in Fig. 1 (a) must be modularized, as illustrated in Fig. 1 (b)), which distinguishes different IP status.

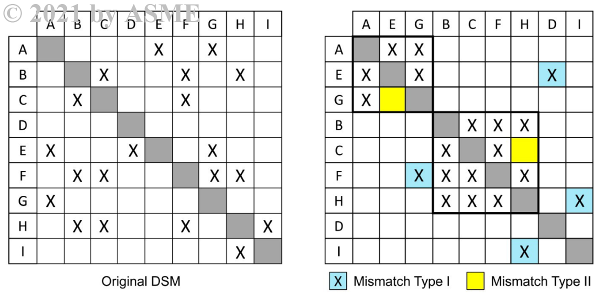
On the other hand, when applying the existing modularization strategy, which strengthens the interconnections between components within the module and weakens the interconnections between modules, the modules of the product can be formed, as shown in Fig. 1 (c). In many cases of reality, the IP-related core elements of the product are highly interconnected with the rest of the system, making it difficult to encapsulate them completely in a module like Fig. 1 (b) [5, 32]. A module designs only based on the IP status may be effective for IP protection. Still, it may not be a feasible/practical design, because in such a case, the physical relationships between components are not considered. As shown in Fig. 1, the modular design of the product requires consideration of the IP status, as well as the various interconnections between components because it may vary depending on which factors are primarily applied.

Rojas and Kim [5] also used the concept of IP modularity to optimize the arrangement of the components of products by considering connectivity and security criteria. The goal was to identify the optimal set of components to share within a product-family platform. The developed model applied security constraints for optimal product design so that components related to sensitive information are in the same module. Yet, their proposed methodology to identify an optimal product architecture that protects IP does not include parameters related to economic or environmental sustainability. In all, previous studies typically focus on an interface or material-based criteria for module selection. Also, even a paper dealing with protection IP only considers IP protection and does not apply sustainability.

2.3 Matrix-based tools for modular and product family design

As illustrated in the previous sub-sections, component-based matrices, especially design structure matrix (DSM), are widely recognized tools to define suitable clusters of components into modules [9, 10, 13, 29]. Several authors have indeed acknowledged the usefulness of DSM for product family design. Actually, redesigning a family of products is not a straightforward task when integrating the number of variables (e.g., the possible combination of modules), competing objectives (e.g., diversity-commonality, environmental sustainability, product security), and actual technical solutions (e.g., cost value, architectural constraints) [9]. While being a practical tool to represent the different interactions of a complex system in a simple, compact, and visual way, DSM also facilitates the improvement of module architecture, specifications, and interfaces.

In a conventional component-based (or interaction) DSM, the three following steps are deployed to construct the DSM: (i) decompose the system into elements, (ii) document the physical interactions between elements, and (iii) analyze potential clustering. A typical DSM is filled out with bi-



	A	B	C	D	E	F	G	H	I
A	▨				X		X		
B		▨	X			X		X	
C		X	▨			X			
D				▨					
E	X			X	▨		X		
F		X	X			▨	X	X	
G	X						▨		
H		X	X			X		▨	X
I								X	▨

Original DSM

	A	E	G	B	C	F	H	D	I
A	▨	X	X						
E	X	▨	X					X	
G	X	🟨	▨						
B				▨	X	X	X		
C				X	▨	X	🟨		
F			X	X	X	▨	X		
H				X	X	X	▨		X
D								▨	
I							X		▨

X Mismatch Type I 🟨 Mismatch Type II

Fig. 2. Unordered and rearranged binary DSMs [13]

nary values, indicating whether a relationship exists or not between components, as shown in Fig. 2. In addition to these primary relationships, DSM can be built on other complementary measures such as the characteristics of interfaces, the flow of energy or information, and sustainability aspects to generate modules.

Interestingly, Deng et al. [10] proposed a DSM-based approach to breakdown a product into several subcomponents to mitigate the leakage of protected information. In this case, the DSM and its associated algorithm are computed to evaluate the potential risk of IP leakage considering different types of interactions between product components. Based on the obtained DSM, an appropriate suitable product decomposition is generated regarding IP protection and manufacturing cost reduction issues. Similarly, Zhang et al. [33] deployed a Function-Parameter (FP) matrix to model and assess the leakage of confidential information through inferences in product supply chains. The FP matrix, representing a parametric design problem, includes three types of entities, namely: protected parameters, shared parameters, and protected functions. Using the FP matrix, the protected parameters are first identified, then the protected functions are highlighted as the functions that are linked to the protected parameters.

In this study, in addition to the existing interaction between components, sustainability modular drivers (material and lifespan) proposed by Kim and Moon [11] are applied to generate new modules that facilitate their sustainable maintenance and management. Designing product architecture based on similar materials, lifespan, is indeed essential for the overall sustainability performance of a product. Modules with similar or compatible materials make the disassembly, recovery, and recycling stages easier [34]. Concretely, besides component-based DSM, a lifecycle and a material-based DSM are employed here to identifying further potential clusters of similar components in terms of lifetime and materials compatibility.

3 MATHEMATICAL MODEL

The purpose of this paper is to identify the optimal product family architecture design that considers sustainability while protecting IP-related components and to select candidates that can be shared in consideration of the cost-benefit (potential residual value) of commonality within the product family. The study is particularly intended for OEMs who want to redesign a previously designed product family into sustainable designs while protecting sensitive components from third-parties.

3.1 Problem Statement

The developed methodology is built upon the prior relevant framework and studies focusing independently on sustainable design, design for IP protection, and commonality decisions (see, for example, [5, 11, 13]). The workflow of the proposed methodology is shown in Fig.3. In phase 0, the current product architecture design of the product family is analyzed, and the required data are collected and filled out in design structure and function-component matrices (DSMs and FCMs), and secured component data associated with critical (sensitive) functions. For DSMs of individual product designs, the information includes not only interaction information between components, but also component lifespan and material types to consider their sustainability performance. Phase I consists of optimizing the architecture of individual products in a way that addresses secured modules separately and concurrently increases the sustainability performance. Phase II selects candidates for modules and/or components to be shared between products, taking into account redesign risks and potential value for future reuse, based on the structure of products acquired in the previous phase. After selecting shared candidates, the environmental impact saving that can be obtained by this sharing strategy is estimated and checked against the target value. Phase III is to verify the termination condition, and once the stopping criteria are satisfied, the return loop is stopped. Finally, appropriate decisions can be made by product designers and engineers about the product family architecture and commonality on new redesigns that would increase the environmental performance, while protecting their sensitive information.

3.2 Product Architecture Analysis

This preliminary phase deals with the analysis of the current product family to redesign its product architecture to increase sustainability and secure IP. Product architecture design requires a clear understanding of the types and number of components that constitute the product, as well as the relationships between them. In particular, as opposed to single product design, designing multiple products requires a comprehensive understanding of whether they perform similar functions or differences between products and which components are involved, as well as analyses of individual products [5].

In this study, in addition to the existing interaction between components, sustainability modular drivers (material and lifespan) proposed by Kim and Moon [11] are applied to generate new modules that facilitate their sustainable maintenance and management. Designing product architecture based on similar materials, lifespan, is important for the overall sustainability performance of a product. Modules with similar or compatible materials make recycling easier [35]. Besides, if components within a module have a similar resid-

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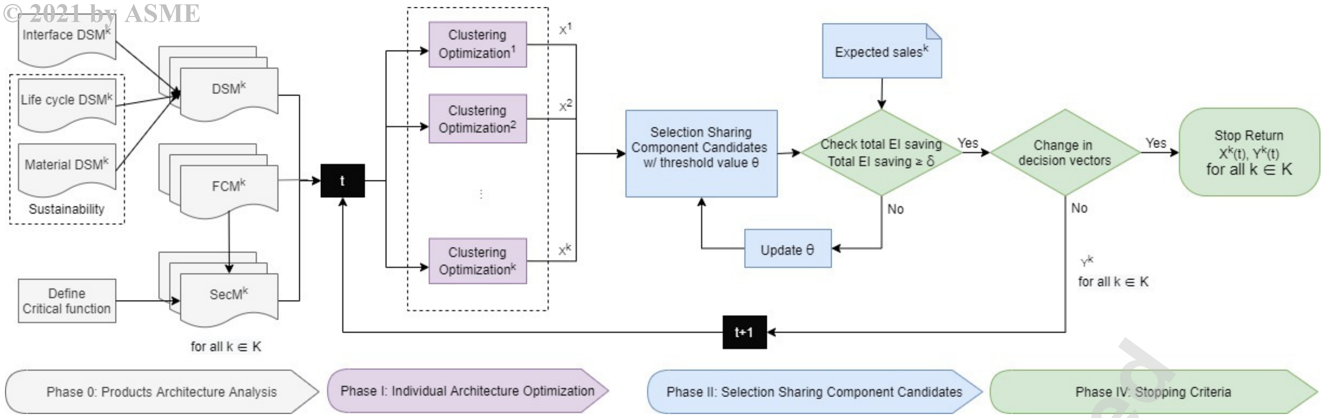


EI: Environmental Impact; θ: Criterion for determining the shared candidates; δ: Target of environmental impact saving

Fig. 3. Schematic overview of the proposed methodology

ual lifetime [26], it facilitates maintenance, saves time and effort by not requiring further disassembly operations when replacing the module.

Each DSM cell (i, j) for component interaction $(I_{i,j})$, material $(M_{i,j})$, and lifespan $(L_{i,j})$ is simply created with a value between 0 and 1, based on the following equations (Eq. 1-3). The calculation of lifespan similarity $L_{i,j}$ between components is expressed as a ratio of the minimum and maximum lifespan between components, as shown in Eq. (3). If the two components i, j have the same lifespan, the value $L_{i,j}$ is 1 and $L_{i,j}$ becomes smaller if the remaining lifetime difference between components is large.

$$I_{i,j} = \begin{cases} 1, & \text{if there are interactions between } i \text{ and } j \\ 0, & \text{otherwise} \end{cases} \tag{1}$$

$$M_{i,j} = \begin{cases} 1, & \text{if same material is used for } i \text{ and } j \\ 0.5, & \text{if similar material is used} \\ 0.3, & \text{otherwise} \end{cases} \tag{2}$$

$$L_{i,j} = \frac{\text{min lifespan } (i,\ j)}{\text{max lifespan } (i,\ j)} \tag{3}$$

$$W_{i,j} = \alpha_1\ I_{i,j} + \alpha_2\ M_{i,j} + \alpha_3\ L_{i,j} \tag{4}$$

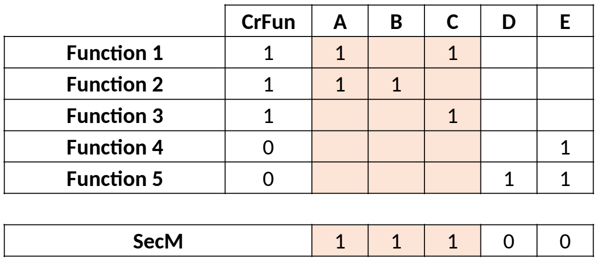
The component-based, material-based, and lifespan DSMs are combined through the weighted average method, as shown in Eq. 4. This method is in its simple form (simplicity), but the reason for using this formula is that it can handle a variety of purpose functions (e.g., interfaces, life cycles, and materials). The importance of each purpose function may vary depending on the company's strategy or product characteristics (flexibility).

3.2.1 Function-Component Matrix (FCM)

A Function-component matrix (FCM) is a representation of the functions and components of a product. It represents the relationship between each function and the parts involved in performing it [13, 36]. When analyzing multiple products rather than a single product, it is necessary to identify similarities and differences between the products. Even a product family that performs similar functions does not often have the same or identical architecture design. In this case, it is difficult to understand the overall relationship by using only each product's DSM. To address this issue, Rojas and Kim [5, 13] proposed a functional matching method that utilizes FCMs to find a set of components involved in performing similar functions for each product variant automatically.

3.2.2 Security Matrix (SecM)

The FCM mentioned above can also be deployed to find a set of components related to sensitive (or critical) functions. Rojas and Kim [5] proposed using FCM to automatically find a security matrix (*SecM*), which means the set of sensitive components related to critical functions (*CrFun*). The critical function (*CrFun*) used in this study refers to the function that contains important information and technologies related to the IP of the product. It is assumed that the designers are at the redesign stage for their product family and can easily identify *CrFun*. *CrFun* is expressed as a 0 or 1 binary number, the value of 1 indicating that its corresponding function is critical. Figure 4 shows how to find *SecM* based on FCM and *CrFun*. Functions 1 through 3 are critical functions and the components A, B, and C, which are associated with these functions are expressed as 1 in the security matrix. This information is used in the next phase of product architecture



	CrFun	A	B	C	D	E
Function 1	1	1		1		
Function 2	1	1	1			
Function 3	1			1		
Function 4	0					1
Function 5	0				1	1

SecM		A	B	C	D	E
		1	1	1	0	0

Fig. 4. Example of security matrix (*SecM*)

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optimization for individual products.

3.3 Phase I: Individual Architecture Optimization

Based on the data analyzed in the previous phase, the architecture optimization of individual products is carried out at this stage. The basic product architecture design aims to maximize internal interconnections within the module while minimizing outer interconnections between modules [8]. In this study, the product architecture of individual products is designed to achieve the objective of the existing architecture design while minimizing the additional penalty costs associated with the IP and easiness of sharing.

3.3.1 Basic Coordination Cost

For optimal product architecture, existing studies use the same principles, although they are different manners to modularize products [5, 13, 37–39]. They aim to maximize interconnection within a module while minimizing external interconnection between modules. In this study, the coordination cost proposed by Thebeau was used as the objective function [37]. The coordination cost is calculated using the DSMs and the cluster matrix that defines which elements are in each cluster. The coordination cost consists of internal cluster cost and external cluster cost. Equation 5 shows the coordination cost. The IntraCluster is calculated for interaction between components j and k generated within the module. On the other hand, for interaction between components j and k occurring outside of any clusters, the ExtraCluster is calculated. The coordination cost is calculated from the sum of all IntraCluster and ExtraCluster costs.

$$\begin{aligned}
&\mathrm{IntraCluster} = (\mathrm{DSM}(j,k) + \mathrm{DSM}(k,j)) \times \mathrm{Clustersize}(y)^{power}\\
&\mathrm{ExtraCluster} = (\mathrm{DSM}(j,k) + \mathrm{DSM}(k,j)) \times \mathrm{DSMsize}^{power}\\
&\mathrm{Coordcost} = \sum \mathrm{IntraCluster} + \sum \mathrm{ExtraCluster}
\end{aligned} \tag{5}$$

where DSM(j, k) is the interaction between component j and k. Clustersize(y) is the number of components in the cluster y. DSMsize is the number of elements in the DSM. The parameter *power* represents the penalty factor for the size of clusters.

3.3.2 IP-related Penalty Cost

To ensure IP protection, this study uses the concept of IP modularity integrated into product design. The IP modularity refers to the component boundary in different IP status that corresponds to the technical boundary of module [4]. Rojas and Kim [5] also suggested the concept of restricted modules for constraints that a set of components in the security matrix cannot be distributed to other modules and exist within one module. The method proposed by Rojas and Kim [5] is applied for the penalty cost that reflects IP modularity. For this constraint, the number of mismatches between their clustering solution and security matrix is calculated through P_s as shown in Eq. 6.

$$\begin{aligned}
P_s = &\sum_{i=1}^{n_{rel}} \sum_{j=1}^{n_{cl}} \left[SecM_i(e - X_j^T) \min\left\{ \min\left\{ SecM_i X_j^T, SecM_i(e - X_j)^T \right\}, 1 \right\} \right]\\
&+ \sum_{i=1}^{n_{rel}} \left[SecM_i e^T (1 - \min\left\{ SecM_i X_j^T, 1 \right\} \right]
\end{aligned} \tag{6}$$

where X_j is the j^{th} row vector of clustering matrix (X), and e is a unity row vector of the appropriate dimension. n_c is the number of components. n_{rcl} is the number of restricted set, and n_{cl} is the cluster number.

$$\mathrm{Penaltycost} = P_s(n_c + n_{rcl} + n_{cl}) \tag{7}$$

The penalty cost is calculated by multiplying this mismatches (P_s) by the description length (n_c + n_{rcl} + n_{cl}) as defined in Eq. 7, since the description of this mismatch would be given by the number of components, restricted sets, and clusters.

3.3.3 Design for Easy Sharing

When designing the architecture of a product family that includes IP-related parts, designers should choose a design with a low risk of redesign. The reason is that it will require more time and cost if more parts need to be changed to redesign existing designs. Therefore, it is necessary for the solution generated in the next stage to be reflected in the individual product architecture so that the shared candidates can be easily shared.

To do so, a metric proposed by Rojas and Esterman [40] is applied to measure the ease of changing components in a given architecture. The Cost Impact Metric (CIM_j^k) of component j in product k is calculated by multiplying the MDL_j^k and CI_j^k, whose the detailed descriptions and formulas are as follows: MDL_j^k represents the number of links from the component j in product k which measures how strongly the component j is connected to other parts [41]. CI_j^k is the Coupling Index (CI) of component j in product k, which represents the impact of a change in the specifications of the components [42]. The effects of a component specification include both the repercussions of changes in that component on other components (CIS) and the effects of other components (CIR).

$$\begin{aligned}
&\mathrm{CIM}_j^k = \mathrm{MDL}_j^k\, \mathrm{CI}_j^k\\
&\mathrm{MDL}_j^k = \mathrm{MDL}_j^{(c)} + \mathrm{MDL}_j^{(o)} = -\sum_{u=\{c,o\}} \log_2 \left(N_j^{(u)} \Big/ \sum_{k=1}^{N^{(u)}} N_k \right)\\
&\mathrm{CI}_j^k = \mathrm{CIS}_j^k + \mathrm{CIR}_j^k = \sum_{i=1}^{n_c^k} \mathrm{DSM}^k(i,j) + \sum_{i=1}^{n_c^k} \mathrm{DSM}^k(j,i)
\end{aligned} \tag{8}$$

where $N_j^{(u)}$ is the number of components connected to component j, and $N^{(u)}$ is the number of components at the level

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in which the component j is. $\{c, o\}$ represent components and interfaces, respectively.

The penalty cost for easiness of sharing is calculated as Eq. 9 [5]. This penalty cost readjusts the individual architecture design in a form that makes it easier to share the candidates that are subsequently determined.

$$\text{Sharingcost} = \beta_1\, Y_c^k\, \text{CIM}^k + \beta_2\, Y_m^k\, \text{CIM}^k \tag{9}$$

where Y is the decision vector representing the suitable and sustainable candidates derived through phase II. Y_c excludes all components within the security matrix from Y. Y_m represents a module that contains the restricted modules among the modules designated as shared candidates under Y. β_1 and β_2 are weighting factors.

3.3.4 Total Coordination Cost

To integrate these objective functions, the total coordination cost is redefined as Eq.10. The basic coordination cost, IP-related penalty cost, and sharing cost are simply combined through the weighted average method. The weight value can be applied differently according to the company's strategy or product characteristics.

$$\min f = \gamma_1\, \text{Coordcost} + \gamma_2\, \text{Penaltycost} + \gamma_3\, \text{Sharingcost} \tag{10}$$

where γ_1, γ_2, and γ_3 are weighting factors.

3.4 Phase II: Selection of Shared Candidates

After optimizing the individual product architecture design, the next phase is to select candidates that can be shared between products within a product family. Based on the architectural design of the individual products in phase I, this phase aims to select suitable and sustainable shared candidates (components and/or modules) between products. The Phase II results (Y) are returned to the individual design optimization problem again (Phase I), and the module is optimized in a structure in which the parts or modules selected as candidates are easily replaced and deformed.

When selecting the candidates to be shared, one needs to consider not only the cost of redesign that may occur during the sharing but also the potential value of the shared components for possible future reuse. It is important to select the shared candidates with a high potential residual value at the end-of-life (EoL) stage because commonality can lead to economic and environmental savings when recovering EoL components.

Unlike previous studies that considered only the redesign costs for sharing [5, 13], the Cost Impact Metric (CIM) and the Benefit Impact Metric (BIM) are applied simultaneously. The shared component selection algorithm calculates for all the components the CIM (Eq. 8), which reflects the risk of redesign that can occur when shared, and the BIM, which reflects the benefits that might arise from sharing. The BIM is indicated by a score of the integer value from 1 to 9, and components with a high residual value are rated at 9 and those with a low residual value at 1 point. For example, materials such as steel and copper, which are highly recyclable materials, receive a relatively high score. For materials with low recyclability such as Polystyrene (HIPS), a lower score is assigned.

$$\text{IM}_j^k = \frac{\text{CIM}_j^k}{\text{BIM}_j^k} \tag{11}$$

The Impact Metric (IM_j^k) is obtained by dividing CIM_j^k into BIM_j^k and normalizing it to a value of 0-1, according to Eq. 11. After obtaining the IM value of each part, this algorithm performs a functional matching to find suitable and sustainable shared candidates with IM below θ. θ is the criterion for determining the shared candidates, parts and/or modules with the IM value of less than θ are considered to be appropriate shared candidates. According to the value of this parameter, the number of candidates that can be shared between products can be adjusted. According to the value of this parameter, the number of candidates of the parts that can be shared between products can be adjusted.

The pairwise comparisons for products are performed after the functional matching process finds the set components for a particular function. In both products, if the sum of the IM of the components associated with that function is less than θ, those parts are set as shared candidates (Y) for both products.

3.5 Phase III: Checking the Environmental Impact Saving

The commonality is one of the new attributes of the product family that can lead to economies of scale that will affect positively the environmental impact saving [14]. Sharing components within a product family eliminates the need to develop or manufacture other components that perform the same function because they use the same part between different product variants. In addition, at the end-of-life stage, the commonality has the advantage that enough parts are available for product recovery so that sufficient material can be secured, and the degree of the environmental impact that can be caused by securing raw material can be reduced. This phase identifies the environment impact saving that could occur if components are shared among products, according to Eq. 12. Different environmental indicators such as global warming potential, ozone depletion, human toxicity, and ecotoxicity can be used to compute the EP parameter (see below), and the environmental impact saving target (δ) depends on what indicator is used. If the target of environmental impact saving (δ) is not satisfied, the criterion for determining the degree of commonality (θ) in the next step increases gradually until the target is met. As the value of θ increases, the number of parts and/or modules shared within the product family increases.

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$$\sum_k \sum_j \mathrm{EP}_j^k \, Y_j^k \text{ sales}^k \geq \delta \tag{12}$$

where EP_j^k denotes the environmental impact saving of j component in product k. δ represents the target of environmental impact saving. sales^k denotes the expected sales volume of a product k.

The process is repeated until the change in the decision vectors (Y) for all the products being considered is below a given tolerance ε:

$$\sum_{k=1}^{m} \parallel Y^k(t) - Y^k(t-1) \parallel^2 \leq \varepsilon \tag{13}$$

4 ILLUSTRATIVE CASE STUDY: APPLICATION TO A PRINTER-PRODUCT FAMILY

To demonstrate and test the new methodology developed in this paper, an illustrative case study is conducting on (re)designing printers in the context of product family with both security and sustainability considerations. Printers are an example of products that use design strategies for IP protection to prevent the recycling of products to sell parts that require replacement and to prevent their designs from leaking to other companies. For example, HP uses different printhead components between product variants, even though the printhead is a general functional component that does not give customers any additional satisfaction [6]. The reason for not generalizing print heads is to prevent third parties from increasing competitiveness in the printer and replacement parts markets due to lower recovery costs. The proposed methodology is applied to redesign printers. In this study, three printers from the same OEM are analyzed to identify their product architecture and shared component candidates to improve their sustainability while protecting their security.

4.1 Presentation of the case study

The case study on a product family of inkjet printers used by Rojas and Kim [5] is extended here to demonstrate the newly developed approach. A set of three different printers is considered, each having its "own architecture and printing subsystem, while providing the same overall functionality: (i) an entry-level printer (Printer model 1, P1), including a cartridge that integrates the ink with the printhead; (ii) a photography-oriented printer (Printer model 2, P2), including individual colored ink cartridges with the printheads fixed to the printer; and, (iii) a professional-level printer (Printer model 3, P3), including not only colored ink cartridges but also individual printheads. Note that the DSM has been developed only for the subsystems related to the (black and white, and colored) ink cartridges and printheads. Also, in the initial study performed by Rojas and Kim [5], no detailed cost consideration or environmental performance of each possible module instance was considered in the analysis and optimization model.

4.2 Printers Architecture Analysis

The interface DSMs, FCMs, and *CrFun* of printers developed in the previous study were applied [5]. In this study, in addition to interface DSMs, both lifecycle and material-based DSMs were deployed to identifying further potential clusters of similar components in terms of lifetime and materials compatibility, facilitating thus their sustainable maintenance and management. The sustainability-related DSMs were built based on the printer case study [43] and incorporating materials compatibility and recyclability elements according to the estimated bill of materials [44]. In addition, for the DSMs for life cycle similarity, the average replacement cycle for each part was utilized. These DSMs and FCMs are not provided in this paper due to space limitations but are available on demand.

4.3 Printers Architecture Design

The individual product architecture design algorithm was performed based on the DSM algorithms developed by Thebeau [37]. The total coordination cost includes the structure of modular models, penalty costs for IP, and ease of sharing. The objective function of the algorithm for the design of individual product architectures is the one defined in Eq. 10. The results of the individual architecture design of the printer models 1, 2, and 3 are shown in Fig. 5, 6, and Fig. 7, respectively. The results of the product architecture design confirmed that the IP-related components are within one module and separated from other components through IP modularization, as in the previous security-only paper [5]. Most parts with the similar or same material or life cycle were composed of modules when compared to previous studies.

For printer model 1, ESD spring and ESD blade of the same module were made of steel, and parts of the module except wiper (2 years) had the same average life span of five years. Likewise, the carriage belt and belt attach of printer model 2 were made of the same aluminum. The top case and serv. station body of the printer model 3 were made of the steel, and all parts within the modules of the two printer models had the same average life span of five years. These modules with similar or compatible materials make recycling easier. Besides, if components within a module have a similar residual lifetime, it facilitates maintenance, saves time and effort by not requiring further disassembly operations when replacing the module.

Also, note that some of the shared candidates were already composed in the form of modules, not individual components. In the previous study, all other parts were designed as individual parts except for the modules composed of IP-related (security) parts. This facilitates the redesign process because it is easy to distinguish and separate shared candidates from other parts.

4.4 Selection of Shared Candidates

The results of the selection of shared candidates between the printer model 1,2, and 3 are shown in Tab. 1. ESD spring and ESD blade are two components that are only for printer model 1. This is one of the features of the product family that

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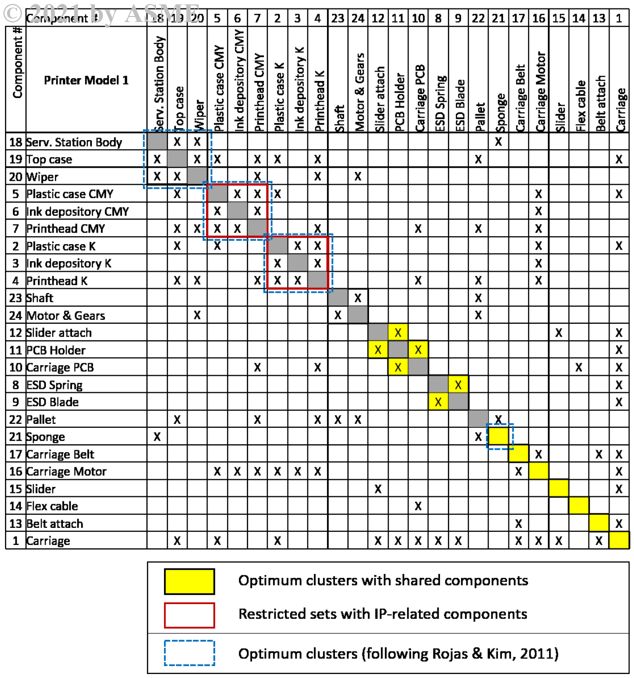

Fig. 5. Optimum clusters for the printer model 1

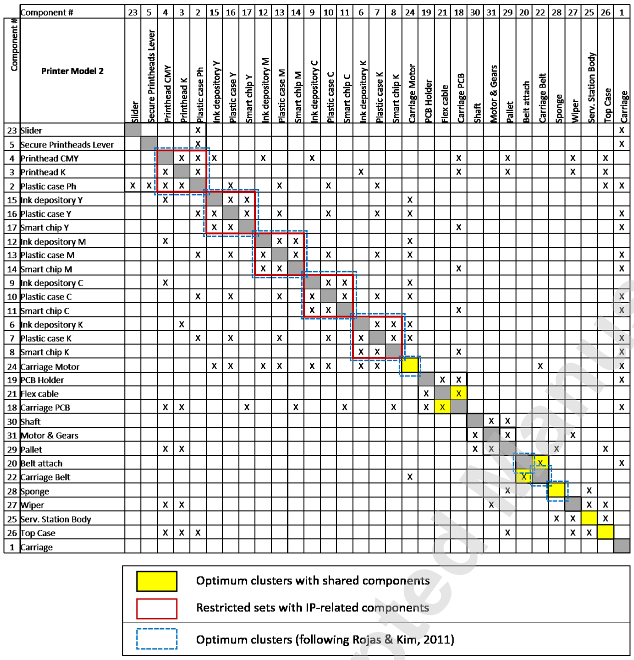

Fig. 6. Optimum clusters for the printer model 2

performs the same (or similar) function but can use different parts. It indicates the case that can be shared with the parts of printer model 3 that perform the same function (i.e., function 11: provide support for movement).

Table 4.4 shows the results of Rojas and Kim [5], which only considers security. Comparing the two results, components and modules with more potential value were selected as shared candidates when both sustainability and security were taken into account, rather than only security. The part that can be shared among the three printers was the sponge in the previous security-only paper, as shown in Tab. 4.4.

However, with this methodology, various parts, including the sponge were selected as candidates for common commonality: belt attach, flex cable, carriage PCB, carriage belt, carriage motor, and sponge (Table 1). Since sponges have fewer connections to other parts, the risk of a redesign can be small when sharing this part. However, since sponges are consumables, they are difficult to recycle, and the environmental impact that can be saved is insufficient. Considering not only security but also sustainability, many components that are not related to IP and can be effective in reducing environmental impact have been selected (i.e., composed of parts made of materials of high-value for recycling, such as aluminum and copper).

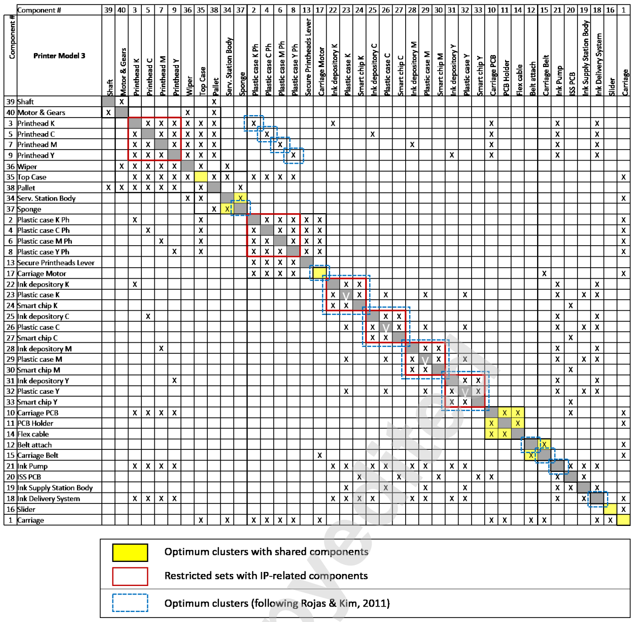

Fig. 7. Optimum clusters for the printer model 3

Commonality		Components
Variant	P1 & P3	Carriage, PCB Holder, Slider, Slide attach, ESD spring$^{(1)}$, ESD Blade$^{(1)}$
	P2 & P3	Serv. Station body, Top case
Common	P1, P2, P3	Belt attach, Flex cable, Carriage PCB, Carriage belt, Carriage motor, Sponge

(1) Component only used in P1

Table 1. Candidates for sharing based on the proposed method

4.5 Checking the Environmental Impact Saving

Commonality		Components
Variant	P2 & P3	Carriage belt, Carriage motor, Belt attach
Common	P1, P2, P3	Sponge

Table 2. Candidates for sharing based on Rojas & Kim [5]

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In this study, SimaPro software (version 8.5) [45] was used to model the product systems and to complete the environmental impact assessment. Within SimaPro 8.5, the ecoinvent database (version 3.4) [46], and the ReCiPe Midpoint/Endpoint (H) methodology [47] have been used to conduct the environmental evaluation according to the life cycle assessment ISO standard (14040:2006). Particularly, in the present study, the indicator of climate change (global warming potential, GWP100a) is used to quantify the carbon footprint associated with each potential module and associated components. For reference, the GWP100a is an indicator of how much heat is trapped in the atmosphere over a period of 100 years by greenhouse gases emitted by human-made activities. The GWP100a impact is expressed in terms of kilograms of carbon dioxide equivalent (kg of CO_2 eq.). The environmental impact includes the impact generated from the manufacture of the printer parts (processing of the components), as well as the impact from the extraction and production of all its constituent raw materials. Manufacturing processes are approximated using industry average processes for metal processing, and injection molding for plastic parts.

The target of environmental impact may vary depending on the nature of the product or the company's strategies and associated commitment to achieve sustainability-related goals. In this illustrative case study, the target value of total environmental impact saving (δ) was assumed to be the amount of carbon dioxide kilograms to be saved in the production process, which was estimated to be 100,000 (kg of CO_2 eq.). The estimated number of sales for each printer model was assumed to be 10,000 units each. The initial θ value was set to 0.1, and the final θ value satisfied the target of environmental impact saving was 0.6. The final environmental impact saving is 137,800 (kg of CO_2 eq.). Figure 8 shows the environmental impact saving that changes with θ (threshold level for the IM). As the value of θ increases, the selection of the candidates with values smaller than θ increases. As the number of shared components increases, the environmental impact saving will also increase. As shown in Figure 8, the final theta value in the case study was determined to be 0.6 as the target value of total environmental impact saving (δ) was set to 10,000.

5 CONCLUSION AND FUTURE WORK

The methodology developed in this paper, combining matrix-based tools with a new optimization algorithm, contributes to identifying optimal sustainable product family architecture design while protecting the security of IP-related parts. The methodology particularly enables the selection of shared candidates based on product architecture design. It aims to present product architecture design alternatives to companies that need to establish a sustainable design strategy for the environment while protecting their sensitive design and technology. The main contribution of this study is that security and sustainability, which are rarely considered concurrently in previous studies, are here incorporated together in the product family architecture design and commonality decision.

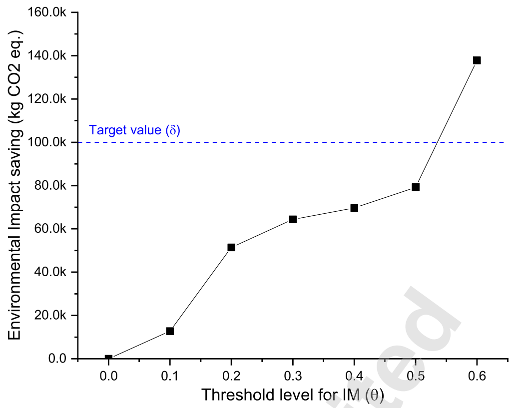

Fig. 8. Environmental impact saving change according to θ

A case study on a printer-product family is used to experiment and demonstrate the new methodology developed in this paper. This example is a first good illustration of how sustainability can be considered while keeping the security components in product family design. The initial findings validate the usefulness of the framework for designing product structures and selecting components in consideration of sustainability while meeting design constraints for IP-related elements. The results of the individual product architecture showed that the IP modularity was satisfied by encapsulating IP-related components contained in the restricted sets in the same module. Other components were modularized, considering the relationship between components, material, and life compatibility. Besides, the comparison between the present findings and the previous study [5] which considered only security, the proposed methodology for both sustainability and security identified and selected more parts and modules with higher potential values as shared candidates.

The proposed methodology can be used as a decision support tool to help product designers identify appropriate product family architecture design and find commonality candidates within a product family by considering sustainability and security. This study uses printers as an example of application but can be applied to various system analyses and designs, including security-critical military equipment, or industries that are designing high-value and technological products such as the aeronautic or spatial industries.

Future research can be oriented towards the application of various factors affecting commonality decisions. Currently, the difficulty of redesigning and the benefit of sharing in determining commonality are applied, but performance differentiation can be considered by applying a demand model for sharing component decisions. Furthermore, design for intellectual property in a context of remanufacturing or circular economy (e.g., closing-the-loop of product family through remanufacturing, reuse, or recycling, while preserving IP) is a promising line of future research to be explored to achieve more economic and environmental savings. Last but not least, to avoid negative impact transfers

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when redesigning product systems to mitigate the emissions of carbon dioxide (global warming potential indicator), complementary sustainability and circularity indicators have to be integrated and computed in future work [48].

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