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ORIGINAL ARTICLE

A systematic literature review of modular product design (MPD) from the perspective of sustainability

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Abstract Modular product design (MPD), as its name implies, subdivides complicated products and systems into components and considers them individually instead of as an amalgamated whole. Because of its merit in reducing complexity, MPD is widely used in engineering fields, especially in design engineering. Over the last decade, increasing concerns about environmental impact have driven manufacturers to reconsider their product design processes from the view of sustainability. The blending of these concepts—modularity and sustainability—has attracted significant attention from both academia and industry. The ways in which sustainability influences MPD are not fully understood, evidencing a gap that needs to be further researched. This review examines more than 100 studies addressing ways MPD is associated with sustainability factors and classifies these studies based on major sustainability themes. The initial review and analysis were conducted using literature summarization tables and a maturity index. Our search emphasized not only the performance of MPD methodologies with respect to sustainability factors but also the relationship between MPD and sustainability categories. Our review results indicate that from an academic perspective, research over the last 15 years has seen a significant increase in studies involving MPD and product life cycles, MPD and product innovation, and MPD and environmental management. Secondarily, our findings reveal that from an industry perspective, the literature shows that modularity has a positive impact on sustainability and identifies several social sustainability-related areas in MPD that could benefit from further investigation.

Keywords Modular product design (MPD) · Sustainability · Sustainable product design · Systematic literature review

1 Introduction

As time passes, our world becomes more and more complex. While continually investigating the nature of the world from the perspective of both micro and macro levels, we have collected and accumulated significant quantities of data. How do we analyze this complicated information? One common way is to reduce its complexity by decomposition, which splits the harder, larger systems into easier, smaller subsystems. By applying this philosophy inversely to design engineering, modular product design (MPD) has evolved. MPD involves clustering simple and small product components into more complex subassemblies, and then combining these subassemblies to create a complete product. In modular product architecture, each functional product component is implemented in exactly one subassembly, with few interactions between subassemblies [1]. Many practical advantages of modularity have been examined in recent research. MPD has been shown to increase manufacturing efficiency [2,3]; it can benefit the supply chain by reducing inventory cost and saving distribution time [4–8]. It can also satisfy the demand for mass customization [9–15].

Given the advantages of MPD, much research has been conducted in the literature. There are many ways to categorize the findings. Zhang and Gershenson [16] classified modular

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design methods into two groups: (1) matrix based and (2) function based. Matrix-based methods cluster product components based on matrix or matrix-related methods [17–23]. Function-based methods group product components according to independent functions [24–26]. Jose and Tollenaere [27] distinguished modularization methods into five categories: (1) clustering methods, (2) graph and matrix partitioning methods, (3) mathematical programming methods, (4) artificial intelligence methods, and (5) genetic algorithms and heuristics. Clustering methods group components into clusters according to similarities or differences in their design criteria [2, 20, 28]. The investigations of Kumar and Chandrasekharan [29] and Huang and Kusiak [18] can be incorporated under graph and matrix partitioning methods. Fan et al. [30] employed network graph methodology to solve the structure-oriented MPD planning. Kusiak and Wang [21] presented a mathematical programming method, which searches for modules through the use of linear programming. The work of Zhang et al. [31] discussed an evolving knowledge-based artificial intelligence technique for the modularization of components. Kreng and Lee [32, 33] proposed an MPD method that uses nonlinear programming to construct an objective function that is subject to certain constraints, and then using a grouping genetic algorithm heuristic to search for an optimal or near-optimal modular design. Yu et al. [34] developed a group genetic algorithm-based method to incorporate modular design and product life cycle assessment. Fujita et al. [35] combined genetic algorithm and a simplex method to solve the simultaneous design problem of module communalization strategies under the given product architecture and supply chain configuration.

Recently, the trending focus in MPD is sustainability, due largely to the fact that the environment and environment-related issues have increasingly become a matter of concern. Sustainable development, as the World Commission on Environment and Development (WCED) defined it more than a quarter century ago, is “meeting present needs without compromising the ability of future generations to meet their needs” [36]. More recently, the US Environmental Protection Agency described sustainability as “the satisfaction of basic economic, social, and security needs now and in the future without undermining the natural resource base and environmental quality on which life depends” [37]. Sandborn and Myers [38] modified the definition of sustainability from a more technical vantage point, stating that sustainability means keeping an existing system operational and maintaining system field versions such that the original requirements are satisfied. Based on this definition, they classified sustainability into three broad groups: environmental, business or corporate, and technology. An additional popular categorization includes economic sustainability, environmental sustainability, and social sustainability [39, 40], and proponents suggest sustainability should consider these three factors simultaneously. Figures 1 and 2 show the details for each of these factors and their overlapping regions.

By combining and redefining the elements from Figs. 1 and 2, sustainability indicators and their corresponding major themes are summarized in Table 1. In each table cell, key items associated with major sustainability factors or their intersecting factors are listed.

With respect to the definition and categories of sustainability, how does research take sustainability into account in MPD? While there is no literature answering this question directly, some literature discussed sustainability partially, either in environmental or economic terms, and mostly in relation to product design [41–44]. Gungor and Gupta [41] presented the development of Environmentally Conscious Manufacturing and Product Recovery (ECMPRO) and provided a state-of-the-art survey of related work. The ECMPRO has been divided into several layers, including Environmentally Conscious Manufacturing (ECM), Materials & Products Recovery (M&PR), etc. Within each of these categories, sublayer items exist. For example, ECM has Environmentally Conscious Manufacturing General Discussion (ECMGEN), Environmentally Conscious Design (ECD), and Environmentally Conscious Production (ECP). The relevant product design papers were discussed with respect to each of these categories. As a complement of Gungor and Gupta’s work, Ilgin and Gupta [42] added evolution of ECMPRO research after 1998. They categorized literature into four major groups: environmentally conscious product design, reverse and closed-loop supply chains, remanufacturing, and disassembly.

In their state-of-the-art review of product family and platform concepts, Jiao et al. [45] discussed modularity focusing on cost and profit implications. On the other hand, Otto and Wood [43] discussed reverse engineering-based design approaches and summarized the literature with respect to their environmental friendliness. Pigosso et al. [44] summarized eco-design approaches with concentration on integration of several “end-of-life” strategies and remanufacturing. Ljungberg [46] defined the characteristics of sustainable product development as the following:

- Reduce the materials and the usage of energy for a product, including life cycle services
- Reduce the emissions, dispersion, and creation of toxic elements during the life cycle
- Maximize the amount of recyclable materials and renewable resources
- Maximize the useful life of a product
- Minimize the service intensity for a product and its services
- Minimize the environmental impact over the product’s lifetime
- Increase product efficiency in its life cycle

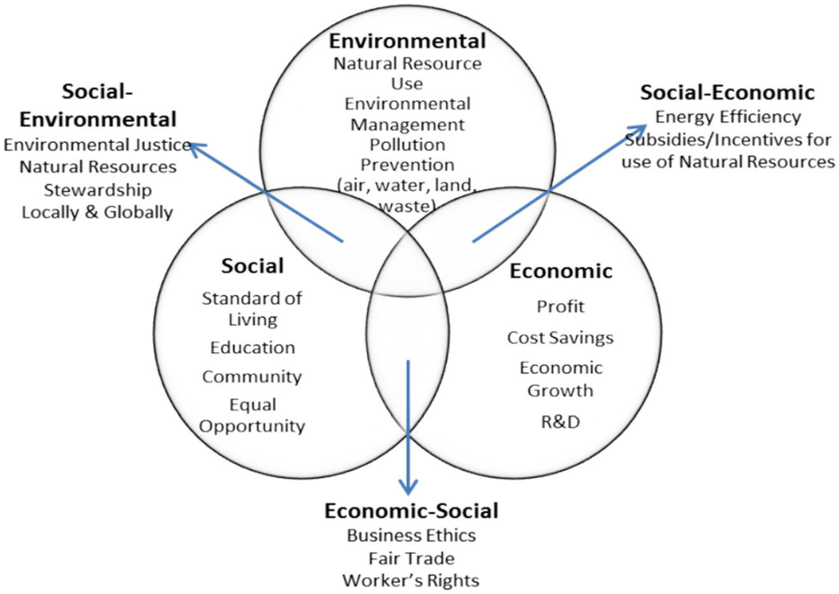


Fig. 1 Three spheres of sustainability—version 1 (adopted from Rodriguez et al. [39])

Ljungberg [46] identified the ideal product according to sustainability; however, the definition considers only environmental and economic factors along with their related indicators, such as life cycle management, profit, and cost saving, while it ignores any social indicators. In addition, it describes only general product design and does not really focus on MPD. Finally, Ljungberg's definition does not consider how each sustainability indicator affects the MPD independently. Therefore, there is a need to organize and summarize the ways in which these significant indicators influence MPD both separately and aggregately.

2 Literature search methodology

The popularity of combining sustainability and MPD is evident in a review of the literature. Based on our investigation using the database "Compendex," the number of papers in this field has steadily increased during the last two decades. Figure 3 shows this trend, based on a search using the keywords "sustainability" and "modular product design."

We searched the literature related to both indicator subjects in the Compendex database, combining the autostemming

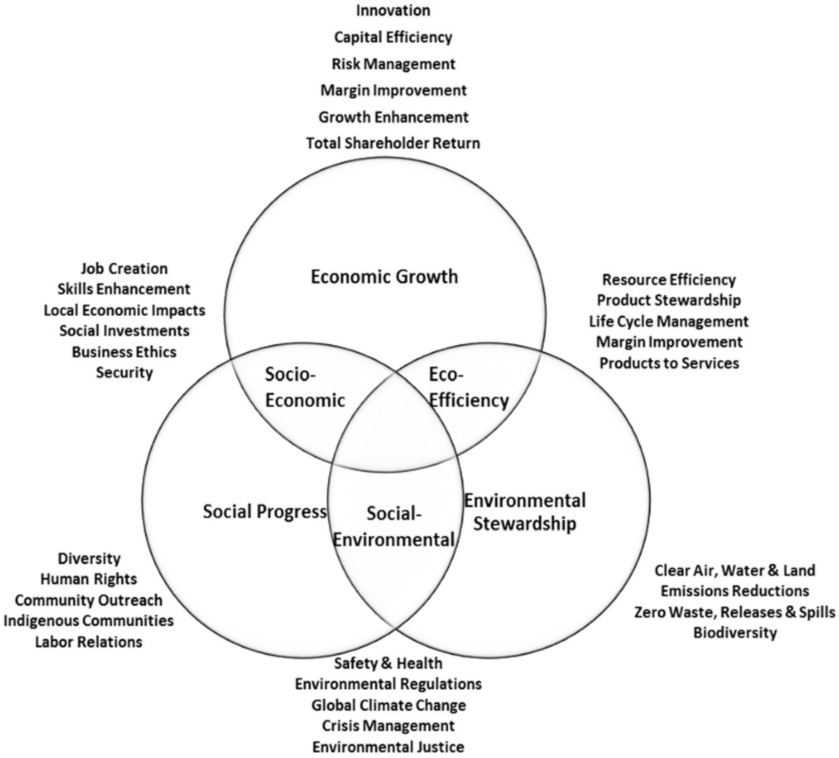


Fig. 2 Three spheres of sustainability—version 2 (adopted from Geniescafe, http://geniescafe.tumblr.com/)

Table 1 Sustainability indicators and major themes

Sustainability indictors	Economic	Eco-environmental	Environmental	Social-environmental	Social	Social-economic
Major themes	Risk management; profit; cost saving; product innovation	Energy efficiency; life cycle management	Emissions reduction; environment management; environmental assessment; natural resource management	Safety and health; global climate change	Human diversity; human rights; labor relations	Customer ethics; security

function and limiting the date range from 01 January 1980 to the present. For example, to search for product innovation, we used the keywords *modular product design* and *product innovation* and located 116 papers. The majority of papers addressed other domains and did not connect to our main concern. To narrow down the fields, we refined the search by selecting only the classification codes *product design* and *product development*, which yielded 67 papers, many of which were also irrelevant. Therefore, we continued to pare down the field by incorporating the controlling vocabulary to include *industrial engineering and management*, *product engineering*, and *industrial economics*, and 65 papers remained. Using the same method, we collected the data for all the major theme-related papers. We tabulated them as shown in Table 2 by time period, category, and corresponding keywords.

3 Sustainability literature review

In this section, MPD literatures are critical reviewed in terms of sustainability indicators. The review is presented in accordance with the six sustainability indicators shown in Table 2.

3.1 Economic sustainability literature

3.1.1 Product innovation

Product innovation is a sustainable economy theme which focuses on improving product performance by taking innovation into account. One of the most commonly used definitions of product innovation is product newness, which can be operationalized as newness to the customer, to the firm, or to the industry [47]. According to Garcia and Calantone [48], when considering product innovation, both marketing and technological perspectives as well as macro-level and micro-level perspectives should be considered. For instance, MPD as a creative design method has been widely accepted as a way to benefit product innovation without making heavy sacrifices in development time and cost [1]. Therefore, we classify innovative methodologies of MPD into this product innovation group.

Lau [49] researched MPD from the perspective of the managerial side and addressed the whole supply chain. He identified seven critical factors for exploring the management of MPD and subsequently developed a strategic guide for use in analyzing and improving product innovation related to MPD. Lau's seven factors are as follows: (1) predefined product advantage, (2) selectively used design rules, (3) module definition, (4) system integration, (5) technological newness, (6) internal communication, and (7) supplier and customer involvement. The managerial guide Lau derived for MPD elaborates on those seven factors, based on these six criteria:

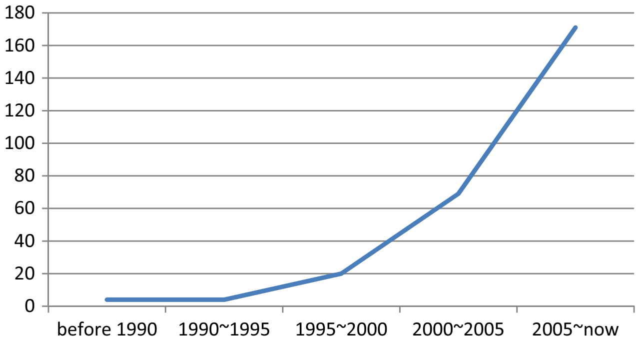


Fig. 3 Sustainability and MPD publications

(1) product modularity decisions, (2) MPD at the product level, (3) MPD at the organizational level, (4) internal coordination of MPD, (5) supplier coordination with MPD, and (6) customer coordination with MPD.

The guide Lau [49] generated focuses on MPD from a managerial perspective and can benefit both industrial and academic fields. However, the work does not provide a specific management method for MPD itself, and therefore, it can only be judged as a guideline. Moreover, it is based on one critical assumption that MPD is positive relative to product innovation. In a subsequent work, Lau proves this assumption to be only partially correct.

Lau et al. [50] investigated the impact of product modularity and internal integration on competitive capabilities. Product modularity relates to each component's separateness, specificity, and transferability within the product assembly. Internal integration is defined as the business processes that integrates internal functional units needed to improve overall corporate performance. Competitive capabilities include product innovation, low price, product quality, delivery, flexibility, and customer service. Lau et al. used multiple regression analysis on data from 251 manufacturers in Hong Kong. Their results show that both product modularity and internal integration have positive impacts on all competitive capabilities except low price and that the interaction of internal integration and product modularity has a significant effect on both product innovation and product quality.

Although Lau et al. [50] identified several relationships associated with competitive capabilities and found that product modularity and internal integration, as well as their interaction, are positively related to product innovation, their work is based on empirical data that may not represent all situations. Competitive capabilities involve many issues, of which product innovation is only one. Their regression analysis for product innovation failed to account for associations with other competitive capabilities issues and focused only on product innovation. Their later work shows a reversal of results between product innovation and product modularity.

Lau et al. [51] conducted two pilot studies to narrow down the research area emphasizing the relationship between

Table 2 Sustainable modular product design papers reviewed

Sustainability indicator	Indicator major themes	Before 1990	1990~1995	1995~2000	2000~2005	2005~2013	Total	Keywords
Economic	Product innovation (PI)	1	0	0	15	34	50	MPD + product innovation
	Risk management (RM)	0	0	4	4	7	15	MPD + risk management
	Profit (P)	0	0	2	3	2	7	MPD + profit
	Cost saving (CS)	0	1	2	9	22	34	MPD + cost saving
Eco-environmental	Energy efficiency (EE)	0	0	0	0	4	4	MPD + energy efficiency
	Life cycle management (LCM)	0	0	4	37	82	123	MPD+ life cycle management
Environmental	Emission reduction (ER)	0	0	0	1	3	4	MPD + Emission reduction
	Natural resource management (NRM)	0	0	2	0	1	3	MPD + natural resource management
	Environment management (EM)	0	0	1	17	26	44	MPD + environment management
	Environment assessment (EAss)	0	0	0	5	6	11	MPD + environment assessment
Social-environmental	Client safety and health (CSH)	0	0	0	1	2	3	MPD + client safety and health
	Global climate change (GCC)	0	0	0	2	1	3	MPD + global climate change
Social	Human diversity (HD)	0	0	0	0	1	1	MPD + human diversity
	Human rights (HR)	0	0	0	1	5	6	MPD + human rights
	Labor relations (LR)	1	0	1	0	1	3	MPD + labor relations
Social-economic	Security (S)	0	0	1	9	13	23	MPD + security
	Customer ethics (CE)	0	0	0	0	2	2	MPD + customer ethics

product innovation and product modularity. They measured product modularity according to product component separateness, specificity, and transferability, and they measured product innovation according to product newness. Following a statistical analysis on these two studies, they found that product modularity has an inverted U-shaped relationship with product innovation. The positive and negative impacts of product modularity on product innovation are summarized in Table 3.

Lau and colleagues [51] pointed out that modularity initially has a positive relationship with innovation; after a certain point, however, higher modularity will lead to a decrease in innovativeness. They found that product innovation has a positive effect on new product performance. Interestingly, they also found that while product modularity does not have a significant impact on new product performance, it can affect new product performance by affecting product innovation. Conclusively, the work of Lau et al. shows how product modularity affects product innovation and provides insights that could guide design decision-making. However, further modeling and validation is needed to arrive at generalizable relationships.

Some researchers have developed new and creative MPD methodologies to improve product innovation. Yen and Smith [52] proposed a product design method to form modules by applying atomic theory modeling. They modeled a product as an atom and product modules or components within the product as electrically charged objects within the atom; they then calculated Coulomb forces between positively charged and negatively charged objects within the products to establish relationships between every pair of objectives. They then used a touch-matrix to record physical relationships between components and integrated the design constraints into a distance matrix. Their work provides a new perspective of module forming. It also overcomes the limitations of the widely used group genetic algorithms (GGA) in MPD, which involve easily reaching unreasonable solutions and dramatically increasing computational time with increasing product complexity.

The theory of inventive problem solving (TRIZ) offers another reliable method for increasing product innovation. Its underlying idea is that invention has logical rules and principles that lead from problem to solution. To achieve this basic goal, TRIZ offers a system involving abstract principles and laws that can be merged together with a huge number of collection of facts and examples into a readable application [53]. There are several TRIZ-related MPD methods which incorporate the primary TRIZ theory. Regazzoni and Rizzi [54] proposed a road map for complex MPD based on the combination of modular function deployment (MFD), TRIZ, and design structure matrix (DSM). Their new design paradigm was built on the scheme of MFD based on Ericsson and Erixon [55], which consists of five steps:

1. Collect and formalize customer requirements (via quality function deployment, QFD)
2. Analyze and select technical solution (via Pugh matrix and function decomposition)
3. Define modules (via the module interface matrix)
4. Evaluate modules
5. Optimize modules

Regazzoni and Rizzi [54] pointed out and responded to certain drawbacks to the original MFD. In step 1, QFD is hard to determine, because assessing the real needs of customers by simply asking them to guess their "wants" and "wishes" rarely yields complete satisfaction. Therefore, Regazzoni and Rizzi decided to incorporate human-centered design (HCD) during step 1 of their process. In step 2, the Pugh matrix has two significant disadvantages: first, the results obtained rely strongly on expert experience and understanding of the problem; and second, psychological inertia limits engineers to the set of known solutions and leaves out new ideas. To overcome this drawback, Regazzoni and Rizzi adapted a TRIZ-based analysis that incorporates a function tree diagram, a TRIZ functional model, RCA+, and a RelEvent diagram. In step 3, the original MFD uses module drivers and Module Indication Matrix (MIM), although module drivers do not consider basic interactions among components. Therefore, Regazzoni and Rizzi applied DSM to the analysis in this step. Steps 4 and 5 of the original MFD were deemed viable. Subsequently,

Table 3 Positive and negative impacts of product modularity on product innovation

Positive impact	Negative impact
Product modularity helps manufacturers accelerate product innovation. Modular product architecture facilitates designers to find a superior solution. Modular design may facilitate radical innovation. Firms tend to standardize the product module and interfaces for economies of scale. Modular product design facilitates the injection of external innovative sources into the internal product innovation process.	Product innovation is often introduced in a nonmodular form. Different development teams concentrate on designing specific innovative modules, resulting in less coordination with each other, reducing knowledge sharing between/among the different teams. A product modularization process usually generates a large number of separate and specific modules to be selected by users or developers to create new products.

Regazzoni and Rizzi proposed a new road map for MPD involving these five revised steps:

1. Collect and formalize customer requirements (via HCD)
2. Choose technical solution (via TRIZ-based analysis)
3. Define modules (via DSM)
4. Evaluate modules
5. Optimize modules

Regazzoni and Rizzi's [54] work shows a TRIZ-based MPD method that is creative and one that could improve product innovation. However, they did not provide a specific method for module forming.

Davis et al. [56] proposed a systematic and biomimetic-based design method to aid designers in generating postmarket module concepts for a given platform. The concept of a postmarket module is based on a discussion of Baldwin and Clark's [28] one of six modular operators: augmenting. Using the concept of a postmarket module, Davis et al. applied the factors of *host product* and *derivative product*. A host product is a basic product platform, and derivative products refer to the postmarket modules added to the product after it is sold to the end user. Three guidelines were set to align the derivative product and the host product: (1) usefulness depends on host product, (2) the derivative product does not replace a similar function already existing in the host product, and (3) the derivative product should have a novel function or design. With those guidelines as a basis, Davis et al. developed a seven-step MPD-based design methodology complying with symbiotic principles found in nature. These seven steps are as follows: (1) host product functional modeling, (2) modularizing the host product, (3) translating to biologically meaningful keywords, (4) searching with biosearch, (5) aggregating results, (6) identifying results for analysis, and (7) examining and translating results.

The work of Davis et al. [56] provides a useful method to illustrate the coordination of a design method and symbiotic principles. However, translating design keywords to biological keywords determines whether or not the design meets with success or not and the methodology for performing that translation requires more detail.

Because an integrated use of diverse methods for product design has the potential to bring about certain benefits, Tsai et al. [57] presented another unique combination analysis method, using a computer-supported model to aggregate MFD, the theory of inventive problem solving (TRIZ or TIPS), and case-based reasoning (CBR) to aid in MPD. They use MFD to collect and transfer customer demand into possible modules, TRIZ to identify potential conflicts and resolutions between possible modules, and CBR to provide analogous design cases for inventive problem-solving reference. The drawback of Tsai et al.'s method is that it relies on QFD, a disadvantage identified previously with respect to Regazzoni and Rizzi [54].

Another series of research papers put emphasis on sequential product innovation with an emphasis on product modular upgradability [58–61]. These papers focused on product architecture development related to product market performance. Because the results were geared toward saving cost or increasing profit, we discuss them in the cost savings Subsection 3.1.3 or the profit group Subsection 3.1.4.

In summary, this body of literature suggests that MPD affects product innovation through views of marketing and technology, and both have a positive influence on product innovation. Therefore, MPD is an appropriate method for use to achieve product innovation improvement.

3.1.2 Risk management

Risk management related to sustainability issues associated with MPD aims to anticipate and reduce operating risk. Simon et al. [62] proposed a nine-step plan to address risk management: define, focus, identify, structure, ownership, estimate, evaluate, plan, and manage. Smith and Merritt [63] proposed an abbreviated five-step process: identify, analyze, prioritize and map, resolve, and monitor. An innovative and popular method for risk management analysis is risk diagnosing methodology (RDM) proposed by Keizer et al. [64]. The following steps illustrate the outline of this method.

Risk identification

- Step 1: Initial briefing between project manager and risk facilitator
- Step 2: Kick-off meeting: project manager and team and risk facilitator
- Step 3: Individual interviewing of participants by risk facilitator

Risk assessment

- Step 4: Development of a risk questionnaire by the risk facilitator
- Step 5: Answering the risk questionnaire by participants
- Step 6: Constructing the risk profile by the risk facilitator

Risk response development and control

- Step 7: Preparing risk management session by project manager and risk facilitator
- Step 8: Risk management session: project manager and team and risk facilitator
- Step 9: Drawing up and execution of risk management plan

Wang et al. [65] observed that general risk management methods such as RDM could be used in risk management for MPD with certain modifications. Their research focused on risk management in collaborative MPD and identified four significant risk areas:

- Risk management process problem
- Partner selection risk
- Coordination problem
- Information communication problem

This identification of risk types related to collaborative MPD may help narrow down the known and unknown risk areas during the planning stage and may help improve risk management efficiency in the MPD process.

In summary, although the literature about economic risk management and sustainability is not as robust as that for product innovation and sustainability, it does raise issues for consideration. Risk management is an application of modularity in project management that primarily addresses risk reduction, intended to control and minimize risk in complicated environments.

3.1.3 Cost savings

As a primary concern of sustainability, the element of cost savings has attracted increasing attention. This section discusses the literature related to the impact of MPD on supply chain costs and on product development and production costs. That MPD could lower supply chain costs is evident, because it can reduce inventory costs and save distribution time [1, 5–7]. However, the way in which MPD lowers the cost of product development and production is somewhat obscure. The connection is made through product variety. The increasing demand for product variety from customers forces companies to concentrate on product families rather than on single products; however, high product variety will greatly increase administrative and manufacturing costs as a result of the need for more specialized materials, processes, and quality control [66]. MPD is one of the approaches used to save costs and still offer a variety of products [67, 68].

Lau and Yam [69] conducted research on the relationship between MPD and supply chain design/coordination in a case study involving a large-scale audio consumer electronic manufacturing firm in Hong Kong and China, examining the impact of MPD on its total supply chain costs. The findings are summarized as follows:

- The supply chain of the MPD has one more level than the integrated product design supply chain, because MPD requires reconfiguration of an existing supply chain.
- For both modular and integrated product design, an innovative product requires more supply chain coordination than a conventional product since conventional product modules or components are available in the market.
- Product modularization with close supply chain design or coordination lowers the inventory level, improves the product quality, and reduces development lead time.

Evidence suggests that MPD associated with close supply chain design/coordination could both improve product performance and reduce development lead time, therefore saving certain development costs. Although Lau and Yam (2005) illustrated the relationship between MPD and supply chain design/coordination, there still exist limitations in their research; specifically, all three propositions are derived from a single case study which is not enough to validate the evidence; in addition, the case study focuses on a specific large-scale electronics firm, which may reflect unique, nontransferable industrial characteristics for the derived propositions.

Ernst and Kamrad [5] proposed a conceptual framework for evaluating product supply chain structures through product modularization and postponement. They defined modularization as inbound logistics, related to combining different components or modules to assemble the final product. Postponement is associated with outbound logistics, because it is through the distribution function that specific customer demand is satisfied. Both inbound and outbound logistics influence MPD. Therefore, based on the classification of modularization (inbound logistics) and postponement (outbound logistics), Ernst and Kamrad introduced a structured supply chain framework as shown in Fig. 4.

In Fig. 4, *rigid* represents a traditional vertical supply chain structure where the objective is to maximize economy by keeping a high level of finished products inventory. *Flexible* represents the opposite supply chain structure, in which different components are produced and stored so that different products can be assembled in response to specific demands. These two supply chain structures show two opposite and extreme cases. *Modularized* and *postponed* supply chain structures represent intermediate cases. Modularized structures involve having multiple sources for components, and the assembly output generates a finished product. Postponed structures entail a single source for components, and various assembly outputs are made according to different demands.

Ernst and Kamrad [5] used total costs to evaluate these four supply chain structures using a mathematical model. Their results show that different structures are effective in different cases. Although they proposed this framework to identify these structures and evaluate them in terms of costs, their model is limited to comparing vertical or horizontal structures only. In addition, the framework analysis is based solely on an empirical study.

Kim and Chhajed [68] developed a model to analyze market entry timing for modular products and to determine how much modularity should be offered. They used MPD as an

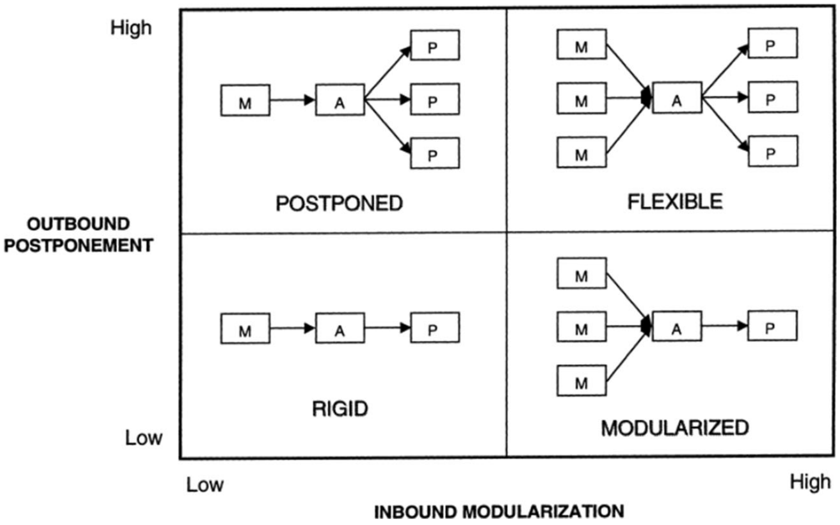


Fig. 4 Framework of supply chain structure. *M* manufacturing, *A* assembly, *P* packing (adopted from Ernst and Kamrad [5])

approach for product platform design to improve commonality among product variants. They posited that higher commonality will lead to product cannibalization as well as lower costs, since commonality would decrease production costs but make the products more indistinguishable from one another. A model was built to assess trade-off cost savings and product cannibalization through two types of cannibalization problems commonly associated with MPD for two product classes: a low market segment and a high market segment. High commonality products correspond to the low market segment, while low commonality products are related to the high market segment. The model Kim and Chhajed generated provided a framework to find the commonality conditions that help firms to increase revenue and also showed that product similarity would lead to product cannibalization. While Kim and Chhajed's [68] work provides a trade-off between modularity level and market performance, it is based on two assumptions: one, a product can be represented by a single dimension (quality); and two, the total market is divided into high and low segments, and there is no middle segment between them. Therefore, more investigation is needed.

Product modularity can enhance the agility of a manufacturing system. It allows manufacturing systems to be built under the high product customization as well as low product development time. Kahoo and Situmdrang [67] investigated this angle from the perspective of impact of product modularity on assembly configuration. They developed an immune algorithm approach to tackle the design for assembly problem in modular products. The immune algorithm is based on principles of natural immune systems. In comparison to heuristic algorithms and genetic algorithms, the immune algorithm is better in terms of convergence trends, distribution of near-optimal solutions, and quality of solutions. A mechanical pencil assembly case study showed that the immune algorithm outperforms a genetic algorithm and a heuristic algorithm in terms of convergence and computational efforts. However, the case study is simple and may not adequately provide a medium for comparisons; more complex case studies are needed to further demonstrate the benefits of this algorithm.

Sand et al. [70] developed a new modular design method named House Of Modular Enhancement (HOME) for product redesign in order to assist the reconfiguration of products, reducing design and manufacturing lead time, as well as improving the ability for upgrading, maintenance, customization, and recycling. The authors analyzed product functional requirements, product architecture, and life cycle requirements and came up with corresponding functional structure matrix (FSM), product architecture matrix (PAM), and life cycle matrix (LCM). By integrating these three matrixes together, modular information matrix (MIM) was developed, and then MIM is transferred to enhanced modular information matrix (EMIM) through radial axis method (RAM) to categorize components into modules. The HOME method combined three design criteria into a matrix by using matrix operations. The primary drawback of this approach is in the matrix forming stage. For example, in the life cycle matrix, the authors only considered service, reuse, and recycle, which cannot represent the entire product life cycle. Service is corresponding to maintenance; reuse and recycle are only part of end-of-life treatment.

MPD is logically associated with cost savings, and therefore, the level of modularity in product architecture is also directly related to cost savings. Several measures have been used to evaluate measures of modularity. Mikkola and Gassmann [60] summarized these measures as shown in Table 4.

In addition to compiling and classifying the papers given in Table 4, Mikkola and Gassmann [60] proposed a new mathematical model to measure modularity in terms of the degree of modularity, called the *modularization function*. The degree of modularity depends on the extent of (1) economies of substitution of components across product families [77]; (2) disaggregating and recombining the system into new

Table 4 Summary of measures of modularity (adopted from Mikkola and Gassmann [60])

Authors	Purpose	Approach and method
Ulrich and Pearson [71]	To measure the manufacturing content	Product archeology—an approach to gather objective data for product development research
Ulrich et al. [72]	To estimate the impact of different design alternatives on the net economic benefit of a product	Economic model to illustrate the relationships among DFM, lead time, and profit
Fisher et al. [73]	To examine variation in component sharing practice and to identify factors that can explain the variation	Mathematical model (complemented with optimization, simulation, and regression analysis)
Ulrich and Ellison [74]	To develop a theory to explain when a firm can benefit from designing product-specific components	Regression analysis based on survey on engineered, assembled goods
Collier [75, 76]	To measure the effect of components standardization on aggregate safety stock levels and service levels	An analytical measure of product structure termed "the degree of commonality index"

configurations, or mixing and matching [77]; and (3) a system achieving greater functionality through components [78]. Mikkola and Gassmann took into account the following variables for determining the degree of modularity: components, degree of coupling, and substitutability of new-to-the-firm components. These variables are related to product architecture. Table 5 lists these product architecture elements and their related managerial implications.

Mikkola and Gassmann [60] derived a modularization function and a sensitivity function such that:

$$M(u) = e^{-u^2/2NS\delta}$$

$$S_u^M = \frac{u}{M}\frac{\mathrm{d}M}{\mathrm{d}u} = -\frac{u^2}{Ns\delta}$$

Where:

$M(u)$	is the modularization function
S_u^M	is the sensitivity function which shows sensitivity of the modularization function $M(u)$ with respect to the new-to-firm (NTF) component composition u, u is the number of NTF components
N	is the total number of components
s	is the substitutability factor, and
δ	is the degree of coupling.

The functions capture the complexity of product architecture designs from the perspective of the specific firm. These functions are of benefit to both academic research and practice. For academic researchers, the functions help derive the theoretical test causal linkages of the variables, as they shape the product architecture to modular or integral. For practitioners, the functions can help them analyze various managerial and strategic implications of architecture design decisions. However, these functions are derived based on several assumptions, noted by Mikkola and Gassmann [60] as follows:

- The functional specifications of components, including interface specifications, do not change over time.
- The product architecture comprises a combination of standard and NTF components.
- NTF components impose higher technological risks and greater interface compatibility issues with other components within the product architecture.
- All standard components, NTF components, and interfaces are equally critical.

Ray and Ray [79] proposed an investigation to show how a combination of existing and newly innovative component technologies could be used to create a modular product that would meet the price requirements and demand for innovation in a market in India, using a case study of Tata Motors. They found that collaboration with suppliers about component design and its early integration in the design phase could substantially lower costs and help eliminate unnecessary frills

Table 5 Elements of product architecture (adopted from Mikkola and Gassmann [60])

Elements of product architecture modularity	Managerial implications
Standard components	Economies of scale; cost savings; specialization; development of capabilities; standardized interface specifications
NTF (new-to-the-firm) components	Technological risk; product novelty; superior performance; limited imitation; long NPD lead time; nonstandardized interface specifications
Degree of coupling	Synergistic specificity; identification of critical components; tightness of coupling among components
Substitutability	Economies of substitution; component sharing; product variety; upgradability

while still incorporating features valued by the mass market. Their work shows the importance of integrating suppliers and customers into the design phase. However, their research work was based solely on a market in India, and all the data are drawn from that Indian market; thus, the overall conclusions are limited to this set of market constraints and demands.

Hopp and Xu [80] proposed a mathematical model to show the impact of MPD on the length of product line and price. They separated the total operation costs into product development costs and production costs, and they represented customer demand using a Bayesian logic model. They showed that reducing cost had a positive impact on both product line length and product market share for different producers, such as reducing both product development cost and production cost could increase both product line length and market share for risk-seeking producer. They noted the impact of degree of modularity and production costs on price markup and market share, observing that production cost reductions will increase price markup, and the degree of modularity improvement will influence the price markup. Hopp and Xu's [80] work illustrated how MPD affects product line and price. However, their work left potential space for improvement. Their conclusions are based on the assumption that there are no economies of scale in production and distribution, and the procedures focused on reducing product development costs by sharing components. All the conclusions Hopp and Xu reached are limited to monopolistic markets.

Ramachandran and Krishnan [61] presented a model combining product innovation and MPD that is intended to facilitate decision-making associated with pricing and timing for managing the introduction of rapidly improving products. They analyzed a merger of modular product architecture and product introduction time in order to maximize company profit and reduce customer costs by considering the modular product installing and upgrading costs, both of which fall under product development costs. Ramachandran and Krishnan also defined three systems for modular upgrading: (1) the proprietary modular upgradable system (MP) represents the case in which customers must buy improving and stable modules from the same firm, (2) the nonproprietary modular upgradable system (MN) represents the situation in which customers can buy improving and stable modules from different firms in the open market, and (3) the proprietary integral system under which a firm provides integral products with inseparable improving and stable modules. By considering installing and upgrading costs, they derived optimal price formulae for these three systems. Ramachandran and Krishnan's [61] work shows how the integration of product innovation and MPD may be affected by pricing and timing management related to product introduction. However, marginal production costs are ignored and only product development costs are considered.

In summary, the literature shows that MPD has a positive impact on both the supply chain and product development cost savings when certain production activities are performed simultaneously.

3.1.4 Profit

Profit is also a crucial theme related to sustainability. Profit is equal to total revenue minus total costs; therefore, cost savings generate increased profit. However, profit increase is not only due to cost savings. Thus, we addressed the literature related to profit and cost savings separately.

As manufacturing competition has restricted high profitability and added external constraints, design for multiple products or product variety design has become increasingly essential. Fujita and Yosshida [81] presented a product variety optimization method for both module combination and module attributes of multiple products. The proposed approach combined genetic algorithm, mixed-integer programming, and constrained nonlinear programming. The methodology was composed of three optimizations with respect to three layers: commonality and similarity pattern, similarity directions, and module attributes.

The proposed product variety optimization method has investigated three layers of product modularity optimization and an individual optimization method is provided for each layer. The primary drawback for this research is that three different optimization methods are applied for the same product; the consistency of each method should be checked through implementations on a broad array of products.

Fixson and Park [58] demonstrated the relationship between product architecture, innovation, and industry structure using the case of a bicycle drivetrain system. They added *integrating* as a new design operator in the product architecture, along with *splitting*, *substitution*, *augmenting*, *excluding*, *inverting*, and *porting* [28]. The common belief suggests that product architecture migrates more toward modular structures in the long run, while the case study shows the reverse—that product architecture tends to become integral in the long run and that the corresponding industry tends to act like a monopoly. The integration in the long run is beneficial for industrial competition and for profit. Fixson and Park's [58] work reaches a distinct conclusion about modularity and industry competition (and hence profit) over the long run, which brings a new concern to discussions about product architecture and competition. However, their work is based only on one industry and is particular to one case study.

Lau et al. [82] conducted an empirical study about the impact of MPD on competitive capabilities and performance. They measured and categorized competitive capabilities by low price, product quality, delivery, flexibility, and customer service. All these items relate directly to firm profits. In their later papers (i.e., [50, 51, 83]), they presented related hypotheses and then regressed data to model and conclude. Those conclusions were as follows: product modularity does not have a significant positive relationship associated with low price and product quality; product modularity has a positive relationship associated with delivery, flexibility, and customer service; delivery and flexibility have a positive relationship with product performance; and low price, product quality, and customer service do not have a significant positive relationship with product performance. As reviewed, Lau et al. [82] identified the relationships between MPD and competitive capabilities and performance that could help managers select sufficient competitive capabilities to improve the company's competitiveness and profit level. However, generalizability of the observations from these studies is limited.

Krishnan and Ramachandran [59] found that the firm's preference for product modularity in the early period will vanish in later periods; they termed this condition *design inconsistency* and posited that it would reduce the firm's profit and customer surplus. To remedy this problem, Krishnan and Ramachandran proposed a modular upgrading guideline for integrating design decision and pricing decisions in order to optimize firm profit and customer surplus. They modeled the firm's decision (architecture) and the customer's decision (pricing) by separating product modules into either stable or improving subsystems that could be upgraded to enhance customer appeal based on quality preference. They found that careful coordination between design decisions and pricing decisions could enable the firm to commit to a future price that the customer would find credible. Krishnan and Ramachandran's [59] work was intended to help enhance profits for emerging firms, established markets, dynamic markets, and demand uncertainty cases. However, this study is based on the assumption that product quality is evaluated by a single dimension, which greatly limits its application.

Das and Chowdhury [84] proposed a reverse supply chain planning process associated with MPD. Their work is based on two advantages of MPD: reduced lead time [7] and ease of manufacturing [2]. They considered returned products collection: the recovery process in the total supply chain. They categorized returned products as products' after use (end-of-life or before end-of-life), products returned under warranty, defective products, obsolete products returned by a retailer, and products returned by customers. The collection of returned products entails third party logistics, such as a collection center opened by the manufacturer, remanufacturer, or retailers. The returned products can re-enter the market after recovery. This reverse supply chain categorizes products into three levels: products that use all new components/modules, products that use a mixture of new and recovered components/modules, and products that use only recovered components/modules. Once these categories were defined and the relevant data generated, Das and Chowdhury analyzed profit maximization using mixed-integer programming.

Das and Chowdhury's [84] model involving reverse logistics in the supply chain considers three different products based on recovered components/modules consideration. This contribution fits very well into the real marketplace. However, their study considers the retailer as the most *efficien*t collection option and third party logistics as the most *effective* recovery option, and there may be a negative correlation between these two options. In addition, they assume that product cost has a positive relationship with module numbers, while it instead may depend on the number of modules.

Mukhopadhyay and Setoputro [85] treated MPD as a competitive tool for build-to-order (BTO) because it could positively influence customer return policy and also reduce lead time and production costs, hence influencing profits. They considered three factors related to maximizing profit: return policy, modularity level, and product price, focusing primarily on the first two factors. They theorized that customer demand is positively related to profit; therefore, they used customer demand as an intermediary to build the relationship between these three factors and profit. Based on their results, they identified several conditions under which both return policy and modularity level should increase: one, the market is more sensitive to return policy or modularity; two, the sellers want to decrease product development costs; three, the sellers want to salvage more; and four, the constant market price is increasing. Mukhopadhyay and Setoputro's [85] work provides a guideline for increasing profit in the BTO business. However, their model is empirically derived, and their demand function is a linear one of return policy, modularity level, and price. Their conclusions are based on the assumption that these three elements are all positive in relation to customer demand, lacking proof and verification. Also, the market price in this work is set (unrealistically) as a constant.

Following up on the limitations of Mukhopadhyay and Setoputro [85], Konstantaras et al. [86] conducted research extending the 2005 study by taking selling price of BTO into account as another main variable. They considered two extreme conditions: no customer refunds at one end and full refunds for customers at the other. The conclusions they reached echoed those of Mukhopadhyay and Setoputro [85], except in the case of the full refund. Full refund case showed that return rate is positively and linearly related to modularity level and inversely and quadratically related to optimal price.

Ulku et al. [87] evaluated MPD from the customer's perspective. They designed a series of three experiments, based on elements of psychology, marketing, and behavioral economics, to show how customers responded to MPD. They analyzed the survey data using ANOVA to generate results. Their findings suggested the following: (1) customers tend to discount cost at a high (low) rate associated with MPD with short (long) upgrade intervals, (2) the firm's total profit could be improved by charging a low (high) initial price and high (low) upgrade price for products with short (long) upgrade intervals, and (3) the attractiveness of a modular upgraded product is higher in the short term than in the long term.

This work yields insights that could help firms to integrate customer opinion during product design; yet, further verification is needed.

Wu et al. [88] investigated how to increase MPD-related profit from the perspective of component reuse-redesign and product launch time. They added reuse-redesign as a factor in new product development. Based on their model, they reached these conclusions: (1) firms should upgrade every component for new products to generate more profit when development costs are negligible, otherwise reuse components for new products; (2) a launch time postponement for new products could improve product quality when design teams have low product-development productivity; and (3) an earlier (old) version of a product should be removed from the market when the marginal cost of the new product is equal to that for the earlier (old) product. This work was intended to help design teams evaluate whether to apply reuse or redesign techniques to a modular product for a succeeding generation of the product. However, their model was built around the ideal assumption that each component is uniquely associated with a single product attribute. Therefore, to make this model more practical, that assumption should be removed during a model modification.

Dong et al. [89] proposed a flexible MPD optimization model to help resolve conflicting criteria: satisfying mass customer demands and controlling economies of scale. Their work proposed the use of two flexibility levels to fulfill mass customer requirements: embedded options for small adjustments and evolution within the overall structure of product design for radical adjustments. The model included six submodels: an engineering model, a cost model, a value model, a demand model, a price model, and a profit model. These were integrated using the common elements of internal/external input and output. Some creative aspects of the work of Dong et al. [89] include the evaluation of flexibility in product design using real options and the application of geometric Brownian motion to model uncertainty demand.

Since a product family evolves from the construction of a product platform, and a product platform could incorporate MPD, we categorized product family papers into this modularity/profit category. Kumar et al. [90] proposed a novel product family design method that focuses on total profit optimization from the aspect of market share. They adapted Meyer and Lehnerd's [91] market segmentation grid (MSG) and a nested logit demand method to derive a product family design methodology. The market segmentation grid divides the market into submarkets, with market segment as the horizontal coordinate and product performance/cost as the vertical. Each product in the product family corresponds to one segment of the grid in MSG; competitor's products could also be located in the MSG. The demand model based on nested logit is associated with engineering attributes, socioeconomic and demographic attributes, and price. Product performance and cost models are built to trade-off between product performance and cost in conjunction with the demand model. Kumar et al. used the information provided from these models with a profit optimization function to derive the optimized product family design. Their methodology can be summarized in four steps: (1) build an enhanced market segment grid, (2) generate a demand model, (3) generate product performance and cost models, and (4) optimize the product family.

The market-driven product family design model from Kumar et al. [90] takes market issues into account in the product family design, which fits the customer-driven design trends. It also considers profit, which fits the firm's most important requirement. However, there are limitations and potential for improvement in this work, such as how to convert the market data in a reasonable and correct way into a demand model. In addition, the computation required by the model is extremely complex, which means the algorithm still has potential for improvement.

Asan et al. [92] considered future market uncertainty and proposed a scenario-based management method for function-based MPD, in order to maximize future profits. They believed that MPD flexibility could enhance success related to uncertainty in the market. Their management approach is as follows: (1) identify the future market needs, (2) translate those needs to modular design objectives, (3) design MPD methods, and (4) evaluate the MPD process. The work of Asan et al. [92] considers future market uncertainty and, based on this consideration, derives a management approach for MPD. However, their description of capturing future needs is not precisely clear, which may cause some confusion in efficiently applying their method.

To summarize the findings of this section's findings, MPD is positively related to profit increase without cost savings being involved, which means that when properly applied, MPD can generate more revenue in the market.

3.2 Eco-environmental sustainability literature

3.2.1 Energy efficiency

Energy efficiency-related MPD addresses modular design from the perspective of energy consumption, with the goal of using energy effectively and efficiency. Because no literature was found combining the theme of energy efficiency and MPD, we propose that the design criteria should be set to minimizing energy usage rate and minimizing energy waste.

3.2.2 Life cycle management

Life cycle analysis is regarded as one of the most important and efficient eco-environmental management tools. Life cycle management considers how MPD affects the entire life cycle, including product design stage, product updating, and product end-of-life options. Many MPD-based tools have been developed in this area of study such as green design, module updatability, design for End-of-Life (DfEOL) options, and reverse supply chain design. In this section, the literature was divided into two parts: whole life cycle and end-of-life options. Whole life cycle refers to all phases that a product goes through, including design, manufacturing, assembly, service, maintenance, and recycling [93, 94]. End-of-life options address the last phase of the entire life cycle, generally including reuse, recycle, and disposal [95]. The former group discusses how MPD affects entire life cycle (e.g., [33, 34, 96–101]); the latter group focuses on how to deal with retired products (e.g., [19, 95, 102–104]).

Gonzalez and Adenso-Diaz [105] developed a bill of materials-based approach to determine product/component end-of-life strategy. They considered reuse, recycling, and remanufacturing as three good end-of-life options for reducing environmental problems from landfills. The methodology was built based on product structure (obtained from bill of materials) and the joining and geometrical relationship among components (obtained from 3D CAD representation). The proposed approach addressed not only the product/component end-of-life option but also the most profit disassembly sequence. The scatter search metaheuristic was employed to determine the disassembly cost at each level of bill of materials. Overall, Gonzalez and Adenso's [105] work presented a new end-of-life option determination approach with bill of materials consideration, which is a new angle of design for environment. They also applied scatter search metaheuristic algorithm to estimate disassembly cost. However, the scatter search requires more calculation work, and some other alternative algorithm might be better in terms of cost evaluation.

Li et al. [95] proposed a fuzzy graph-based MPD method with product life cycle consideration. They summarized the relationship between life cycle performance and modularity of a product into objective levels as shown in Fig. 4. The overall objective relates to the aggregate value, which represents the total life cycle performance of the MPD component. The objectives are divided into four subfactors: disassembly, reuse, material selection, and serviceability. These are further decomposed into lower level criteria, such as energy and standard time in disassembly, human factors and facility factors in serviceability. Based on the level of objectives, Li et al. created an index for each subobjective and applied analytic hierarchy process (AHP) to aggregate and derive a life cycle performance index. They set up the objective functions to minimize intercluster distance and maximize extracluster distance by taking the index information and fuzzy graph product representation into account, and adopted a K-ordered greedy clustering algorithm to form modules.

This work by Li et al. [95] provides a framework of design for environment (DfE) based on fuzzy graph application. However, when calculating index of life cycle performance, the authors did not rank the four subfactors, which means that all have equal importance. In addition, they did not provide a calculation of serviceability index. Finally, their discussion is based on the entire life cycle performance perspective, but the title of this research implies a focus on end-of-life issues, which is slightly misleading.

Gao et al. [106] presented a gray system theory-based clustering method to perform subassembly identification. Usually black and white are used to represent completely unknown and completely know information, and gray is between black and white, meaning partially known information. The approach categorized components into groups according to gray-based adjacency relation within a product and end-of-life options. Four clustering indices were developed based on rough estimation and direct input from a CAD system, including disassembly energy consumption index, disassembly time index, disassembly direction index, and diameter of part pair index, which were used to come up with information to cluster. This approach explored the subassembly identification problem. The authors considered the incomplete information or the vague environment in the design phase and provided the systematic suggestions to deal with the uncertainty in the design stage. However, since the gray system theory-based approach is employed, it is necessary to prove that the method resulted in appropriate decisions. Also, additional work is needed to illustrate the efficiency of this methodology.

Lai and Gershenson [102] proposed an MPD analysis method from the perspective of the product retirement process, represented by two aspects: similarity and dependency. They considered postlife intent (recycle, reuse, and disposal), material compatibility, and components connection type/disassembly direction as factors for quantifying similarity sequentially. They considered accessibility, disassembly force, positioning, tool requirements, material handling, and fastening to quantify dependency. Based on their quantification of similarity and dependency, Lai and Gershenson set the objectives as maximizing component similarity in modules and minimizing component dependency out of modules; then they applied a design structure matrix (DSM)-based clustering method to form modules. Lai and Gershenson's [102] work quantified similarity and dependency by forming a design matrix, which shows a metric view for evaluating the product retirement process. However, for the quantification of similarity, they did not give a specific method to rank and show the importance order of three factors (postlife intent, material compatibility, and components connection type/disassembly direction). In one example, they assumed postlife intent > material compatibility > components connection type/disassembly direction. Therefore, based on their method, which lacks a ranking technique, an evaluation of similarity may come up with several different results.

Tseng et al. [103] proposed a disassembly-oriented assessment method for MPD in four stages by considering economic performance from recycling. The liaison intensity was used to quantify the connection relations among components in stage 1; the grouping genetic algorithm (GGA) was employed to modularize product to be recycled in stage 2; at stage 3, the disassembly cost and recycle profit of modules were estimated; and an interference matrix was developed to specify the disassembly sequential order of product modules and parts.

In this work, Tseng et al. [103] provided a systematic evaluation method for the economic performance in green design. They primarily concentrated on application of MPD in assembly and came up with positive suggestions of cost/profit by analyzing the entire process of assembly. The four-step assessment methodology is well organized and can be applied to real practice. However, a major disadvantage lies in the liaison intensity quantification. They evaluated component interactions roughly and subjectively, and a more robust and objective quantification way is needed to improve this methodology.

Newcomb et al. [100] explored the application of product modularity to design for the life cycle practices. They defined and analyzed product architecture characteristics with respect to life cycle concerns. The eventual product module structure was formed by architecture decomposition algorithm. They still provided two modularity measures to analyze product modularity: one is correspondence ratio (CR), which is used to measure module correspondence between several viewpoints, and another is cluster independence (CI) that measures coupling between modules. This work investigated the impact of product modularity on life cycle engineering. The life cycle concerns were analyzed and the decomposition algorithm was employed to form product modules. In addition, two indexes were developed to explore the internal and external characteristics of product modularity. However, the overall measure of modularity relies on subjective weights.

Gu and Sosale [97] proposed an integrated MPD approach for the life cycle engineering. They summarized eight MPD objectives related to life cycle engineering: dividing design task for parallel development, production and assembly improvement, standardization, services, upgrading, reconfiguration, recycling, reuse and disposal, and product variety and customization. These eight objectives provide a guide for MPD, and designers should identify the relative importance of these objectives and achieve life cycle goals accordingly. The MPD methodology is composed of three phases: problem definition, interaction analysis, and module formation. The simulated annealing algorithm is employed to cluster components into modules based on component interaction information.

Gu and Sosale's [97] work provided a comprehensive approach to accommodate many life cycle objectives by developing a simulated annealing algorithm-based MPD methodology. In addition, they still presented two ways to tackle conflict objectives in MPD. One is forming modules based on each objective separately and then making trade-off decisions; the other is modularizing products based on weighted average objectives. However, there are still drawbacks in their research. The primary one is that interaction analysis is not clear enough, and lots of subjective evaluations, such as weights and components mutual interaction analysis, are needed; thus, the methodology result (module structure) strongly depends on external assessment.

Bryant et al. [96] presented an MPD-based redesign tool which reduces part count and improves the life cycle impact of a product. They combined functional-based MPD with an elimination preference index (EPI) metric to measure the life cycle impacts of a design. Based on the functional modules of a product, Bryant et al. considered six life cycle factors (assembly time, part necessity, ease of component handling and manipulation, ease of component insertion for assembly, recyclability, and dismantle-ability) to quantify and assess life cycle. They calculated EPI values to form an EPI metric, where the components with high EPI values are candidates for elimination and low EPI value components are those with potential to improve the environment impact. The work of Bryant et al. [96] applied EPI to measure and assess life cycle impacts and quantify the disassembly of a product. However, the six life cycle factors are summarized based on an empirical study and may change for different products. In addition, the method is shown to work well with a product having a small number of components; for a product with a large number of components, more investigation is required.

Kreng and Lee [33] proposed a QFD and linear integer programming (LIP)-based MPD method. They believed that all MPD methods should consider some of the following modular drivers as design objectives: carryover, technology evolution, planned product changes, standardization of common modules, product variety, customization, flexibility in use, product development management, styling, purchasing modularity components, manufacturability refinement and quality assurance, quick services and maintenance, product upgrading, recycling, reuse, and disposal. Based on QFD, Kreng and Lee divided MPD into two phases: a modular driver selection and modular design. In the first phase, customer requirements, company requirements, and design requirements are transferred and summarized as modular drivers. In the second phase, Kreng and Lee derived a LIP model based on two relationships: modular driver and components, and component and component, with the idea that MPD should maximize similarity within a module and minimize interaction among modules. Based on the calculation of LIP, modules were formed. Kreng and Lee's [33] work aggregates market's requirement and competitive strategies into a modular design, which originally includes only physical and functional relationships in terms of modular drivers. However, QFD makes it difficult to correctly determine all the real needs of the eventual customers because simply asking the most important customers to guess their "wants" and "wishes" rarely yields complete satisfaction [54].

Seliger and Zettl [101] presented a life cycle-oriented modularization methodology based on module drivers and specifications, and a corresponding software tool was also proposed. The methodology was developed based on conceptual product model supported by modularization criteria, nine module drivers, and corresponding tasks. The module configuration was operated by a developed software tool. The basic idea of the software tool is the generation of module configurations by allocating at least one functional carrier to a module considering relevant module driver specifications.

Seliger and Zettl's [101] work provided a framework of module structure selection based on several design criteria consideration. Multicriteria decision-making (MCDM) and mix-integer programming (MIP) are employed in developing this methodology and software tool. However, the methodology development lacks information, and the case study does not illustrate the entire process very well.

Yan et al. [104] proposed a new sustainability-oriented MPD method. The authors took several sustainability issues into account, such as society, economic, environment, material, manufacturing, and end-of-life options. A quantitative sustainability assessment method was provided to constrain the design criteria. Figure 5 shows the assessment attributes. A kernel-based fuzzy c-means algorithm was used to integrate components of a product into different modules based on their correlation distance. Meanwhile, a genetic algorithm was employed to determine the optimal clustering number, based on its efficiency in coming up with global solutions. The work of Yan et al. [104] combines several sustainability factors into MPD analysis. However, their work is based on a limited empirical study and requires additional investigation (Fig. 6).

Ji et al. [98] proposed an effectiveness-driven modular design method in order to solve the problem that different module forms are required due to the diverse design objectives of different phases. The effectiveness of each module is regarded as the ability of a module to fulfill the expected objective at a certain phase of the entire life cycle; phases include design, manufacturing and assembly, service, maintenance, and recycling. Ji et al. took all possible effectiveness scenarios of all life cycle phases into account and balanced the granularity and compositions of modules during the clustering process. They used a product descriptive model, which is composed of components, interaction attributes, and a liaison graph as a basis for determining effectiveness-driven modular design. The interaction attribute shows a relationship between two components. Table 6 summarizes all interaction attributes during the life cycle; the liaison graph represents a product structure that includes all interaction attributes. They applied a quantitative split method to the liaison structure to cluster components into modules. Then with all effectiveness scenarios considered, they used three aggregation rules to maximize and finalize the effectiveness of modules.

The work of Ji et al. [98] attempted to combine all life cycle phases and derive an appropriate module-forming method. However, they did not provide any ranking method or guidelines for weight determination in each phase, and attributes are randomly assigned. In addition, they only considered

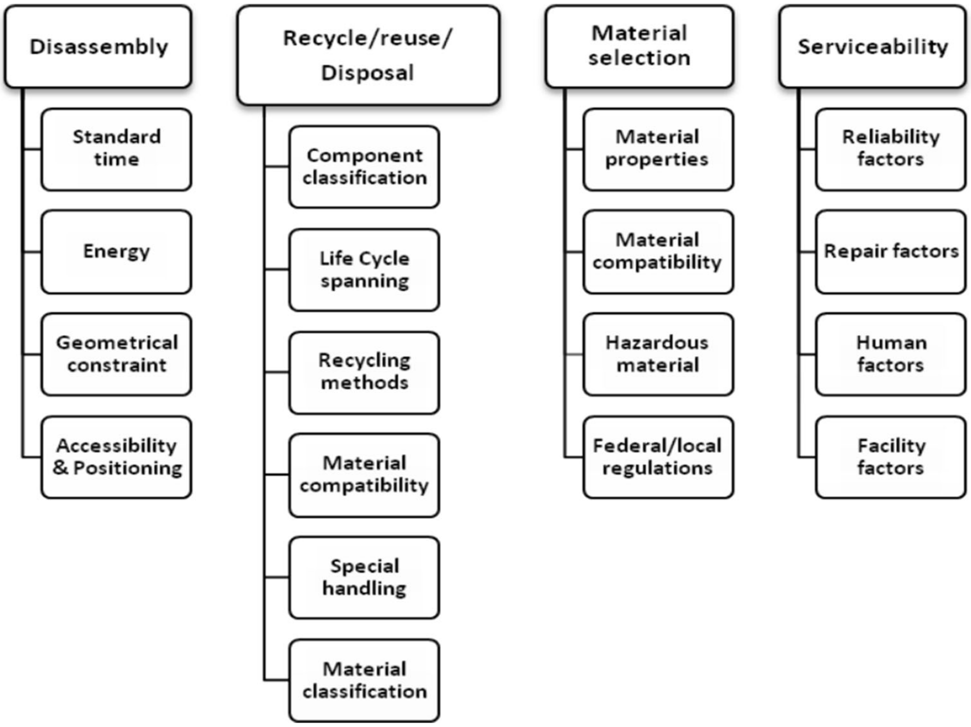
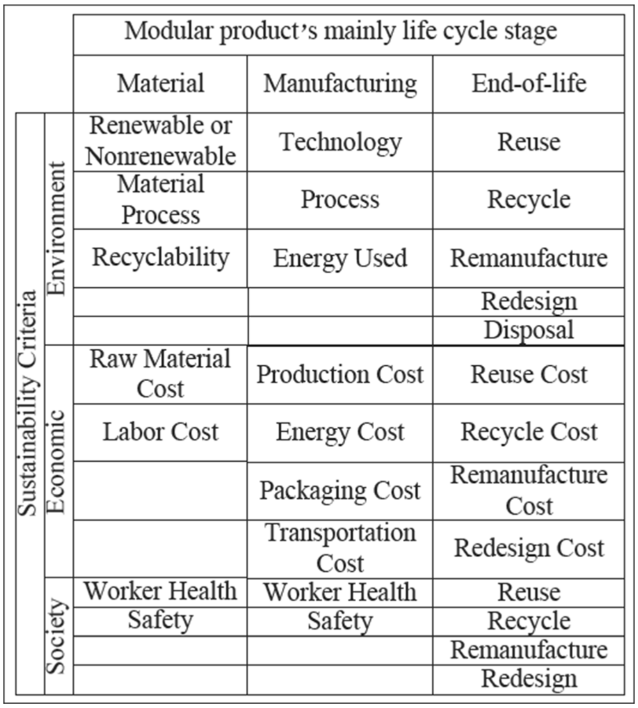


Fig. 5 Life cycle objective structure for modular design (adopted from Li et al. [95])



		Modular product's mainly life cycle stage		
		Material	Manufacturing	End-of-life
Sustainability Criteria	Environment	Renewable or Nonrenewable	Technology	Reuse
		Material Process	Process	Recycle
		Recyclability	Energy Used	Remanufacture
				Redesign
				Disposal
	Economic	Raw Material Cost	Production Cost	Reuse Cost
		Labor Cost	Energy Cost	Recycle Cost
			Packaging Cost	Remanufacture Cost
			Transportation Cost	Redesign Cost
	Society	Worker Health	Worker Health	Reuse
		Safety	Safety	Recycle
				Remanufacture
				Redesign

Fig. 6 Sustainability issue and modular product life cycle stage (adopted from Yan et al. [104])

recycling during the last phase of the product life cycle, which is partial. Reuse and disposal should also be considered.

Tseng et al. [99] proposed a green life cycle-driven MPD method. They observed that product use and recycle or disposal options are the main determinants of a green life cycle. To conduct the research, they used a liaison graph model with four types of engineering attributes to represent the product structure. These engineering attributes include contact type, combination type, tool type, and access direction. Based on the liaison graph, Tseng et al. derived an index, liaison intensity (LI), to show component relationships. Then they adapted Falkenaur's [107] GGA to cluster components into modules based on the liaison graph information. The GGA was used to overcome several limitations of traditional genetic algorithm (GA), such as the need for module numbers and module size to be set a priori. Tseng et al. also balanced the green design and cost issue by comparing pollution value and total cost. The pollution value was calculated using Simapro as the eco-indicator. The goal of green product design could theoretically be achieved by replacing materials and updating liaison intensity continuously, based on the initial module results in their GGA analysis.

The work of Tseng et al. (2008) provides the framework of green life cycle-based MPD, and designers could apply this framework to reduce assembly time and control life cycle cost. However, their approach to green design is based on replacing and updating component materials and structure continuously, which is not efficient. In addition, like other methods that use GGA (e.g., [32, 108]) exhibit, a significant problem is that when the number of components in a product increases, computational time increases dramatically.

Ji et al. [19] developed a MPD-related methodology to facilitate life cycle material efficiency by considering component material reuse and minimizing resource commitment throughout the product realization process. They emphasized on leader-follower joint optimization and leveraged technical system modularity (TSM) and material reuse modularity (MRM) and, therefore, proposed a comprehensive framework. They employed modularity metrics taxonomy to measure component interaction and grouped into modules accordingly. Multiattribute utilities of different dimensions of component similarity were used to quantified and aggregated modularity measures. A bilevel constrained genetic algorithm was put forward for the joint decisions of TSM and MRM.

The work of Ji et al. [19] is motivated by material efficiency improvement from the view of life cycle, which is different from most traditional MPD methods' low-cost concentration. The only possible drawback is that genetic algorithm might require huge computation efforts when component number increases.

Umeda et al. [94] proposed an MPD methodology for aggregating product life cycle-related attributes and component/module geometric feasibility. They employed self-organizing maps (SOM) to integrate product life cycle attributes, such as life cycle options (LCOP), materials, and physical lifetime. The SOM was used to cluster components into groups based on the similarity of life cycle attributes. Umeda et al. took geometric feasibility into account by introducing several indexes, such as combination, density, and connection. These indexes were used to show the relationships between

Table 6 Attribute list for all life cycle (adopted from Ji et al. [98])

Phase	Interaction attributes
Design	Transverse service level; longitudinal service level; upgrade level; customer participation level
Manufacturing and assembly	Manufacturing location; assembly location; process
Service	Value lifetime; upgrade level
Maintenance	Value lifetime; maintenance frequency; maintenance technology level
Recycling	Material compatibility; value lifetime; material value; eco-indicator; processing mode

components in the same groups formed by SOM. The work of Umeda et al. [94] takes both product life cycle and component/module geometric feasibility into account during module forming. However, their method requires the designer to set the number of modules in advance, which may not optimize the module design.

Based on the MPD methodology of Umeda et al. [94], Umeda et al. [109] provided a life cycle evaluation method for MPD from the perspective of resource efficiency in order to clarify the effectiveness of modularity on environmental consciousness. They introduced an index, resource efficiency (RE), which represents the resource time length of utilization per amount of resource consumed in whole product life cycle, to evaluate the modular structure. Since life cycle options have a great impact on modular structure forming and since certain external factors such as labor costs will affect the life cycle options, there is equilibrium between life cycle costs and environmental load. Umeda et al. introduced probability for life cycle options of modules to represent this equilibrium. They applied the probability function to each module and derived the RE value for each product. They found the higher the RE value, the better the product life cycle was. Therefore, designers could improve RE value by removing or inserting module components.

The work of Umeda et al. [109] provides a useful evaluation method for modular design with life cycle consideration. However, their work is based on the assumption that a product's lifetime is equal to the lifetime of the product component with the shortest life. In addition, they emphasized only components in modules and ignored single components.

Smith and Yen [110] employed atomic theory-based MPD method from their earlier work (2009) and added green design constraints such as material compatibility, part recyclability and part disassemblability to form a unique green design method. In it, a module represents a subassembly of a product and is formed by considering component spatial locations, structures, and life cycle options. They developed a touch matrix based on atomic theory and defined green objectives as design constraints, allowing them to form modules. This work provides a new green MPD method which overcomes limitations of GGA and DSM modularity design related to computational time and number of components.

Koga and Aoyama [111] investigated ways to balance the long life cycle of product and market change from the view of modularity. They did not adapt traditional analysis such as modular updating to conduct the research. Instead, they tried to predict the market change in the life span of product family, and based on the estimation of that change, they developed a modular product family design method. They assumed that the market change is modeled as a quantity change of sold products; setting life cycle and product sale scenarios as input for product family design, they then drew a product family graph. Koga and Aoyam's [111] work aggregates product life cycle and market change issues in product family modular design. However, their work focused solely on product family graph drawing while overlooking ways to predict market change and to form modules specifically.

Cebon et al. [112] conducted research on the impact of product modularity on the product life cycle. They observed that many product life cycle theories (related to technical innovation, marketing, strategy, and product development) are based on the assumption that products are integrated wholes. However, the modularization of products undermines specific synergies and aggregation. The arguments of Cebon et al. suggest that the product life cycle will be dramatically altered and attenuated if a product has full, nonspecific synergy between modules and subsystems. Although this work investigates the relationship between product modularity and product life cycle, only suggestions for basic guidelines are provided.

Chung et al. [113] proposed a robust modular architecture methodology based on life cycle assessment from the perspective of the supply chain. The authors evaluated product life cycle from the views of life cycle cost (LCC) and life cycle energy consumption (LCEC) in a closed-loop supply chain. They initialized modular architecture elements using a physical connectivity graph involving component attributes (vertices) and component interactions (edges). A supply chain optimization model was developed and could be used to evaluate any possible modular architecture structures in terms of LCC and LCEC. Starting from an initial modular architecture, a robust modular structure could be derived by evaluating the supply chain model heuristically. The work of Chung et al. [113] provides an optimal module-forming method based on an evaluation of supply chain and sustainability. However, using the heuristic method for analysis requires significant computational time.

Shin et al. [114] proposed a product concept selection methodology based on extended QFD and mixed-integer nonlinear programming (MINLP) with the consideration of life cycle and resource allocation. They collected data on customer requirements and product life cycle requirements from an extended QFD and then used these data to form the MINLP constraints. The MINLP objective was to maximize product design satisfaction according to the degree of design qualities for engineering characteristics, incorporating the customer and product life cycle requirements from the extended QFD. Investment budget figures and resources (such as number of human resources or software licenses available) were also constraints. Greedy algorithms and net search algorithms were used to find the optimal solutions for MINLP, identifying robust product concepts.

The work of Shin et al. [114] combined QFD and MINLP to search for an optimal product concept by considering both life cycle and resources. However, that their work contained several uncertainties in the conceptual stage may suggest that some optimal values derived from this method might be questionable. The proposed approach may be regarded as a one-time approach for generating an optimal product concept.

Overall, MPD can improve product life cycle performance by allocating cluster components into modules from the view of the entire life cycle. The key feature of the current analysis is the application of optimization algorithms or methodologies across the product life span.

3.3 Environmental sustainability literature

3.3.1 Emissions reduction

Emissions reduction related to sustainability considers how to apply MPD methodology to reduce emissions. Some green design methods are categorized into this group.

Dai et al. [115] proposed a modular-based green design method for use at power plants for considerations of effective emission reduction, effective water-saving, and an effective control system. They considered several design criteria, such as an optimized plan layout of the factory area, an optimized co-location of auxiliary machines, minimized pollutant emission levels, and minimized water consumption. Based on the resulting design criteria, they proposed some multiobjective optimization functions. The work of Dai et al. [115] briefly introduced the application of modular-based green design in a power plant and provided a guideline for power plant construction. However, their work was based on a rough discussion and no details were provided.

To summarize, MPD plays a role in green design and can be associated with multicriteria design-making methods to satisfy the requirement of emission reduction.

3.3.2 Environment management

Environment management considers how to apply MPD methods in managing environment issues. This field focuses on ways to provide benefits to the environment from the view of modules. Certain green product design methods are categorized under this group.

Luh et al. [116] developed a systematic managerial methodology combining environmental regulations and economic considerations by taking both green and nongreen variants into account at the same time. They found that the major challenge in the development of green and nongreen products in a mixed manner is to manage, maintain, and generate the bill of materials (BOM) effectively and that product modularity is a useful tool to help solve this problem. Luh et al. aggregated product modularity with generic product architecture to effectively manage green and nongreen product data within one modularized BOM representation. The integration was accomplished using product data management. An LCD TV family was used to illustrate the process. A set of guidelines is provided here for small- and medium-sized enterprises (SMEs) to meet strict environmental requirements in an economical way. However, their work is limited to specific SMEs, such as electronics enterprises; further research is needed to investigate the performance of the proposed methodology in other SMEs and industrial sectors.

Wang et al. [117] proposed an environment-related MPD method. They applied QFD in relation to green design, a process known as green quality function development (GQFD), and derived customer requirements associated with environment requirements. They transferred customer and environment requirements into design criteria and then adapted a DSM to cluster components into optimized modules based on comparative algorithm and loop analysis. The work of Wang et al. [117] proposed a new MPD method for linking modularity with environment consideration, fitting the recent trend of environmental sustainability concerns. However, the method has only been applied to the analysis of a small number of components; to determine its applicability for use with a large number of components, more research is required.

In summary, modularity and green design analysis involving optimization methodologies for managing the environmental impact are sparse; this area requires further investigation.

3.3.3 Environmental assessment

Environmental assessment addresses ways to assess the environment from the perspective of modularity. In this field, modular product design is treated as a useful tool to evaluate environmental performance, such as developing a higher rate of reuse or recycle components, resulting in a higher environmental assessment. The end-of-life option directly affects environmental assessment.

With regards to increasing concern of pollution and now more common use of modularity in product design, Qian and Zhang [118] developed an assessment approach to evaluate modular designs in products. The fuzzy analytic hierarchy process (FAHP) was employed to evaluate and rank all considered environmental criteria, including usage life compatibility, technology life compatibility, material compatibility, maintainability, geometric connection, disassembly time, disassembly energy, and assemblability. The fuzzy numbers were used to combine uncertain judgments of decision makers with crisp numbers, and a comprehensive framework was built based on similarity and independence analysis of each modules. Qian and Zhang's [118] work presented a systematic approach to evaluate the environment performance of modular designed products from the view of the entire life cycle. They considered uncertainty of perceptions from decision makers as well as eight environmental indices. The major drawback of their work is the life cycle they considered is not comprehensive. The end-of-life strategy, such as reuse, remanufacturing, and recycle, should be taken into account in environmental impact assessment. In addition, the manufacturing environment performance should also be considered within the design phase.

Fitzpatric et al. [119] concentrated on the concept of modular digital electronic circuits based on programmable logic device technology and examined the suitability of an eco-design methodology based on reusable modular units. The eco-design methodology focuses on incorporating the reusable subsystems or modules into the current generation of products and future generations. They discussed the general concept of eco-design and applied their analysis in a study using an electronic device. However, their work focused only on eco-design from the perspective of one electronic device; more general product examples must be investigated to show the broader advantages of eco-design.

Further research on MPD associated with end-of-life strategy management could help develop a useful tool to assess environmental impact.

3.3.4 Natural resource management

Natural resource management emphasizes utilizing natural resources efficiently and effectively by applying MPD methods. Modular product design has a positive impact on natural resource management primarily because people could control and consume natural resources according to different product modules. In reality, people can group high natural resource using parts into the same module and consider them together to improve natural resource usage efficiency.

3.4 Social-environmental sustainability literature

Social-environmental related MPD covers client safety and health, including global climate change. Client safety and health-related issues require that products have high rates of reliability and are not harmful to clients. Global climate change literature could be expected to emphasize how MPD affects long- and short-term weather changes. We found no research papers focused specifically on these fields. However, we imagine that MPD in client safety and health should focus on reliability within and between modules, thus ensuring client safety. MPD's relation to global climate change might be seen in emissions, and therefore, we imagine that related research should focus on how to reduce pollution and how to minimize carbon footprints.

3.5 Social sustainability literature

3.5.1 Human rights

Human rights consider how modular product design affects human basic rights, such as right to no discrimination, respectability, and survival. The only way to take human rights into account in MPD is involving customers in design stage.

Lau [83] conducted research exploring what contextual factors affect supplier and customer involvement altogether and how such involvement affects new product performance. Lau applied a structural equation model to analyze survey data from 251 manufacturers in Hong Kong, finding that MPD, product innovation, and internal coordination are positively related to supplier and customer involvement and that such involvement and product innovation will lead to better product performance. Lau's [83] work provides a guideline for supplier and customer involvement in the design stage. Further research is needed, however, to substantiate this relationship.

3.5.2 Labor relationship

Labor relationship considers how MPD affects labor level and quality involved. There is no related paper found. We imagine that the laborers' work on the same product modules or highly related modules provides a harmonious setting boosting team communication.

3.5.3 Human diversity

Human diversity, within the context of this paper, focuses on how MPD impacts customer diversity. There is once again no paper that has specifically tackled this topic. It is conceivable, however, that MPD could benefit human diversity as it enables customization in products to fit requirements of different groups.

3.6 Social-economic sustainability literature

3.6.1 Security

Security considers how modular product design impacts community security. There is no paper emphasizing this area, and only a few papers refer to it secondarily. We imagine that security-related MPD is associated with product innovation, because new technology could always benefit community security.

3.6.2 Customer ethics

For the time scope covered, no research paper has focused on customer ethics as it relates to MPD. However, we believe that MPD can affect customer ethics through customization of product features, uses, or cost; future research should address this direction.

4 Discussion

In this section, we summarize the literature presented above, identify gaps, and point to potential future directions for the sustainability literature associated with MPD.

4.1 Literature summarization for MPD in sustainability fields

As shown in Table 1, our definition of sustainability involves 17 factors. We reviewed the related literature for each of these factors. We summarize all findings of sustainability-related MPD in Table 7. During the review, we recorded each *major focus* by using "#" and a *minor focus* by using "*" for each paper. There is only one "#" for each paper, and "#" indicates the main topic; however, there could be several "*" in one paper, since "*" represents a brief mention. We summarize all papers by "#" and "*" as shown in Table 8.

Using "#" and "*" to represent sustainability-related MPD was not sufficient for our needs, because it was difficult to identify how each paper emphasized different sustainability factors. For example, Yan et al. [104] mentioned cost saving, client safety, and health, all represented by "*," while the work mainly focused on life cycle management which was represented by "#." From a simple "#," we could not identify and evaluate all the authors' work on life cycle management. Therefore, we adapted a categorizing idea from Chiu and Okudan [120]. They developed a systematic "guideline, metric, mathematical model and method" for clustering literature based on (1) tool complexity, (2) comprehensiveness (step by step instructions or overall directions), and (3) result generation (tangible evaluations). We applied this tactic to the "#" group and summarized the literature in terms of main foci, as shown in Table 8. According to Chiu and Okudan [120], guidelines provide the direction and ideas that need to be followed (e.g., Koga and Aoyama 2008, in the section of life

Table 7 Sustainable MPD literature findings summary

Sustainability indicator	Indicator major themes	Main findings
Economic	Product innovation (PI)	MPD affects product innovation from vantage points of marketing and technology development, and both of these have positive influences on product innovation.
	Risk management (RM)	Risk management is an application of modularity in project management that primarily addresses risk reduction or control and minimization of risk in complex environments.
	Profit (P)	MPD is positively related to profit increase without cost savings being involved. This means that when properly applied, MPD can generate higher revenue in the market.
	Cost saving (CS)	MPD has a positive impact on both the supply chain and product development cost savings when certain production activities are performed simultaneously.
Eco-environmental	Energy efficiency (EE)	MPD should be used to minimize energy usage rate and minimize energy waste.
	Life cycle management (LCM)	MPD can improve product life cycle performance by allocating cluster components into modules from the view of the entire life cycle.
Environmental	Emission reduction (ER)	MPD plays a role in green design and can be associated with multicriteria design-making methods to satisfy the requirement of emission reduction.
	Natural resource management (NRM)	Natural resource management emphasizes utilizing natural resources efficiently and effectively by applying MPD methods.
	Environment management (EM)	Modularity and green design analysis involving optimization methodologies for managing the environment impact are sparse and require further investigation.
	Environment assessment (EAss)	MPD associated with end-of-life strategy management could help develop a useful tool to assess environmental impact.
Social-environmental	Client safety and health (CSH)	MPD in client safety and health should focus on reliability within and between modules, thus ensuring client safety.
	Global climate change (GCC)	MPD in global climate changes should focus on how to reduce pollution and how to minimize carbon footprint.
Social	Human diversity (HD)	MPD affects human diversity by bringing a variety of products that fit requirements of different groups.
	Human rights (HR)	MPD can facilitate involvement of customers in design stage.
	Labor relations (LR)	Laborers' work on the same product modules or highly related modules provides a good setting for team communication and responds to the need for harmony.
Social-economic	Security (S)	Security related MPD can be associated to product innovation.
	Customer ethics (CE)	MPD can affect customer ethics through customization of product features, uses, or cost.

Table 8 Literature summarization

Author name	Content	Publish date	Economic				Eco-environmental		Environmental				Social-environmental		Social			Social-economic	
			PI	RM	P	CS	EE	LCM	ER	EM	NRM	EAss	CSH	GCC	HD	HR	LR	S	CE
Yan et al.	Sustainability-oriented product modular design	2012				*		#			*		*						
Koga and Aoyama	MD for sustainable life cycle with future market changes considered	2008				*		#	*										
Lau et al.	MPD improves product competitive capabilities	2007			#	*													*
Lau	Management of MPD	2009	#																
Lau et al.	Impact of product modularity on product innovation	2011	#																
Yen and Smith	MPD by using the atomic theory	2009	#					*											
Tsai et al.	Aggregate MFD and TRIZ and CBR	2012	#			*		*											
Regazzoni and Rizzi	Aggregate MFD and TRIZ and DSM	2008	#			*													
Lau et al.	Impact of product modularity and internal integration on competitive capabilities	2009	#		*	*													*
Lau et al.	Product modularity, product innovation, and internal correlation are positive corrected to supplier and customer involvement	2011	*												*	#			*
Mikkola and Gassmann	Measurement of modularity: degree of modularity	2003	*		*	#													
Ramachandran and Krishnan	Integration of product innovation and MPD in order to aid decision-making of pricing and timing	2008	*		*	#													
Fixson and Park	Relationship between product architecture, innovation and industry structure	2008	*		#	*													
Krishnan and Ramachandran	Integrated product architecture and pricing strategy for sequential product innovation management	2011	*		#	*													
Keizer et al.	RDM for risk management	2002		#															
Wang et al.	Four area risks in collaborated modular product development	2004		#															
Kim and Chhajed	Commonality in product design	1999			*	#													
Lau and Yam	Impact of MPD on SC design	2005	*		*	#													
Ernst and Kamrad	Evaluate SC by modularization and postponement	2000			*	#													
Ray and Ray	Combination of supplier, demander, and product innovation	2011	*		*	#													
Hopp and Xu	Impact of MPD on product line selection and pricing	2005		*	*	#													
Ulrich and Pearson		1998			*	#													
Ulrich et al.		1993			*	#													
Fisher et al.		1999			*	#													
Ulrich and Ellison		1999			*	#													
Collier		1981			*	#													

Table 8 (continued)

Author name	Content	Publish date	Economic				Eco-environmental		Environmental				Social-environmental		Social			Social-economic	
			PI	RM	P	CS	EE	LCM	ER	EM	NRM	EAss	CSH	GCC	HD	HR	LR	S	CE
Collier		1982			*	#													
Gu and Sosale	Product modularity assisted life cycle performance improvement	1999						#	*	*									
Newcomb et al.	Modular design for product life cycle	1998				*		#	*	*									
Seliger and Zettl	Modular design for life cycle economic performance	2008			*	*		#		*									
Tseng et al.	Product modularity for disassembly	2010	*		*	*		#		*									
Gao et al.	Modularity for subassembly	2008				*		#		*									
Das and Chowhury	Reverse logistics network for return products and quality based on product mix plan	2012			#	*		*											
Dong et al.	Real options applications in product design	2011	*		#	*													
Konstantaras et al.	Optimal MPD for BTO in two parties supply chain system	2009			#	*													
Kumar et al.	Market-driven MPD	2009			#	*													
Mukhopadhyay and Setoputro	Optimal return policy and MPD for BTO products	2005			#	*													
Ulku et al.	Customer evaluation of modular upgrading	2012			#	*										*			*
Wu et al.	Modular product updating	2012	*		#	*		*											
Asan et al.	Scenario-driven MPD	2008	*		#	*													
Dai et al.	Green design of power plant	2009					*		#	*	*							*	
Luh et al.	Data management of green product development	2010				*				#	*								
Wang et al.	GQFD and DSM in product development	2010						*		#									
Fitzpatrick et al.	Environmentally superior implementation of electronic hardware	2006						*		*		#							
Davis et al.	Host product and derivative product	2011	#					*		*									
Li et al.	Life cycle issues driven MPD	2008						#		*									
Lai and Gershenson	Product representation for retirement process: similarity and dependency	2009				*		#											
Byrant et al.	EPI metric for sustainability design	2004				*		#											
Kreng and Lee	QFD and LIP for MPD	2004						#											
Ji et al.	Effectiveness-driven MPD	2012						#											
Tseng et al.	Green MPD	2008				*		#	*										
Umeda et al.	Product life cycle and geometric feasibility MPD	2008						#											
Umeda et al.	Evaluation of MPD for life cycle design	2009				*		#		*									
Smith and Yen	Green product design based on the atomic theory	2010	*					#											
Cebon et al.	Impact of product modularity on product life cycle	2008	*			*		#											

Table 8 (continued)

Author name	Content	Publish date	Economic				Eco-environmental		Environmental				Social-environmental		Social			Social-economic	
			PI	RM	P	CS	EE	LCM	ER	EM	NRM	EAss	CSH	GCC	HD	HR	LR	S	CE
Chung et al.	MPD improves life cycle performance from optimized SC	2011				*		#	*	*									
Shin et al.	Extended HOQ and MINLP for MPD	2011				*		#											
Gonzalez and Adenso	End-of-life strategy determination	2005				*		#	*	*									
Kahoo and Situmdrang	Immune algorithm for solving assembly configuration	2003			*	#													
Qian and Zhang	FAHP assessment for modular products environmental performance	2003							*			#							
Sand et al.	HOME modularity method	2002	*		*	#													
Yu et al.	GGA incorporates modular design and life cycle issues	2011				*		#											
Ji et al.	Green modular design for material efficiency	2013				*		#											
Fujita and Yoshida	Product variety optimization	2004			*	#													

"#" shows main foci, and "*" represents brief mention

cycle management). Metrics might involve guidelines, but they are presented in quantitative terms (e.g., [52]). Mathematic models include equations and formulas that are used to model design contents (e.g., [60]). A method has a systematic structure and procedure to verify design details (e.g., [104]). Based on the discussion of these four categories, the MPD approaches have been presented in more detail from guidelines to method. We also listed available case studies from the corresponding literature in the same table, in order to facilitate future MPD studies and implementations.

As per the information provided in Table 8, most of the MPD literature emphasized economic, eco-environmental, and environmental topics and seldom touched upon social impacts of sustainability, merely mentioning the core issues. Most MPD literature relied on guidelines and mathematical models to study main sustainability topics, and very few studies adapted metrics and methods as shown in Table 9.

4.2 Maturity measure for modular product design associated with sustainability factors

As part of our comprehensive literature review, we introduced a maturity index to show how much effort the research community put into research on the MPD associated with various sustainability factors. Table 9 shows the paper distribution with respect to all sustainability factors. We also assign "1, 3, 5, 7, 9" corresponding to "mention, guideline, metrics, mathematical model, method" to represent the maturity index shown in Table 10.

Reviewing the data in Table 10, we find that from the view of merging MPD analysis with economic sustainability, cost savings has attracted the most research attention: 13 papers focus primarily on this topic and 24 papers briefly discuss it. Other strong themes that emerged in this investigation include product innovation, profit, and life cycle management. The reason why these topics receive more attention is that the data is relatively easy to get and the research problem is relatively easy to define and evaluate. For example, profit is effortlessly defined as increasing total profit and evaluated as the difference between revenue and cost and can just as effortlessly be incorporated into MPD considerations. Some sustainability themes are more difficult to research using MPD as a factor, such as global climate change and labor relationships. The reason is partially because MPD research is mostly conducted from a micro (limited) perspective, while certain of these themes focus on a macro (broad, long-term) view, such as global climate change. Another reason is that MPD emphasizes detailed and specific characteristics, while these themes focus on summarized and indistinct areas, such as labor relationships.

Table 11 shows the maturity scores for each sustainability theme and sustainability factor. The score order of sustainability *factors* follows that in Table 10, but the score order of

Table 9 Literature summarization—main foci

Author name	Case study						
	Product	No. of components	Publish date	Guideline	Metrics	Mathematical models	Methods
Yan et al.	Reduction gear	36	2012				*
Koga and Aoyama	Laser printer	12	2008	*			
Lau et al.			2007	*			
Lau			2009	*			
Lau et al.			2011	*			
Yen and Smith	Motor end of a windshield wiper	20	2009		*		
Tsai et al.	Bicycle		2012				*
Regazzoni and Rizzi			2008	*			
Lau et al.			2009	*			
Lau			2011	*			
Mikkola and Gassmann	Schindler-Tracing elevator system; hydraulic elevator system		2003			*	
Ramachandran and Krishnan			2008			*	
Fixson and Park	Bicycle drivetrain	6	2008	*			
Krishnan and Ramachandran			2011	*			
Keizer et al.			2002	*			
Wang et al.			2004	*			
Kim and Chhajed			1999			*	
Lau and Yam			2005	*			
Ernst and Kamrad			2000			*	
Ray and Ray	Tata Motors		2011	*			
Hopp and Xu			2005			*	
Ulrich and Pearson			1998	*			
Ulrich et al.			1993			*	
Fisher et al.			1999			*	
Ulrich and Ellison			1999	*			
Collier			1981	*			
Collier			1982	*			
Gonsalez and Adenso	Cell phone	10	2005				*
Kahoo and Situmdrang	Mechanical pencil	7	2003	*			
Qian and Zhang			2003	*			
Sand et al.	Two-way radio	24	2002				*
Fujita and Yoshida	Aircraft families		2004			*	
Das and Chowhury			2012			*	
Dong et al.			2011			*	
Konstantaras et al.			2011			*	
Kumar et al.	Universal Motors family		2009				*
Mukhopadhyay and Setoputro			2005			*	
Ulku et al.			2012	*			
Wu et al.			2009			*	
Asan and Polat			2008		*		
Dai et al.	Power plant		2009	*			
Luh et al.	LCD TV family		2010	*			
Wang et al.	Electronic translator	32	2010		*		
Fitzpatrick et al.			2006	*			
Davis et al.	Bicycle	11	2011				*
Li et al.	Electrical alternator	16	2008			*	

Table 9 (continued)

Author name	Case study						
	Product	No. of components	Publish date	Guideline	Metrics	Mathematical models	Methods
Lai and Gershenson	Rear drag spinning reel	11	2009		*		
Bryant et al.	Bissell hand vacuum	19	2004		*		
Kreng and Lee	Vacuum	34	2004			*	
Ji et al.	Wheel loader	10	2012				*
Tseng et al.	Table lamp	22	2008				*
Umeda et al.	Printer		2008	*			
Umeda et al.	Printer		2009	*			
Smith and Yen	Table lamp	22	2010		*		
	Motor	20					
Cebon et al.			2008	*			
Chung et al.	Refrigerator		2011			*	
Shin et al.	Locomotive wheel		2011				*
Gu and Sosale	Vacuum cleaner	24	1999				*
	Starter	25					
Necomb et al.	Center console	19	1998		*		
Seliger and Zettl	Mobile phone	17	2008	*			
Tseng et al.	Stapler	18	2010				*
Gao and Duan	Heat machine	70	2008				*
Yu et al.			2011				*
Ji et al.	Refrigerator		2013				*

Guideline, metrics, mathematical model, and method are used to represent main foci of literature

sustainability *themes* has some differences from Table 10. The highest score among sustainability themes in Table 10 is for cost saving, while the highest in Table 11 is for life cycle management. A possible reason for this is that although the research community built complex models and tools for life cycle management research, very few of them were discussed sufficiently; most researchers mentioned cost savings but seldom use comprehensive tools. From another point of view, however, it reflects the fact that life cycle management research has been the trend in recent years and there are many research gaps and much potential for improvement; cost saving has already been well investigated, and many mature and valuable tools could be referenced and refashioned.

4.3 Research gaps and future direction

As per our review of sustainability-related MPD literature presented above, there are several research gaps and potential opportunities. First, there is a need to aggregate as many sustainability themes as possible into a framework. Since sustainability as presented here involves six branches and 17 sub-branches, taking all of them into account is complex. There is a recent trend to consider different themes for each sustainability indicator: e.g., Mikkola and Gassmann [60] and Ramachandran and Krishnan [61] considered product innovation, cost saving, and profit as they relate to the sustainability indicator of economics; Dai et al. [115] and Luh et al. [116] discussed emission reduction, environment management, and natural resource management as they relate to the indicator of environmental concerns. Seldom does research take different themes from different indicators into account. One possible reason is that the aggregation into MPD is not always easy, as is the case with global climate change and customer ethics. However, some statistic-based methods could be useful for taking these themes into account in relation to MPD. For example, Lau et al. [50, 51, 82] and Lau [49, 83] provided assumptions based on empirical studies, used regression models to check the correctness of these assumptions, and then applied the verified conclusions to MPD. Therefore, applying the most appropriate methods of analysis could help merge more sustainability themes into MPD research.

In addition, taking the sustainability indicators or themes into account from a dynamic point of view fits the current economic, environmental, and social requirements. A few papers discussed dynamic change in economic sustainability, such as modular upgradability. However, there are few or no

Table 10 Literature distribution

Sustainability indicators	Indicator major themes	Mention	Guideline	Metrics	Mathematical model	Method	Total	
Economic	PI	14	4	1	0	2	21	100
	RM	1	2	0	0	0	3	
	P	19	4	1	5	1	30	
	CS	30	7	0	8	1	46	
Eco-environmental	EE	1	0	0	0	0	1	29
	LCM	7	5	4	3	9	28	
Environmental	ER	7	1	0	0	0	8	27
	EM	11	1	1	0	0	13	
	NRM	3	1	0	0	0	4	
	EAss	0	2	0	0	0	2	
Social-environmental	CSH	1	0	0	0	0	1	1
	GCC	0	0	0	0	0	0	
Social	HD	1	0	0	0	0	1	3
	HR	1	1	0	0	0	2	
	LR	0	0	0	0	0	0	
Social-economic	S	1	0	0	0	0	1	5
	CE	4	0	0	0	0	4	

papers discussing environmental or social sustainability from the perspective of dynamic changes. Dynamic change in environmental and social areas is important and practical. For example, within the life cycle management theme under the eco-environmental indicator, end-of-life options will change based on dynamically changing market conditions, such as varying environment policies in Europe and Asia. Almost all life cycle management literature has one critical assumption: the end-of-life option is fixed. Therefore, considering sustainability indicators or themes with a dynamic view might fit the practical product life stage requirements better.

Finally, there are research gaps which could be bridged by making small changes to certain elements of the work. For example, using TRIZ as a tool to achieve product innovation is a good and reliable method. Tsai et al. [57] combined MFD + TRIZ + CBR to design products. However,

Table 11 Maturity index

Sustainability indicators	Indicator major themes	Mention	Guideline	Metrics	Mathematical model	Method	Maturity index	
Economic	PI	14	12	5	0	18	49	252
	RM	1	6	0	0	0	7	
	P	19	12	5	35	9	80	
	CS	30	21	0	56	9	116	
Eco-environmental	EE	1	0	0	0	0	1	145
	LCM	7	15	20	21	81	144	
Environmental	ER	7	3	0	0	0	10	41
	EM	11	3	5	0	0	19	
	NRM	3	3	0	0	0	6	
	EAss	0	6	0	0	0	6	
Social-environmental	CSH	1	0	0	0	0	1	1
	GCC	0	0	0	0	0	0	
Social	HD	1	0	0	0	0	1	5
	HR	1	3	0	0	0	4	
	LR	0	0	0	0	0	0	
Social-economic	S	1	0	0	0	0	1	5
	CE	4	0	0	0	0	4	
Total		101	84	35	112	117	449	449

Regazzoni and Rizzi [54] pointed that one drawback to the original MFD is its inability to collect customer requirement data correctly. HCD is an alternative method for collecting customer needs; therefore, using HCD to replace MFD in the methodology of Tsai et al. [57] might be more useful.

Beyond the research gaps visible in the descriptive statistics of extant papers for the time scope considered, we observe three broad research opportunities and directions with regard to the integration of MPD and sustainability. Firstly, potential connections between social sustainability and MPD require further conceptual refinement and field observations. As noted in Sections 3.4–3.6, only a few papers discussed integration of social sustainability and MPD. Following the current trend in sustainability research, social sustainability is of increasing importance due to its emphasis on human well-being. Social sustainability covers topics such as human diversity, safety, health, etc. Consequently, corresponding research fields, such as ergonomics, healthcare, etc., should inform future MPD method development. As a matter of fact, several recent design for X (DfX) methods, for example, design for human variability, has relevance; however, studies are needed to clarify conceptual connections between social sustainability and MPD. Secondly, integration of MPD and sustainability as well as close-loop supply chain management could present another fruitful research direction. In Section 3.1.3 (cost saving) and Section 3.1.4 (profit), select papers presented the potential of using MPD to improve traditional supply chain (economic) performance. Moreover, as noted in Section 3.2.2 (life cycle management), it was also shown that MPD can benefit green supply chain (environmental) performance. The web of supply chains plays a key role in the current business environment and will be at the center of the business agenda in the decades to come. The study of supply chains from the view of sustainability has been conducted mostly from the business bottom-line vantage and considered the appropriate management of available resources (e.g., green supply chain management, reverse logistics). Product and process level reengineering of supply chains to improve sustainability will benefit from further integration of MPD concepts and methods. Finally, new sustainability indicators are expected to emerge, revealing correlations and dependencies among economic, environmental, and social sustainability aspects; integration of such indicators will benefit MPD comparison studies that guide the tailoring of product and process designs for various sustainability emphasis. Traditional sustainability indicators, such as cost (presented in Sections 3.1.3 and 3.1.4), carbon footprint (presented in Sections 3.2.2, 3.3.1, and 3.3.2), and energy consumption (presented in Section 3.2.2), have been involved in many MPD methods; new MPD methods and new indicators might stimulate development in a bidirectional way.

5 Conclusions

This paper summarizes our findings collected during a comprehensive literature review of sustainability-related MPD research. In Section 2, we provided our literature search methodology, associated with corresponding keywords for each sustainability theme. In Section 3, we presented a critical and systematical literature review about sustainability-related MPD. Section 4 summarized and assessed the existing literature according to its major focus and minor mentions. Subsequently, we calculated the maturity index for each sustainability theme based on the categorizing method from Chiu and Okudan [120] to indicate the current research scope and potential research opportunities for future work.

Based on the literature review, our findings indicate that MPD has a positive impact on sustainability. It can improve sustainability performance not only from a technological or monetary view, as determined using optimized cluster algorithms and methodologies, but also from the creative or social perspectives, such as MPD for product innovation or MPD for human rights. On the other hand, sustainability extends the research scope and applicability of MPD. Initially, MPD has been applied in design engineering primarily with the economic optimization considerations. In this case, cost minimization or profit maximization has become the design criterion. When integrating sustainability in studies, all dimensions of sustainability would guide MPD, including not only economic view but also environmental and social aspects. With the involvement of sustainability, MPD extends applications to service operations (e.g., green supply chain), environmental protection (e.g., emission reduction), human rights assurance (e.g., labor hour per day constraint), or even government regulation consulting (e.g., climate change). In summary, the intelligent and synergistic combination of MPD and sustainability will benefit future product and systems engineering.

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