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TOOLS FOR THE PLATFORM DESIGNER'S TOOLBOX

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ABSTRACT
Over the last three decades, globalization and customers' buying power has forced many manufacturers to produce an increasingly wide variety of products. Previously, one product could answer most needs, and engineering methods and tools focused primarily on design, development, and deployment of a single product. Today's market is much more fragmented, and niche markets can no longer be ignored. Since the traditional approach (i.e., development of individual products resulting in a set of "orphan" products) will increase costs prohibitively, platform-based product design blossomed and has been adopted in many of today's industries. Platform-based product design enables designers to develop a family of products sharing a common platform such that not one product but an entire family is now taken into account, and this new dimension brings more questions and challenges and obsoletes many existing tools and methods. The goal in this paper is to move the industry closer to the state-of-the-art tools and show companies that operational tools exist and work, while highlighting potential future work for researchers in the field. Thus, we provide a clear picture of (1) the new challenges resulting from differences between traditional and newer approaches (i.e., single product vs. a family of products), (2) solutions for product family design, and (3) remaining opportunities for tool development.

Keywords: Product platform, product family, design, tool, methodology, toolbox

1 INTRODUCTION
Several decades ago many companies shifted their market strategy from mass production to a fragmentation strategy, moving now to mass customization. While mass production focuses on fulfilling the needs of an overall market [1], fragmented markets have appeared in many industries, requiring variants for each market segment [2]. Mass customization [3,4] goes even further, addressing individual customer's needs yet maintaining near mass production efficiency [5]. As a result, most of today's industries benefit from a platform-based product development strategy [6] by targeting several market segments using a common platform to minimize development and manufacturing costs [7]. They define a product platform as "a set of common components, modules, or parts from which a stream of derivative products can be efficiently developed and launched." One of the issues resulting from this new platform approach is that techniques to develop and manufacture the family of products are radically different compared to the development of single products [8]. For instance, the portfolio of the product family needs to be managed while, by definition, single product approaches do not require such an activity. Similarly, product family design needs to integrate the platform and the variety in the family. This is also true for manufacturing design and other stages of product realization. These changes impact the way product lines are designed, and the new approaches are not always mastered by companies working against these new constraints. Furthermore, the literature reviews that exist [6,7,9,10] deal with research status, focusing primarily on product design, whereas this study focuses on both product and manufacturing design. So, the first opportunity is to specify what is currently available in the "toolbox" for platform designers and by doing so make industries aware of recent successful operational tools that address platform-based design challenges. The second opportunity is to ultimately identify areas that lack appropriate tools and highlight potential research opportunities for the academic community. We define a tool as a method supporting activities

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performed during design. For it to be operational, we consider methods with at least one case study and no major reductive assumptions, which will make a real implementation impossible or not representative of the stated results.

Section 2 studies chronologically each stage of single product and platform-based product family design, highlighting their primary differences. Section 3 details the existing tools and recommends a suitable "toolbox" for platform designers. Section 4 discusses opportunities to improve the toolbox. Finally, this study is concluded by presenting future work in Section 5.

2 PLATFORM-BASED PRODUCT DESIGN ACTIVITIES

This section discusses the differences between single product design and platform-based product family design. The following product family process is inspired by the value analysis method [11] and concurrent engineering [12]. Value analysis is a technique using functions of a product to specify appropriate definite design through technical solutions. Concurrent engineering is a process recommending that every company services working together to achieve an efficient design. This process is also based on three existing studies [6,8,13].

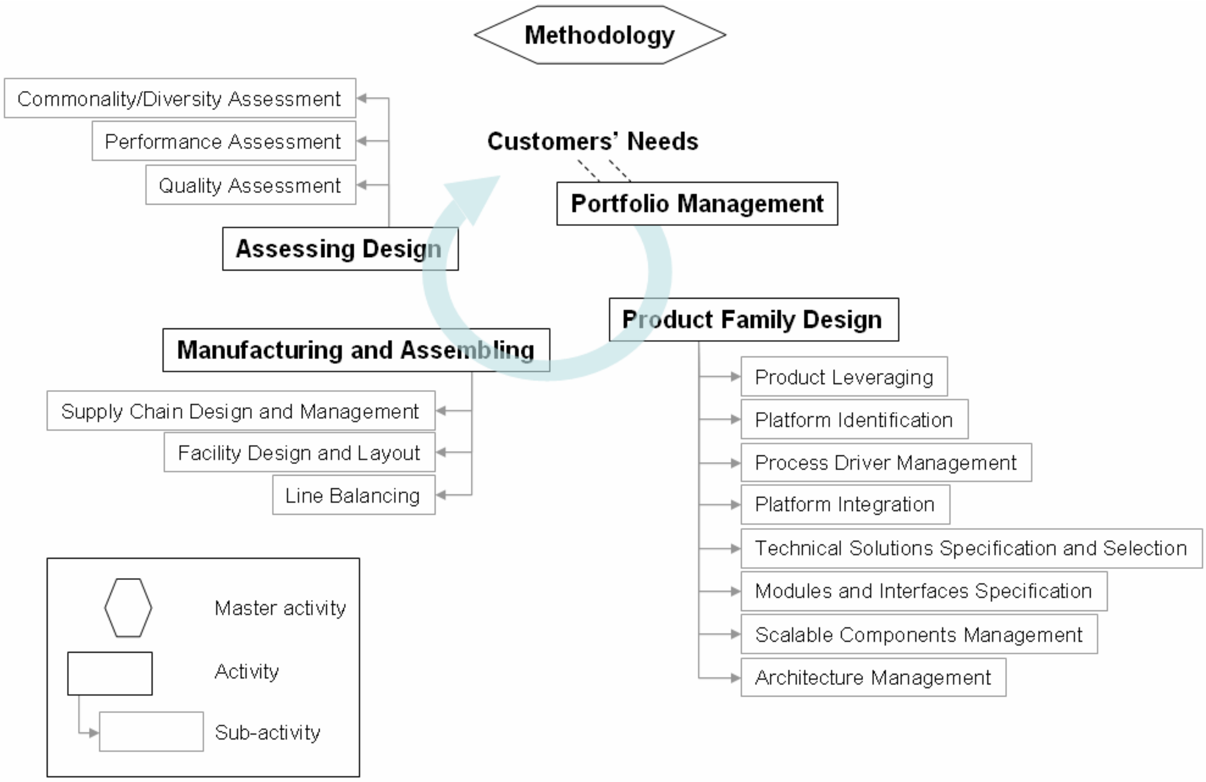

Figure **1**. Product Family Design Process

In Figure 1, we identify the master activity, activities, and sub-activities. The master activity is the *Methodology*; activities are *Portfolio Management*, *Product Family Design*, *Manufacturing and Assembling*, and *Assessing Design*. For instance, sub-activities of the activity *Assessing Design* are *Commonality/Diversity Assessment*, *Performance Assessment*, and *Quality Assessment*. All of these activities are facilitated by tools at a high level of abstraction such as computer-aided design, optimization, visualization, etc. These tools are not considered in this study, which focus on basic activities. In the next section, we chronologically study the design process of both single product and platform-based product family design highlighting new challenges. Methodologies enable designers building a design approach to reach the goal of a definite product; as a result, this tool is considered as a master activity. A given methodology is composed of steps and tasks to design the family of products. Methodologies are required for both single and product family design. The starting point of the design is the customers' needs expressed through the portfolio of products. Thus, product family design requires *Portfolio Management* while single product design does not (targeting a single customer group). When the products are defined, in term of features, the activity *Product Family*

Design can start. The sub-activity *Product Leveraging* is one of the first tasks to identify how to leverage the family through segments or through price/performance ranges, etc. This leveraging activity is not needed for the single product. The *Platform Identification* is also one of the initial activities and typically reserved to product family design. The identification of the common platform enables designers to better integrate this platform into each product. Regarding the process now, the early task of the designers is to recommend which process driver should be adopted. In the case of a platform-driven process, the platform is designed as well as the entire family of products, which is launched at once. For the product-driven process only one product goes through the whole design process, indirectly integrating the platform; the rest of the family is leveraged from this first product. These two types of processes have different impact in term of cost, market coverage, customer satisfaction, etc. *Process Driver Management* is not required for the single product. When the platform is identified, the leveraging strategy specified and the process driver defined, designers focus on *Platform Integration*, which by definition is exclusively reserved to product family design. At this stage, the question is how to integrate the platform in each product satisfying its own specificities. The sub-activity *Technical Solutions and Specification and Selection* is required for both single product and product family design, but, once again, the product family requires careful attention to variety and commonality. Functions are translated in terms of potential technical solutions, which are ultimately selected based on cost, performance, etc. *Modules and Interface Specification* can sustain the variety within the family of products by adding, substituting, and/or removing modules to fit specific needs, while *Scalable Components Management*, stretching or shrinking scaling variable(s) to support variety; these tasks are specific to product family design. Finally, *Architecture Management* is required for both design (single and family of product) but product family design requires specific consideration for the variety/commonality, modularity, platform integration, etc. The *Manufacturing and Assembling* activity is composed of three sub-activities, which are highly linked (*Supply Chain Design and Management*, *Facility Design and Layout*, and *Line Balancing*, see Figure 1). *Supply Chain Design and Management* involves many facets, from factory selection to logistic specification. The logistic topology is specified for each component. The rate of its consumption will provide the volume needed in the warehouse and the volume on the workstation. Adding the volume of this component and its required storage surface is known for both the warehouse and the workstation. Then, regarding *Facility Design and Layout*, each function, technical solutions, implying equipment, are generated, studied and selected based on (among others): production rate, cost, automation capability, existing equipment, and quality. Finally, for this activity *Line Balancing* is performed to smooth the work charge (due to diversity) integrating different characteristics like cycle time, cost, diversity, uncertainty, etc. Then, the selected equipment needs to be laid out for each workstation. In parallel, the warehouse is designed based on consumption rate and the type of material handling. The last activity in Figure 1 is *Assessing Design* with three main sub-activities: *Commonality/Diversity Assessment*, *Performance Assessment*, and *Quality Assessment*. These three sub-activities enable designers to make sure that the definite product family design satisfies the customer/company aims.

3 PLATFORM DESIGNER'S TOOLBOX

This study proposes to assess what is in today's platform designer's toolbox. We specify a classification of the tools using several facets of the design process. Thus, five categories of tools are identified based on the mentioned activities: (1) *Methodology*; (2) *Portfolio Management*; (3) *Product Family Design*; (4) *Manufacturing and Assemby*; and (5) *Design Assessment*.

. Two ways were identified to design a product (family or not), the first one being the top-down approach while the second is the bottom-up approach [14]. The bottom-up approach is based on the existing design, which serves to specify the new generation of product(s). In the case of a top-down approach the product(s) is designed from scratch because the needs are too different or a new technology obsoletes the architecture of the existing definite design. For clarity purposes, this paper does not study differences between these two approaches, which are close, although bottom-up is more constrained by existing designs and more manageable for the same reason while top-down is the opposite.

3.1 Methodology

Meyer and Lehnerd [7] proposed a three-step qualitative approach to design a platform: (1) make the segmentation of the market, (2) study the different platforms which have particular interfaces, and (3) make a commonality study for each aspect (customers' insights, product technologies, manufacturing process, and organizational capability). Robertson and Ulrich [15] developed a platform planning method axed on three plans: product plan, differentiation plan and commonality plan. They focused their efforts on the tradeoff between commonality and differentiation defining differentiation attributes (which are important for customers) to drive the differentiation. Then they specify a detail process (actors and detail activities) to find the best compromise tradeoff using loops between differentiation and commonality using a same discussion support for marketing, designers, and process designers. More recently two promising methods have been proposed. Marion et al. [16] introduced an eleven-step method (Mass Customized Product Platform Development) recommending a strong up front marketing analysis. Also, de Weck and Suh [17] proposed an overall methodology to design a product family. This method is composed of seven steps mainly focusing on uncertainty analysis, flexibility, criticality, and cost.

3.2 Portfolio Management

Proposed by Green and Rao [18], conjoint analysis has been used and improved for 35 years now [19] to measure buyer preferences among part-worth for attribute levels. Using this technique, several companies propose a package of tools as product specification, segmentation, product mapping, etc. Regarding market segmentation and product line design, researchers still pursue the goal of maximizing the profit while minimizing the cost of a product line (implying common platform) with more and more realistic models [20-22]. Cannibalization is also a significant issue across brands and within a product line. As a response, Desai [23] introduced a model prioritizing quality with low-valuation ad high-valuation segments. Mason and Milne [24] proposed a model to identify cannibalization within a family of products. Alizon et al. [25] proposed a method based on function highlighting the lack of differentiation. These methods can build the features of a product line ensuring sufficient differentiation.

3.3 Product Family Design

3.3.1 Product Leveraging

Meyer and Lehnerd [7] defined four leveraging strategies based on their market segmentation grid, which are:

a) Horizontal leveraging: a product is horizontally leveraged through equivalent cost and performance classes;
b) Vertical leveraging: a product is vertically scaled up via segments;
c) Beachhead approach: a product fully leverage to cover every market segment based on one product; and
d) No leverage possible.

Alizon et al. [26] adopted a function-based approach and quantified the homogeneity and heterogeneity of a product family enabling managers to select the best of the four mentioned leveraging strategy for a given family of products and for each of its function. Gathering these two methods enables designers to define the appropriate leveraging strategy for a given product line.

3.3.2 Product Identification

Two methods have been developed by Steva [27] to redesign and assess the platform of the product family. The first method is based on a top-down approach (new product family) and the second on a bottom-up approach for an existing family of products. The top-down approach applies on the functions and the bottom-up approach is based on the Bill of Material (BOM). These two methods can also be used to define a platform, for a new or existing product family.

3.3.3 Process Driver Management

Three types of drivers were identified by Alizon et al. [8]: product-driven, platform-driven, and hybrid (mix of the two first). This aspect is important because the driver will lead the development process and impact almost all of the facets of the product and the company.

3.3.4 Platform Integration

This sub-activity does not have a specific answer yet but de Weck and Suh's [17] method can partly answer this need via their stages: (1) Optimize product family and platform bandwidth, (2) Identify critical platform elements, and (3) Create flexible platform elements. These three stages help designers integrating the platform regarding a given family of products. After this sub-activity, all the sub-activities are completed concurrently and need to be studied simultaneously.

3.3.5 Technical Solutions Specification and Selection

The specification of technical solution is related to experiences, creativity, and skills of designers; it is difficult to have exhaustively all the potential technical solutions. Several methods have been proposed to express the relation between function and technical solutions for a single product QFD [28], Value Analysis [11], and Axiomatic Design [29]. Although, none of these methods satisfy the product platform problem, recent tools inspired from these three main methods can help designers. For instance, Martin and Ishii [30] developed a method based on their *Generational Variety Index* considering multiple generation of products. This method is directly related to the technical solution selection procedure identifying which of the potential components (component if it is a redesign) are mostly subjected to change over time to meet future market needs. Their *Coupling Index* highlights the link between these components so that it is possible to select the best over-time technical solution. Similarly, Hata et al. [31] introduced life cycle rules for non-grouping and selection of components having different materials, life cycle time, and/or maintenance interval. Alizon et al. [32] extended Value Analysis to improve an existing product family. Also important to mention, the TRIZ method [33] can help solving technical solution problem [16] and can enlarge the spectrum of technology by recommending the next technologic step for a given technology or related technologies. This method is not a product platform tool but can be used as a tool for multi-selection: each product can be selected/treated and studied as a set.

3.3.6 Modules and Interfaces Specification

For a management point of view, Sudjianto and Otto [34] proposed a framework to develop a modular product portfolio architecture in the context of a brand portfolio. This tool is particularly interesting because at a high level of abstraction it addresses the modular problem for the entire portfolio. Regarding operational tools, heuristic rules to find modules can be found in Refs. [35,36]. Proposed in 1981 by Steward [37], the Design Structure Matrix (DSM) is a relevant tool to specify modules, especially Pimmler and Eppinger's model including flows [38]. Other realistic models can be found in [39-41]. Even if the DSM can be used as a product platform tool, it is not really appropriate for a product family design. Comparisons of methods for modularizing product architectures can be found in Guo and Gershenson [42] and Holtta and Salonen [43]. Group Technology regrouping similar problems to find a common answer are also interesting MODROC [44] algorithm can be used to solve the technology grouping problem. Regarding the specification of interfaces, Blackenfelt and Sellgren [45] developed a robust interfaces method for modular product; Sundgren [46] manages modules interfaces within a product family. Finally, Chen and Liu [47] define an axiomatic-based method to specify interfaces.

3.3.7 Scalable Components Management

When modularity is not possible, scale-based techniques may be possible. This aspect has not been significantly studied, but interesting results have been obtained by industry [48-50]. However, a few significant academic results have been recently obtained. For academia, Seepersad et al. [51,52] developed a methodology to determine the number of scalable and generational product platforms using the compromise Decision Support Problem. Simpson et al. [53] proposed the Product Platform Concept Exploration Method (PPCEM) to define the market segment and product platform specification for a vertically scaled product family. Other scale-based methods can be found in [54,55] and have also successfully be applied. At this stage of the design, the platform is known and modules as well as scalable variables are integrated in the technical solutions. After this, several concepts of architecture are generated to validate the technical solution selection.

3.3.8 Architecture Management

Ulrich [56] defines architecture as the scheme by which the function of the product is allocated to physical components. He proposed a process to build the architecture of a product from functional arrangement of the elements to the specification of the interfaces through the mapping of the functional elements to the physical components. He identifies two types of product architectures: integral and modular. A modular architecture implies a one-to-one relation between functions elements and physical components, while an integral architecture indicates a more complex relation between the two latter. Modular architecture is refined in three categories based on their interfaces: (1) the slot architecture is a specific interface for each component/module; (2) the bus architecture describes a common bus interface for all the component/module; and (3) the sectional architecture where all the components have the same interface. Changes over generations and within a product family via variety are discussed in regard to the product architecture. It is relevant to match this method with Martin and Ishii's method [30] to highlight critical component/module identified by their *generational variety index*. As mentioned before, sub-activities from *Technical Solution Specification and Selection* to *Architecture Management* need to be studied concurrently.

3.4 Product Family Manufacturing and Assembly

3.4.1 Supply Chain Design and Management

Supply chain design is defined first by two high levels: (1) Production planning and inventory control and (2) Distribution and logistic process [57]. As we are studying design activity, only the design aspect of the inventory control (design of the storage policies for raw material) is incorporated in the toolbox. The production planning is related to the entire manufacturing process: starting with factory selection, then for each factory from raw material to final product, including raw material acquisition, manufacturing scheduling, and material handling design. The distribution and logistics process designs and controls the supply chain from the factory to the customer, usually via retailers. These two levels are tightly coupled and describe the entirety of supply chain design and management. Industry already uses tools [58-60] to:

1) Select which of the available manufacturing facilities and distribution centers should be open;
2) What are the raw material and intermediate order quantities for vendors and manufacturing facilities;
3) What are the production quantities of product by manufacturing facility;
4) Specify the product-specific shipping quantities from manufacturing facility to distribution center to customer;
5) Determine the number of echelons (amount of vertical integration);
6) Assign distribution center to customer zones.

These tools maximize after-tax profits, or maximize the system flexibility, or minimize the total cost of distribution centers. Cohen and Lee [61] developed a model to specify material requirement along the manufacturing process this model is composed of four sub-model including (1) material control, (2) production control, (3) finished goods stockpile, (4) distribution. Regarding the material handling system design, static approaches are used to solve design problems [62,63]. Other models applying stochastic, simulation, economic models can be found to design the supply chain in [57].

3.4.2 Facility Design and Layout

The specification of the warehouse and production line in terms of composition and dimension is established by the selection of the required equipment and their layout; which is highly related to the variety of the product, the assembly sequence, the expected volume of production, and labor cost. A significant effort has been made [64-66] to develop and improve the Generic Bill-of-Material (GBOM), to better integrate the product family description reducing the redundancy in the classic BOM. de Lit et al. [67] use GBOM to define the family as an assembly of entities and then study it for the assembly planning and layout. Regarding the assembly sequence, manufacturing companies attempt to commonize their facilities to better manage the product-factory assignment and the next generation of products via, among other advantages, the production ramp-up replacing an existing product and the manufacturing expertise of existing factories. For equipment selection, a method for multi-product, including operations assignment, can be found in [68]. For the platform-based product manufacturing, Alizon et al. [69] developed a model, dedicated to the platform problem, to retrieve and reuse relevant information from existing equipment design and layout. This approach can be transposed to other types of activity (welding, stamping, injection, etc.). Regarding the layout of facilities, product platform design has less impact on the facility layout, and a traditional facility lay out model can be applied. Bukchin et al. [70] proposed a model solving realistic size instances. Banerjee et al. [71] proposed a interactive model which can be very useful to enumerate the solution space more exhaustively. Finally, Chhajed et al. [72] layout the facilities based on flow which could be more appropriate if flows are crucial.

3.4.3 Line Balancing

Line balancing equalizes operations on production lines to optimize the time-cycle of a line; by definition this technique includes multi-product needs. Current models provide answers for the product family problem [73] and multiple-objective.

3.5 Assessing Product Family Design

3.5.1 Commonality/diversity assessment

Considering product development, numerous indices and methods [74-77] address both commonality and distinctiveness (also called *variety* or *diversity*) by assessing and ultimately improving this tradeoff with various aspects of the design (product, process, manufacturing, etc.). Most of them are component-based, but one example [78] addresses multi-levels (functions, components, and family), the functional level allows a non subjective identification of what should be common or specific. Another index [79] addresses the strategic level using factors (product, market, etc.) to specify the correct commonality/diversity tradeoff. A method used throughout the project can be found in [80].

3.5.2 Performance Assessment

Concerning the product, several methods [53,81] integrate performance as a variable/constraint to keep the objective performance of the model. Shooter et al. [82] proposed a performance measure comparing the intended behavior of the product and the observed behavior. This method can easily be extended to a product family since only the behavior of derivative products needs to be checked. Simpson et al. [83] studied the entire family of products and especially the disparity between single product performance and product family performance through commonality. Finally, Fellini et al. [84] propose a model maximizing commonality and minimizing individual product performance deviations. Numerous aspects are studied in manufacturing; productivity of course [85], but also other aspects like work teams (formation, ergonomics, etc.) [86], automatization rate, etc. For instance, MacDuffie et al. [87] studied a large number of factories and found that variety and product complexity have a negative impact on performance. They also bring qualitative answers to avoid such a problem, but currently no metric assesses this performance. Lee, et al. [88] propose a simulation study to measure performance delay at intersections in a network of automatic guided vehicles. Benjaafar [62] propose a model to study the operational performance based on the physical layout of facilities. Other types of performance can be found in [89].

3.5.3 Quality Assessment

The quality of a product family was studied through numbers of studies at a strategic level as Shapiro [90] giving answers regarding the relevancy of adopting a high quality strategy or not. Taguchi [91], is known as the mastermind behind Japanese quality manufacturing. As the father of quality control he brought a battery of tools to achieve a robust quality. All these tools can be applied for an individual product of a product line; however, even if these tools can address the platform quality (considering the platform as a product), the link between the platform and the related derivatives product has not been made yet.

4 OPPORTUNITIES TO IMPROVE THIS TOOLBOX

Table 1 illustrates the tool availability for each activity/sub-activity of the platform design process. Symbols "✓" represent when an activity is required. Symbols "●" means that a tool supports the activity (does not mean that everything is solved but a tool is available); "◖" means that the current tools partly support the need; and "○" means that there is no tool yet to satisfy this need. These results are discussed in detail in the next section.

By nature, product family design generates variance amplification occurring when the demand distortion propagates in the product development. This impacts the entire product development process as well as manufacturing and needs to be better addressed in terms of tools. Starting with the overall toolbox, platform designers already have lots of relevant tools available, and existing tools should be improved in the future bringing more and more realism and making them more applicable.

Table 1. Platform-based design activities and tools

	Design Activities	Product		Manufacturing	
		Activity	Tool	Activity	Tool
	Portfolio Management	✓	●		
Single Product and Product Family Design	Product Leveraging	✓	●		
	Platform Identification	✓	●	✓	○
	Process Driver Management	✓	○		
	Platform Integration	✓	◖		
	Technical Solutions Specification and Selection	✓	◖	✓	◖
	Modules and Interfaces Specification	✓	◖	✓	○
	Scalable Components Management	✓	◖		
	Architecture Management	✓	●		
Manufacturing and Assembling	Supply Chain Design and Management			✓	●
	Facility Design and Layout			✓	◖
	Line Balancing			✓	●
Assessing Design	Commonality/Diversity Assessment	✓	●	✓	
	Performance Assessment	✓	◖	✓	●
	Quality Assessment	✓	◖	✓	●
	Methodology	✓	●	✓	●

Although, deficiencies were highlighted in this study and this toolbox still needs to be improved. For instance, the process design has not been sufficiently studied yet, and several questions are unanswered such as the choice of the product or platform driver and the role of costs, resources, and product in such development processes (○ in Table 1). Regarding the technical solution (◖ in Table 1), there is no customized answer to fit these actual needs in terms of generation and selection, and tools are required to be specified. Scalable platforms (◖ in Table 1) also need to be better studied. Product platform performance and quality (both ◖ in Table 1) need to be better specified; while a quantification of Shooter's model [82] will help having a relevant tool for the performance, applying robust design [91] to the platform approach can bring good insights for platform designers. Finally for the product perspective, if commonality/diversity metrics already provide relevant and useful tool, new metrics addressing performance for platform product must be developed to better manage the tradeoff between this latter and commonality/diversity, quality, etc. Relevant manufacturing and assembly tools already exist - it is probably the most advanced field in terms of integrating variety; however, if many studies integrate product family variety, only few studies focus on the product platform. For instance, a basic need like identifying the manufacturing platform has no answer yet (○ in Table 1). This platform can be different, and this is the base to specify its integration in the factory. Technical solutions do not have dedicated tools to be generated and selected (◖ in Table 1). Finally for manufacturing, product modularity and manufacturing modularity can be different, and there is still no answer to identify/specify manufacturing modularity (○ in Table 1) regarding a platform approach. Considering supply chain design, if the mixed product models are usually integrated in the proposed methods, a common platform is not always integrated. Similarly for facility design, all of the tools presented in this study integrate variety (except the equipment selection) while product design techniques usually deal with a single product and do not directly integrate variety. However, the generation, selection, and layout of equipment need to integrate the platform definition (◖ in Table 1). Another underestimated issue is the formation of a platform designer's discipline. Work have platform designers, work has been done to fit the needs in term of formation [92,93], but the actual lack of formation is a preoccupant issue, because despite the utility of the tools in the toolbox, future platform designers need to be aware of the challenges, constraints, goals, and techniques for platform design to fully benefit from their use. The final remark for the improvement of this toolbox involves the product and manufacturing designers' management. These two fields were already difficult for industries to manage due to the historical distance between these two communities (sequential design). With the platform-based product, the product design is more complex and decisions closely related to the manufacturing design. As a consequence these two main activities, which bring the initial idea to a definite commercial product, should be studied closely.

5 CONCLUSION

Starting by each step of the design process, this study compares activities for a single product design versus a product family design. We specified a generic product family process driven by activities inspired by four existing studies. Comparing the activities and the existing tools, lack of assistance was highlighted, and opportunities for new tools were identified. As a conclusion, numerous platform tools are successfully used in different case studies and we hope that this study will help mangers to get a better picture of what is available to assist designers in their task, as well as research via the lack of tools to develop future. As mentioned in the opportunity section, the number of design process stages requires new tools or more adapted tools. Tool opportunity need to be performed for process driver management, platform integration, technical solutions definition and selection modules and interfaces specification, scalable components management, and quality and performance assessment for the product design; while platform identification, technical solutions definition and selection modules and interfaces specification, and facility design and layout should be developed or enhance for the process design. Future work will consist to develop these missing tools and improve tools that need to be enhanced.

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