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PRODUCT PLATFORM PROBLEM TAXONOMY: CLASSIFICATION AND IDENTIFICATION OF BENCHMARK PROBLEMS

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ABSTRACT

Many companies are using product platform concepts to gain economies of scale and to identify new market opportunities. Though the area of product platforming continues to be actively investigated by both industry and academia, there is no comprehensive classification scheme that can provide a clear picture of the existing problems and possible future research directions. Hence, in the present paper, we introduce a broad taxonomy that classifies product platform problems based on the product development stages. This can serve as a basis to: (1) Extract and categorize problems from research literature; (2) Identify potential extensions and/or new problems that have not been addressed in the literature; and (3) Identify existing problem sets and/or develop new problem sets for benchmarking purposes. We introduce a Conditions and Assumptions Code (CAC) scheme and use it in the identification of benchmark problems as well as in analyzing two classes of evaluation methods adopted for the platform problems: metrics-based and optimization-based. Thus, we have not only categorized existing problems but also identified possible future research problems in each of the categories. This categorization serves as a navigation tool to understand the progress made in this field so far and to identify new research directions.

Keywords: Product Platforms, Taxonomy, Strategic and Tactical decisions, Benchmarking Problems.

1. INTRODUCTION

Global competition is driving many companies to implement strategies and tactics to produce customized products at prices comparable to those of mass-produced goods. In the last decade, several companies have successfully deployed product platform and product variety concepts lured by the potential to gain economies of scale advantage and the opportunity to enter new growth market segments quickly. The pioneering texts by Pine [42] in the area of mass customization, Meyer and Lehnerd [37] in the area of product platforms, and Sanderson and Uzmeri [44] on product families have strongly influenced researchers and practitioners in academia and industry in the area of product platforming. The literature reviews of product platform and architecture design methods have been provided by Simpson [51], Krishnan and Ulrich [23], Du *et al.* [7], and Jose and Tollenaere [19]. Traditionally, there have been two separate general bodies of research in the area of product platforming: (1) qualitative product planning problems (management domain) (2) quantitative and highly product-

specific engineering design problems (engineering design domain). More recently, researchers are just beginning to understand the wider scope of integrated product platforming problems that cut across the entire product life cycle phases from the cradle to the grave. For example, Ortega *et al.* [40] considered the end-of-life considerations in the product platform formulation problems. While research in the area of product platform design is steadily progressing, some general observations can be made:

1. Product platform problems from a management perspective typically rely on conceptual and/or qualitative problem solving models whereas engineering design-oriented product platform problems rely on formal/optimization problem solving models.
2. Two broad categories of engineering design product platform problems have been identified in the literature, namely, scale-based (parametric) and module-based (configuration) platform problems. This classification, though helpful to a certain degree, fails to capture the specific problem variants (based on varying problem conditions, assumptions and problem scope) addressed by various researchers. For example, the universal motor platform formation problem has been addressed by Simpson *et al.* [53] as well as by Nayak *et al.* [39], but the problem scope differs. Finding the optimum values of differentiating variables is addressed in the former while justifying the platform formation is addressed in the latter.
3. Many optimization-based methodologies presented by various researchers to solve engineering design product platform problems are highly product-specific (for example, universal motors, pressure vessels, etc.). The claim that a given problem solving technique is generalizable and/or scalable to accommodate real-world cases with a vast number of product variants is often difficult to make.
4. Almost all scale-based test problems cited in the literature are for matured products (e.g. universal motors, pressure vessels, aircrafts, etc.) where the function-technology mapping of the product is not assumed to be changing.
5. The objective function (evaluation criteria) for the product platform problems typically involves some sort of trade-off between pre-assigned criteria. The criteria for trade-offs may be purely technical in nature (such as trade-off between mass and efficiency in the case of universal electric motor problems) or could be a combination of technical and other criteria (such as serviceability, manufacturing

cost, and assembly cost). A survey of the problems in the literature indicates that most research studies use surrogate measures (such as increased part commonality index) and/or partial “true” measures for selecting the optimal solution set. True measures such as total time to market, and total life cycle cost (with appropriate breakdown into various cost parameters) have been seldom considered.

6. There are only a handful of real-life industry case studies published in the literature, even though many industry case studies exist that point to the successful usage of product platforming concepts.
7. There seems to be an inherent bias towards deploying product platforms. Very few papers discuss the option of “not to platform.” It may be advisable to proceed with stand-alone product development in certain situations. The justification of platform formation (in terms of the increased profit, reduced time-to-market, etc.) is rarely considered explicitly. Krishnan and Gupta [22] are among the few who address these issues.
8. There is an emerging body of literature that is mirroring the Design for X (DfX) research trajectory, which we will term “Platform for X” where X = organization resources, manufacturing resources, assembly resources, testing resources, logistics resources, etc.
9. With the exception of a few studies, most engineering design product platforming problem sets consider one product family/platform analysis at a time and do not explicitly consider multiple product families/platforms.

Our literature review revealed that there are several different identified and unidentified types of product platform problems depending on the problem conditions and assumptions. To this end, we argue that there is an imminent need to develop taxonomy to classify product platform problems. Such taxonomy will be the first step to systematically chart out the widely-varying product platform problems landscape. The literature related to product platforms covers a wide spectrum of problems ranging from the purely management domain to the engineering design domain and downstream domains such as manufacturing, assembly, logistics/supply chain, End-of-life, etc. An effort to create taxonomy of “engineering design focused” product platform problems has been done by Scott *et al.* [45]. Our work on the taxonomy for product platform problems will help researchers conduct the following: (1) Extract and categorize problems from the research literature; (2) Develop benchmark problems for the future and incumbent researchers. Further, we also identify two classes of platform evaluation techniques. These classes are motivated from two types of platform papers existing in the literature, i.e., metrics based problems, and platform optimization based problems. In this study, we have used platform optimization based papers to identify and/or design benchmark problems. The same has been developed based on the CAC scheme developed in the paper.

2. CONDITIONS AND ASSUMPTIONS CODE (CAC) SCHEME

The motivation behind the development of a CAC scheme is to categorize various problems / sub-problems found in the literature. Inspired by Group Technology (GT) codes that are intended to capture design and manufacturing attributes of parts to form part families, we aim to develop a string of codes called the Conditions and Assumptions code (CAC) scheme, to identify various parameters related to product platform problems. The parameters considered in the CAC scheme have been selected based on the factors encountered in the platform problems of the fuzzy end, engineering design, and downstream design phases. These factors are listed in Table A1 of Appendix. We recognize that the CAC scheme can be further refined by including more parameters to discriminate among specific sub-problem types. We invite researchers in the field to utilize this CAC scheme as a starting point for creating a more comprehensive one.

In the present paper, we model a general product platform problem as a “black box” in which there are inputs and outputs along with a listing of various conditions and assumptions that pertain to a particular platform problem. Having enlisted these parameters, we have segregated these CAC codes into three general types:

1. **ICAC code:** This refers to the input CAC scheme. It is used to identify the inputs to a given platform problem variant.
2. **OCAC code:** This refers to the output CAC scheme. It is used to identify the outputs to a given platform problem variant. The same may be further sub-divided into an optimization model’s objective function-specific OCAC scheme and product platform domain-specific OCAC scheme. The objective function-specific OCAC scheme, denoted by **OCAC-Obj**, refers to the criteria that embody the optimization goal(s) while optimizing a specific objective function. The domain-specific OCAC scheme, denoted by **OCAC-Dom**, refers to the output parameters that are directly influenced by the OCAC-Obj. For example, the OCAC-Obj for a product platform problem may include parameters such as “manufacturing cost” while the OCAC-Dom may include parameters such as resulting “module type”, whose selection depends on minimizing the manufacturing costs.
3. **MCAC code:** This refers to the miscellaneous CAC scheme. It is used to identify supplementary conditions and assumptions, intermediate outputs, and other attributes that further define the scope of the given platform problem variant.

There are several scenarios that influence the parameters in ICAC, OCAC, and MCAC, giving rise to different problem variants. The various scenarios could include considerations of uncertainty or commonality (CM) of various CAC parameters listed in Table A1. Thus, if there is an uncertainty in market demand (represented as C in Table A1), then we signify it by using the notation: Uncertainty-C. Also, we use a coupled coding scheme to establish the problem setting. For example, if a functional performance requirement is considered in a problem variant, then the code will be L-K5, where L stands for functions and K5 stands for the level of performance required for that function.

It is important to note that the CAC scheme identifies different variants of a problem in terms of differentiating conditions and assumptions; however, the focus is not to differentiate among different techniques or methods used to solve a specific platform problem.

We illustrate the usage of the CAC scheme to organize and categorize the following three general types of platform problems (described in Sections 3, 4, and 5, respectively):

1. Strategic Product Platform Problems (S/Pd¹)
2. Tactical Product Platform Problems (T/Pd)
3. Tactical Integrated Product/Process Platform Problems (TI/Pd/Pr²)

These general platform problems closely map to the stages of Product development, namely, the fuzzy end of the design, the engineering design, and the downstream design phases, including manufacturing, assembly, logistics/distribution, and End-of-Life (EOL) activities, respectively.

3. STRATEGIC PRODUCT PLATFORM PROBLEMS (S/Pd)

Strategic product platform problems (S/Pd) typically deal with the fuzzy-end problems of product platform planning and pre-technical market opportunity evaluation. They are driven by key business goals such as desired financial performance, market share targets, and product introduction timing. Since, they are defined at a high level of abstraction, more often than not, qualitative and/or conceptual models

¹ Pd denotes Product

² Pr denotes Process

(such as the market segmentation grid by Meyer and Lehnerd [37]) are used to describe and define the problem scope. Examples of various sub-problems in this category and their variants are given in the following sub-sections.

3.1. Product/Platform roadmap evaluation (S/Pd/1)

A product/platform roadmap is a planning document that indicates the expected release date of product/platform, and the number of products/platforms introduced at a time or released over time. The factors influencing the roadmap are the target and estimated values for time of introduction, estimated life time, cost of development, the product's/platform's development time, and the level of commonality among the different products or platforms during a given planning horizon. These factors affect the optimum number of platforms, derivative products, and non-platform products to be introduced during a given planning horizon. Based on the criteria for product/platform evaluation, problem variants are identified as follows:

3.1.1. Strategic product roadmap evaluation (S/Pd/11)

Example problem: Shil and Allada [47]

ICAC scheme: F4

MCAC scheme: A2/B1/C1/D1/F2/H1/J3/Uncertainty-C/F

OCAC-Dom: P2

OCAC-Obj: F4

Case study: Generalized case study.

Problem statement: A methodology for evaluation of a risk neutral product portfolio is developed. The technical, market, and implementation uncertainties are modeled, and cannibalization effects are considered for evaluating product development projects. The project with the highest utility value is selected.

3.1.2. Computation of value of the platform (S/Pd/12)

Example problem: Dahmus *et al.* [3]

ICAC scheme: H1

MCAC scheme: F2/N1/O1/P6/Uncertainty-F/J

OCAC-Dom: H1

OCAC-Obj: F7

Products used: Spacecraft

Problem statement: An appropriate product platform or product family design is selected based on the net benefits and investments for the platform/product development, and company strategies like price movement, optimal sales demand and cannibalization effects. Consideration of uncertainties and risks in the assessment of the value of product platform is used to provide flexibility to the designers.

3.1.3. Evaluation based on strategic decisions (S/Pd/13)

Example problem: Maier and Fadel [33]

ICAC scheme: B1/Uncertainty-K5

MCAC scheme: A2/H1/J2/G1/N2

OCAC-Dom: O1/P3

OCAC-Obj: None

Case study: Data from a Kayak manufacturer

Problem statement: In this paper, an appropriate product family design is selected based on market size, market type, product variability, and number of target market niches. It provides a framework to account for uncertainties in market demand, technology, competition, and stakeholders. Based on the type of product family, a platform strategy is chosen that caters to the needs of both existing and evolving products.

3.2. Product Cannibalization (S/Pd/2)

Product cannibalization is the process by which new products gain sales by diverting the sales from existing products produced by the same company [5,13,62]. It is an important consideration while planning various product variant introductions to the marketplace. Owing to the importance of this concept in product portfolio development, problem variants have been identified as follows.

3.2.1. Measurement of cannibalization (S/Pd/21)

Example problem: Lomax [32]

ICAC scheme: J3

MCAC scheme: A2/ C1/H2/G2/ Uncertainty-D2

OCAC-Dom: Guidelines-J

OCAC-Obj: None

Case study: Three case study problems from a UK detergent manufacturer.

Problem statement: Three different techniques to determine the effect of cannibalization for the same brand product are assumed in this article. The methods suggested are based on the volume of the products sold and the market share captured by each.

3.2.2. Sequencing and timing of product line entry (S/Pd/22)

Example problem: Wilson and Norton [62]

ICAC scheme: I1

MCAC scheme: A2/B1/C2/H1

OCAC-Dom: E-J2

OCAC-Obj: F7

Case Study: Two generalized product case studies with different diffusion rates.

Problem statement: A theoretical framework to determine the optimal entry timing of a new product is presented by identifying three critical factors: (1) the interrelationships of sales of the two products due to substitution and diffusion, (2) the relative margins of the two products, and (3) the relationship of the length of the firms' planning horizon to the original product's diffusion time. It is shown that the entry of the products should be interspersed to ward off cannibalization process.

3.3. Platform formation (S/Pd/3)

The problem of platform formation involves identification of core and differentiating elements of the platform. The elements of the platform at the fuzzy end of product design are customer needs, functions, and technologies. Typically, for innovative products, little information about the function-technology or function-structure mapping is available a priori at the fuzzy end. Two sub-problems of S/Pd/3 type are discussed below.

3.3.1. Customer needs Platform formation (S/Pd/31)

Example Problem: Kurtadikar *et al.* [27]

ICAC scheme: K1/K3

MCAC scheme: A1/B1/C1/G1/G2/H1/O1/N1

OCAC-Dom: P1

OCAC-Obj: None

Products used: Bike, shop vacuum cleaner, camera, smart marker

Problem description: The customer needs with high 'mention' frequency and low 'customer importance weight' are grouped into common clusters for creating customer needs platform. The generation of different product variants relies on using different combinations of differentiating customer needs and the core customer needs platform.

3.3.2. Function-technology platform formation (S/Pd/32)

Example Problem: Kumar and Allada [26]

ICAC scheme: K1/K3

MCAC scheme: A2/B1/C1/H1/G2/M3/N1/F1/O2/W1

OCAC-Dom: P3

OCAC-Obj: F1/F2

Products used: Computer mouse family

Problem description: The functions are grouped into core and differentiating modules. The compatibility is checked between the functional modules and the existing/available technologies to form function-technology (F-T) platforms. They determine the optimum number of F-T platforms for a given set of product variants.

4. TACTICAL PRODUCT PLATFORM PROBLEMS (T/Pd)

The problems related to the design of the product platform solely from an engineering design perspective are referred to as Tactical Product

Platform Problems (T/Pd). This domain focuses primarily on the physical platform formation.

4.1. Structural Platform Formation (T/Pd/1)

In general, there are two types of structural platform formation problems that exist in the literature, namely, module-based and scale-based structural platform design. The combination of these two basic approaches is termed as the hybrid platform design.

4.1.1. Scale-based platform formation (T/Pd/11)

Example problem: Simpson *et al.* [53]

ICAC scheme: B1/H1/P61

MCAC scheme: A1/J2/G2/M2/N2/V1

OCAC-Dom: O1/P61

OCAC-Obj: L-K5

Product used: Universal electric motors

Problem statement: The aim is to find the values of the common variables and the scaling variables (values), while minimizing the performance loss with respect to the individually optimized family of products.

4.1.2. Scale-based platform formation and subsequent variant design (T/Pd/12)

Example problem: Messac *et al.* [36]

ICAC scheme: B1/H1/P61

MCAC scheme: A1/J2/G2/M2/N2/V1

OCAC-Dom: O1/J2/P61

OCAC-Obj: L-K5

Product used: Universal electric motor

Problem statement: After the determination of the values of the common variables and scaling variables of a scale based platform, different product variants around which the platform has been formed are also determined.

4.2. Interface design (T/Pd/2)

Interface design aims to reduce the various types of costs like assembly cost, etc., by designing or redesigning the interfaces based on the interactions between the components and the modules. It aids in minimizing the complexity of the product architecture and increasing its modularity.

Example problem: Slevinsky and Gu [54]

ICAC scheme: H1/G2/T2

MCAC scheme: P5/X11/T1/Q1

OCAC-Dom: T2/S1

OCAC-Obj: None

Product used: Edger, Chain saw, Hedge Trimmer

Problem statement: The problem is to redesign existing products for standardizing the interfaces between modules in a module-based platform. The components are grouped into modules and the commonality in the functions of the products is identified. The interfaces between these core modules and add-on modules are standardized using mechanical buses.

5. TACTICAL INTEGRATED PRODUCT/PROCESS PLATFORM PROBLEMS (TI/Pd/Pr)

The tactical integrated product/process platform problems (TI/Pd/Pr) consider the following three types of problems:

1. TI/Pd/Pr/Type1 Problems: The focus in these problems is to design product platforms by considering criteria from multiple perspectives. This is in sharp contrast to T/Pd type problems where the trade-off criteria reside solely within the product's functional performance perspective (e.g., mass vs. efficiency). The TI/Pd/Pr/Type1 problems consider trade-offs from multiple perspectives including functional performance and one or more downstream design implications such as manufacturing cost, etc. However, the focus is still on products while taking into consideration a given set of downstream design criteria (i.e., the

downstream design criteria and their values are fixed and are not subjected to change).

2. TI/Pd/Pr/Type2 Problems: The focus in these problems is to design or analyze downstream processes while satisfying product functional perspective criteria. In this type of problem, the product platform is assumed to be fixed and not subjected to changes, and its implications on various downstream processes (manufacturing, assembly, supply chain, end-of-life etc.) are considered.

3. TI/Pd/Pr/Type3 Problems: The focus in these problems is to design products and processes concurrently by considering criteria from multiple perspectives. This is the most challenging of the platform problems, since the design and downstream processes are not assumed to be fixed and are simultaneously changed within specified constraints to arrive at the optimal set of product platforms and downstream processes platforms (such as manufacturing cells, supplier platforms, etc.).

These three types of problems can be further sub-divided based on the specific types of "processes (Pr)" such as manufacturing (mfg), assembly (assbly), etc. and also other types of enterprise processes, such as human resources, where organizational structure can be configured based on core competency platforms, and project platforms. In the next sub-sections, we present a few sample sub-problems relating to TI/Pd/Pr/Type 1, TI/Pd/Pr/Type 2, and TI/Pd/Pr/Type 3 problems.

5.1. Tactical Integrated Product/Process Platform Problems (TI/Pd/Pr/Type 1)

5.1.1. Module-based platform formation and subsequent variant design (TI/Pd/Pr=Mfg/Type1)

Example problem: Fujita *et al.* [11]

ICAC scheme: Q1/L/H1

MCAC scheme: G2/N2/M2/T1/T2/V2/F2/F3/A1/S2

OCAC-Dom: P5/J2/H1/O1

OCAC-Obj: F2/ F3

Product used: TV receiver circuits

Problem statement: The aim is to develop a modular platform for a variety of products by considering downstream manufacturing criteria such as facility cost, production cost, and material cost. Functional dependency and interface compatibility are also considered. Introduction of the variants from the modular platform has also been considered.

5.1.2. Scale-based platform formation (TI/Pd/Pr=Mfg/Type1)

Example problem: Hernandez *et al.* [14]

ICAC scheme: H1

MCAC scheme: S2/F3/N1/V2/C1

OCAC-Dom: J2/P7/O3/H1/Q2

OCAC-Obj: F3

Product used: Pressure vessels

Problem statement: Given the target product specifications of the product variants, a product platform is designed with the objective of minimizing the average cost of the product comprising the material, welding and forging costs. The material cost is taken as the sum of the cost of raw material actually used in each vessel and the cost of the raw material wasted by cutting the components to required dimensions.

5.1.3. Module- and Scale-based product platform formation (TI/Pd/Pr=Mfg/Type 1)

Example problem: Fujita and Yoshida [10]

ICAC scheme: H1

MCAC scheme: V2/F3/A1/G2/M2/N1/F2

OCAC-Dom: J2/Q2/P7/O1

OCAC-Obj: F3/K4/F2/F1

Case study: Aircraft

Problem statement: A methodology to form a platform by considering the modules and its design variables is proposed. The modules are identified as common, if their design variables are common and have the same value, scalable if their variables are similar in nature. The

independent modules, which lead to variety in the product family members, have also been identified. The objective used here is to maximize the profit of the manufacturer by decreasing the design and development cost, facility cost, and production cost.

5.1.4. Formation of multiple platforms and subsequent variant design (TI/Pd/Pr=Assbly/Type 1)

Example problem: Seepersad *et al.* [46]

ICAC scheme: H1

MCAC scheme: C1/F1/F3/B2/N2/V2/F3/E3/Uncertainty-C/F

OCAC-Dom: O3/J2/P5-P6

OCAC-Obj: F3/K5/E3

Products used: Absorption chillers

Problem statement: The inputs to the problem are performance requirements of product variants from various market segments. The method determines the optimum number of platforms and the variants associated with them. Multiple criteria such as cost, performance, and cycle time of assembly stations were used to determine product platforms.

5.1.5. Determination of optimal number of platforms (T/Pd/Pr=Mfg/Type 1)

Example problem: de Weck *et al.* [60]

ICAC scheme: O1/H1

MCAC scheme: C1/F1/F3/B2/N2/V2

OCAC-Dom: P5-P6/O3

OCAC-Obj: C1/F1

Product used: Automobiles and trucks

Problem statement: A methodology to determine the optimal number of platforms for a given number of variants is discussed based on considerations such as die and facility costs. Using profit as the criterion, variant-platform allocation and the values of the variables of the variant are obtained.

5.1.6. Analysis of interface design implications (TI/Pd/Pr=Assbly/Type 1)

Example problem: Wie *et al.* [61]

ICAC scheme: R/Q

MCAC scheme: E3/G2/F3

OCAC-Dom: R/Q/T

OCAC-Obj: None

Product used: Consumer products (e.g., desktop stapler)

Problem statement: This paper analyzes the relationship between interfaces and product architecture and introduces a representation scheme for the relationships. It also suggests how the selection of interfaces and modules can affect the manual assembly costs.

5.2. Tactical Integrated Product/Process Platform Problems (TI/Pd/Pr/Type 2)

5.2.1. Assembly Process Sequence Design (TI/Pd/Pr=Assbly/Type2)

Example problem: Siddique [48]

ICAC scheme: F3/P5

MCAC scheme: H1/G2

OCAC-Dom: X3

OCAC-Obj: None

Product used: Coffee maker

Problem statement: The product architecture is assumed to be given. The existing assembly platform is checked to see if it can support the assembly processes constraints of the new product. The assembly sequence that has the minimum modification cost is chosen.

5.2.2. Supplier Network Selection Problem (TI/Pd/Pr=Supply-Chain/Type2)

Example problem: Huang *et al.* [17]

ICAC scheme: O1/H1

MCAC scheme: G2/C1/Q1/S2/E3/E1/Y4

OCAC-Dom: W1/V2

OCAC-Obj: F2/F3

Problem: Notebook Family

Problem statement: Given the product platform and its variants, the components to be bought from external vendors are identified. An appropriate supplier network with minimum total supply chain cost and maximum performance is selected. The quantity discounts offered by suppliers is also considered in this study.

6. PLATFORM EVALUATION TECHNIQUES

Depending on the type of evaluation method used to assess whether a given solution to a product platform problem is to be accepted or not, we identify two classes of evaluation methods, i.e., Class I and Class II. Figure 1 represents the context for a typical platform problem evaluation scenario. These classes have been distinguished based on the mode of evaluation (passive or active) and level of abstraction of the evaluation criteria. For example, the Class I evaluation criteria are more generic and defined at a higher level of data abstraction. On the other hand, Class II methods are more specific to products. For example, pressure vessel and universal electric motor have different governing equations and so Class II problem evaluation methods need to be detailed to each product. This makes this class of evaluation methods to have a very limited application range.

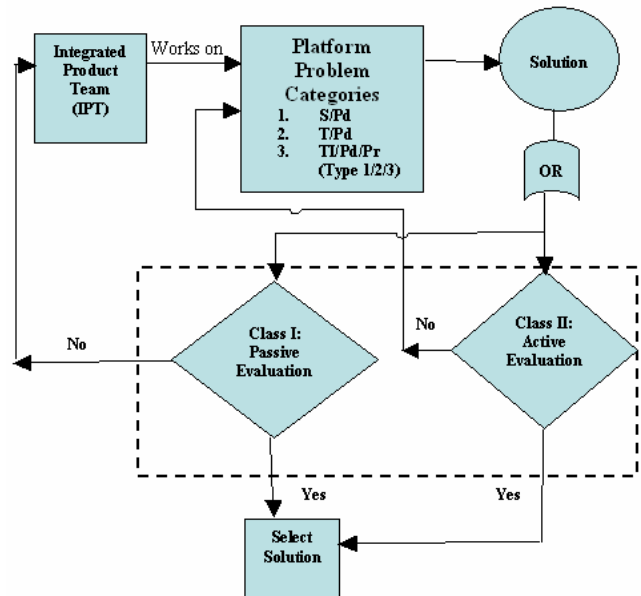


Figure 1: General Scope of Product Platform Evaluation

6.1 Class I Evaluation Methods

Class I evaluation methods employ approaches such as computation of platform indices and/or commonality metrics to determine whether a given solution is acceptable or not. They can be viewed as “what-if” analysis tools that do not actively help the Integrated Product Team to move the initial solution to a more desirable solution.

Table 1 presents a summary of the factors used by some commonality metrics-related papers in the literature. It can be observed from Table 1 that most of the commonality metrics have been developed at the structural (component or sub-assembly) level. Some researchers – Martin and Ishii [34], Siddique *et al.* [50], Kota *et al.* [21], Jiao and Tseng [18], Desai *et al.* [5], and Thevenot and Simpson [57] – have also considered manufacturing/assembly level commonality; however, the comprehensive effect of structural commonality on various other downstream domains is not fully explored in the literature.

In general, Class I problem evaluation techniques assume evaluation criteria (or factors) as independent and defined at a very high level of abstraction. For example, Kota and Sethuraman [20] considered three

disparate factors like size and geometry of components, material and manufacturing considerations, and fastening and assembly scheme.

Table 1: CAC scheme for Class I problems

Sl. No.	References	ICAC-CM
1	Collier [1]	Number of R
2	Wacker and Trelevan [59]	Number of R
3	Siddique <i>et al.</i> [50]	Number of R/X3
4	Martin and Ishii [34]	Number of R
5	Kota <i>et al.</i> [21]	Number of R/X2/X4/X11
6	Jiao and Tseng [18]	Number of R/C/X1/F3/X3
7	Hiller [16]	Number of R
8	Desai <i>et al.</i> [5]	Number of R/F2/F3/K3/K4/K5/F1/X1/X6/X5/E3
9	Thevenot and Simpson [57]	Number of G/ R/E3/F3/X4/X2
10	Fellini <i>et al.</i> [9]	Number of R/X2/X8
11	Siddique and Natarajan [49]	R2

6.2 Class II Evaluation Methods

The Class II evaluation methods are more product-specific (Simpson *et al.* [53], Hernandez *et al.* [14], D' Souza and Simpson [2]) and may not be directly portable to solve similar problems concerning other product types. While Class I evaluation methods suffer with the problem of imprecise evaluation, Class II problem evaluation techniques use more detailed data and capture the interrelationships between various parameters explicitly. For example, in Hernandez *et al.* [14], factors like pressure, volume, wall thickness of the pressure vessel, radius, welding cost, material cost, and equipment cost are interrelated and well-understood (formalized using equations) to help in the formulation of the objective function and constraints. Therefore, we argue that Class I methods to solve a platform problem will eventually lead to the development of Class II methods.

Various optimization-based problems have been formulated for addressing three general types of problems (S/Pd, T/Pd, and TI/Pd/Pr). Table 2 presents a summary of the evaluation criteria and the constraints used by some of the papers in the literature. It is observed that most S/Pd type problems use qualitative models to solve or conceptualize the problem. This may be partly due to the limited usefulness of the formal models to realistically capture the dynamics involved during the fuzzy-end design stage.

In T/Pd type platform problems, most papers consider trade-offs among factors relating to engineering perspective and/or parameters and constraints related to fuzzy-end design product planning stages. The time (E) parameter, though highly critical, is rarely considered explicitly. Little attention has been paid to considering uncertainties in the availability of modules/technology, factors pertaining to module formation (Ericsson and Erixon [8]) and interface design.

Among the TI/Pd/Pr type problems, formal models have been deployed that consider various trade-offs among engineering and post-design perspectives. Various researchers have used different considerations like assembly sequence (X3), manufacturing processes (X2), and workstation commonality (X9) to determine product platforms; however, the cost of the product/module/platform (F2) is modeled differently by different researchers.

Table 2: CAC scheme for Class II problems

Problem types	References	ICAC/MCAC	OCAC-Dom	OCAC-Obj
S/Pd	Kumar and Allada [26]	M compatibility	P3	F1/F2
S/Pd	Shil and Allada [37]	K4/D1	P2	F4
S/Pd	Wilson and Norton [62]	J	J2	F7
T/Pd	D' Souza and Simpson [2]	K5 /F1	O1/P62	K5
T/Pd/Pr	Rai and Allada [43]	K5	P5/O1	K5/F1
TI/Pd/Pr	Fujita and Yoshida [10]	H-K5	J2/Q2	K4/ F2/ F3
T/Pd	Messac <i>et al.</i> [35]	K5	H1/O1/P61	L-K5
T/Pd	Simpson <i>et al.</i> [53]	K5	O1/P61	L-K5
TI/Pd/Pr	Seepersad <i>et al.</i> [46]	K5	O3	E3/ F3
TI/Pd/Pr	de Weck <i>et al.</i> [60]	K5	P5/O3	F2/ F3
TI/Pd/Pr	Fujita <i>et al.</i> [11]	K5/T	H1/J2/P5	F2/ F3

It is noteworthy to mention that profit as an *OCAC-Obj* parameter is commonly used across almost all problems belonging to the three general problem categories. However, the *OCAC-Dom* parameters are quite different and/or are at different levels of abstractions for many of these problems. For example, Kumar and Allada [26] considered minimization of the changeover cost of technology (F1/F2) to form a function-technology platform. D' Souza and Simpson [2] considered operating cost of the product (F1) as a constraint in the objective function formulation for forming a structural platform. Rai and Allada [43] considered overall module cost (F2), and functional performance (L-K5) in their objective function to form a module-based platform (P5). It can be inferred that the objective function factors (or the *OCAC-Obj* parameters) by themselves are not particularly helpful to understand the level of problem abstraction or the problem scope. Thus, ICAC, MCAC as well as OCAC schemes are used in benchmarking. Since most case study oriented platform problems require Class II evaluation methods, the benchmark problems discussed in this paper are directed towards Class II evaluation methods.

7. BENCHMARKING PROBLEM TYPES

In this section, we present a brief overview of the platform problems that can be used as benchmarks. We envision benchmark

Table 3: CAC Codes for “Universal Electric Motor” Problem

Product type	Reference	Common CAC				Differentiating CAC			
		ICAC	MCAC	OCAC-Dom	OCAC-Obj	ICAC	MCAC	OCAC-Dom	OCAC-Obj
Universal Electric Motors	Dai and Scott [4]	B1/H1/P61	A1/J2/G2/M2/N2/V1	O1/P61	L-K5	---	---	---	J2
	Kumar <i>et al.</i> [25]	B1/H1/P61	A1/J2/G2/M2/N2/V1	O1/P61	L-K5	---	---	---	---
	Messac <i>et al.</i> [36]	B1/H1/P61	A1/J2/G2/M2/N2/V1	O1/P61	L-K5	---	---	---	J2
	Messac <i>et al.</i> [35]	B1/H1	A1/J2/G2/M2/N2/V1	O1	L-K5	---	---	P62	---
	Nayak <i>et al.</i> [39]	B1/H1/P61	A1/J2/G2/M2/N2/V1	O1/P61	L-K5	---	---	---	J2
	Simpson <i>et al.</i> [53]	B1/H1/P61	A1/J2/G2/M2/N2/V1	O1/P61	L-K5	---	---	---	---

problems as test problems that can be used by researchers to evaluate the efficacy of their proposed solution methods. Although, considerable work exists in the area of product platform design, very few benchmarking problems exist to compare different solution methods. Further, the existing problems that can be used as benchmarks are narrowly scoped. In this paper, we aim to identify and/or design benchmarking problems by utilizing the CAC scheme. We classify benchmark problems into the following three types: (a) core problems identified from existing literature; (b) future minor extensions to core problems from existing literature; and (c) future new core problems. In the following sections, we elaborate each of these types of benchmark problems and discuss the process of defining benchmark problems.

7.1. Core Problems from Existing Literature

Various core problems can be identified by clustering the common *ICAC*, *MCAC*, *OCAC-Obj*, and *OCAC-Dom* codes used by several existing research problems. In a sense, the core problem becomes a “platform” problem and various minor extensions of the core problem are viewed as derivative platform problems. Hence, we use the term “platforming the platform problems” to convey our basic idea. The problem variants can be differentiated from one another based on the changes made to the CAC scheme of the core problems.

We anticipate at this juncture of research in product platforming, that the immediate step will be to identify core problems and their associated problem variants from existing literature. This will help the research community to better understand the problem scope of existing benchmark problems and hopefully will help to create new minor extension problems or new design problem case studies.

We illustrate the process of identifying a core problem from existing literature by employing a widely used case study problem of the universal electric motor originally proposed by Simpson *et al.* [53]. Refer to Table 3. We have identified papers that used the universal electric motor problem and codified them using the CAC scheme. As can be seen from Table 3, the research papers have a “common” as well as “differentiation” *ICAC*, *OCAC-Obj*, *OCAC-Dom*, and *MCAC* schemes. All the referenced papers in Table 3, have considered the same input, i.e., market segmentation of the electric motors based on the desired functional performance which is known *a priori*, and consideration of a single product family. The *MCAC* scheme for the papers listed in Table 3 is also the same, i.e., the problem setting is same as well. However, some changes are observed in the ‘differentiating’ *OCAC-Obj*, *OCAC-Dom* schemes. By observation, we can then proceed to use the original problem by Simpson *et al.* [53] as the “core problem”, referring to its coding scheme as the “core problem code” as follows:

Core Problem Code

ICAC - B1/H1/P61 (Simpson *et al.* [53])
MCAC – A1/J2/G2/M2/N2/V1
OCAC-Dom – O1/P61
OCAC-Obj – L-K5

Further observation of Table 3 yields us two problem variants to the core problem defined above.

Problem Variant 1 (Messac *et al.* [35])

The first significant problem variant to the base problem is the one attempted by Messac *et al.* [35], which identified the scaling and common variables for the scalable product platforming problem.

ICAC - B1/H1/P61
MCAC - A1/J2/G2/M2/N2/V1
OCAC-Dom – O1/P62
OCAC-Obj – L-K5

Problem Variant 2 (Dai and Scott [4], Messac *et al.* [35], Nayak *et al.* [39])

The second problem variant includes the problems attempted by Dai and Scott [4], Messac *et al.* [35], and Nayak *et al.* [39], where, in addition to the platform formation also product variants have been determined.

ICAC - B1/H1/P61
MCAC – A1/J2/G2/M2/N2/V1
OCAC-Dom – O1/P61/J2
OCAC-Obj – L-K5

7.2 Future Minor Extensions to Core Problems in Literature

This refers to possible minor extensions of the core problems from the existing literature. It can be done by making minor changes to the “differentiation” code while maintaining the same “common” code of an existing core platform. We believe that a vast majority of future case study platform problems will involve minor incremental changes to the core case study problem.

We illustrate the process of identifying a future problem variant from an existing core problem. Consider the universal electric motor case (mentioned in Section 7.1) as an existing core problem. The “differentiation” CAC code of a future variant could include parameters such as demand of individual products © (de Weck *et al.* [60]), market segmentation (B) (Meyer and Lehnerd [37]), and consideration of planning horizon (A) (Kumar and Allada [26], Shil and Allada [47]). Thus, the inclusion of certain parameters to create a future variant is based on the perceived importance of parameters for platform decisions. The sample CAC scheme for a future minor extension to an existing core problem detailed in Section 7.1 is as follows:

ICAC – B1/H2/P62/61
MCAC – A1/J2/G2/M2/N2/V1/C1/2/T
OCAC-Dom – O1/P62/P61
OCAC-Obj – L-K5/F/E

7.3. Future New Core Problems

The future new core problems are platform case study problems that are new to the literature. Some important considerations while defining future new core problems are as follows: scope of the

problem (such as whether it is an S/Pd, T/Pd, and TI/Pd/Pr type problem or one or more of the sub-problems within each of these general problem categories), and importance of the problem to platform decision-making.

The major source for defining future new core problems is often found by investigating the various factors/issues considered in the Class I solution methods and/or viewing the product family from a product development process vantage point (Ulrich and Eppinger [58]). This would help to identify the CAC parameters that will influence the most critical platform decisions. In some cases, the future new core problem may not be entirely new in terms of its problem definition. However, without a realistic case study that represents the problem, the research community cannot compare alternate solution methods. For example, Gulati and Eppinger [12] identified organizational impacts on the product architecture and in an implicit fashion hinted at the importance of organizational platforms; however, to the best of our knowledge, this problem has not been modeled as case study problem that can be used by the researchers to concurrently design product structures and organization structures.

8. IDENTIFICATION OF EXISTING AND DESIGN OF NEW BENCHMARK PROBLEMS

As discussed previously in Section 7, we classify benchmark problems into three categories, i.e. core problems from existing literature, future minor extension to core problems from existing literature, and new core problems. Each of these three types of benchmarking problems can be identified and/or designed for each of the three major platform problem types, namely, S/Pd, T/Pd, and TI/Pd/Pr. It is important to note that the identification of new core problems has been done in TI/Pd/Pr/Type 3 problems because of the lack of any existing case study problems in this area.

8.1 Identification of S/Pd Benchmark Problems

In this paper, we describe two types of S/Pd benchmark problems: core problem from existing literature and a minor future extension to the existing core problem. Each of these benchmark problems has an associated CAC scheme to illustrate its usefulness in identifying and/or designing benchmark problems.

8.1.1 S/Pd Problem from existing literature

Core Problem 1: Evaluation of platform development projects

This problem aims to justify the planned product platform projects to be undertaken by a company. Uncertainties in various factors like technical, market, and implementation are taken into account. The cannibalization effects of competing platform projects are also considered. The platform projects having the maximum payoff are selected. Various factors such as number of competitors and their strategies are also taken into account (Shil and Allada [37], Maier and Fadel [33]). The “core problem code” is listed below:

ICAC – A2/B1/C1/D1/F2/H1/J3/Uncertainty–C/F

MCAC – None

OCAC –Dom – J

OCAC – Obj – F4

8.1.2 Future minor extension to core problem 1

Referring to the Porter’s five competitive forces model (Dess and Davis [6]), we recommend a future minor extension to the core problem 1 mentioned above, which includes the following factors: number of competitors (D), multiple product families (H2), and number of new concurrent platforms (O3). This future minor extension problem can be represented by the following CAC scheme:

ICAC – A2/B1/C1/D1/F2/H1/J3/Uncertainty–C/F/O3

MCAC – D/H2

OCAC –Dom – J

OCAC – Obj – F4

8.2 Identification of T/Pd Benchmark Problems

Of the several core problems that can be identified from the literature for T/Pd problem types, we have defined and discussed the scalable product platform formation problem in this study.

8.2.1 T/Pd problems from existing literature

Core Problem 2: Scalable Product Platform formation

This problem aims to form scalable product platforms by finding the values for common and the scaling variables, while minimizing the performance loss with respect to the individually optimized family of products. In some cases, the scaling and common variables are given *a priori* (Simpson *et al.* [53], Kumar *et al.* [25], Dai and Scott [4]). However, in some other cases scaling and common variables are determined and then the platforms are formed (Messac *et al.* [35], D’ Souza and Simpson [2]). Here, we provide the problem attempted by Simpson *et al.* [53] as the core problem.

ICAC - B1/H1/P61

MCAC – A1/J2/G2/M2/N2/V1

OCAC –Dom – O1/P61

OCAC–Obj – L-K5

8.2.2 Future minor extension to core problem 2

Time to market (E1) and consideration of cost elements (F) are the critical factors in the determination of effectiveness of the platforms (Muffatoo [38]). Future minor extension problem to core problem 2 after incorporating these factors is represented by the following CAC scheme:

ICAC - B1/H2/P62/61

MCAC - A1/J2/G2/M2/N2/V1/C1/2/T

OCAC–Dom - O1/P62/P61

OCAC–Obj - L-K5/F/E

8.3 Identification of TI/Pd/Pr Benchmark Problems

Here, we recommend the identification and/or design of core problems for the following types of TI/Pd/Pr platform problems:

- TI/Pd/Pr/Type 1
- TI/Pd/Pr/Type 2
- TI/Pd/Pr/Type 3

Further each of the above problem categories needs to be further sub-divided based on the downstream process under consideration (i.e., Pr = Mfg, Assbly, Supply Chain, etc.). In the following sub-sections, we will provide a sample benchmark problem for the three types of TI/Pd/Pr problems.

8.3.1 TI/Pd/Pr=Mfg/Type 1 Problem from existing literature

Core Problem 3: Scalable product platform formation problem considering manufacturing aspects

In this problem, a product platform is formed by considering downstream manufacturing issues. It is assumed that the target product specifications of the product variants are given *a priori*. The objective is to design hybrid (both modular and scalar) product platforms that minimize the average cost of manufacturing the product (F2). The cost model considers various elements like material, and welding and forging costs. We have identified the paper by Hernandez *et al.* [14] as the core problem for the Type 1 problems of TI/Pd/Pr. The identification of the core and differentiating codes for the TI/Pd/Pr/Type 1 problem is given in Table 4.

The CAC scheme of the core problem of Hernandez *et al.* [14] is as follows:

ICAC - H1

MCAC - S2/F3/N1/V2/C1

OCAC–Dom - J2/P7/O3/H1/Q2

OCAC–Obj - F3

Table 4: CAC Codes for the TI/Pd/Pr Problems

Product	References	Common CAC				Differentiating CAC			
		ICAC	MCAC	OCAC-Dom	OCAC-Obj	ICAC	MCAC	OCAC-Dom	OCAC-Obj
Electric Knife and Power Screw Driver	Rai and Allada [43]	N/A	V2/C1/S2	N/A	N/A	H2/Q1	U2/A1/N2/G2/F1/M2	P5/O1	K5/ F1
Airplanes	Fujita <i>et al.</i> [11]	H1	V2 /F3 /S2	H1/J2	N/A	Q1/L	G2/M2/N2/T1/T2/F2/A1	P5/O1	F2/ F3
Pressure Vessels	Hernandez <i>et al.</i> [14]	H1	S2/F3/N1/V2/C1	J2/P7/O3/H1/Q2	F3	N/A	N/A	N/A	N/A
Pressure Vessels	Kulkarni <i>et al.</i> [24]	H1	N1/F3 /V2 /Uncertainty –C1	J2/P7/Q2/H1/O3	F3	N/A	A2/B1/G2/M2/U1	N/A	F1
Oil Filters	Ortega <i>et al.</i> [40]	H1	C1/N1	P7/H1/J2/O3/Q2	N/A	N/A	W2/G2/M2/U1/Z1	N1	F1
Airplanes	Fujita and Yoshida [10]	H1	V2/F3	J2/Q2/P7	F3	N/A	A1/G2/M2/N1/F2	O1	K4/F2/F1

Future minor extension to core problem 3

In these type of problems, future minor extensions could be the inclusion of multiple product families (H2) (Rai and Allada [43]), stochastic demand scenario (C2), multiple platforms (O2) (de Weck *et al.* [60]), additional manufacturing and assembly parameters (assembly sequence (X3), material flow (X7), assembling and fastening scheme (X11), etc., (Lee and Saitou [30], Kusiak [28]), consideration of suppliers (Y2) (Sosa *et al.* [55]). Also, factors like time to market (E1), and different types of cost elements (F) can be considered. The motivation behind consideration of stochastic demand pattern (C2) is to design robust platforms (Li and Azarm [31]). One possible future minor extension problem to the core problem 3 could have the following CAC scheme:

ICAC - H1/2
MCAC - S2/F3/N1/V2/C1/2
OCAC-Dom - J2/P5/67/O1/2/3/H1/Q2/X2/7/10
OCAC-Obj - F/E

8.3.2 TI/Pd/Pr=Assbly/Type 2 Problem from existing literature

Core Problem 4: Implications of Product Platform Design on Assembly Operations

Here, we have utilized the code scheme of Siddique [48] to serve as a core problem. The existing assembly sequence is checked to see if it can support the assembly constraints of the new product platform. The assembly sequence that has the minimum modification cost is chosen. The “core problem code” is listed below:

ICAC - F3/P5
MCAC - H1/G2
OCAC Dom - X3
OCAC Obj – None

Future minor extension to core problem 4

Potential minor extension to core problem 4 described above could be to consider of one or more parameters like product demand (D) (Lee and Tang [30]), manufacturing and assembly parameters ((assembly sequence (X3), material flow (X7), assembling and fastening scheme (X11) etc., (Lee and Tang [30]), supply chain parameters (number of suppliers (Y2), number of tiers (Y1), types of relationship (Y3) etc., (Tenneti and Allada [56]), and end-of-life considerations (Z), multiple product families (H2), and time considerations (E). A possible future extension could have the following CAC scheme:

ICAC - F3/P5/6/7
MCAC - H1/2/G2/C/D
OCAC Dom – X2/7/10/Y/Z
OCAC Obj – F/E

8.3.3 Design New Core Problem for TI/Pd/Pr=Assbly/Type 3

The TI/Pd/Pr/Type 3 problems are the most challenging problems and no case study examples exist for these types of platform problems. This motivates us to develop a CAC scheme for new core problem that will guide during the case example development. As mentioned above, these problems focus on the simultaneous development of product and process platforms. Therefore, the OCAC-Dom significantly changes in these types of problems when compared with other problem types. However, we envision that the ICAC, MCAC, and OCAC-Obj codes do not necessarily have to change from the TI/Pd/Pr/Type 1 and TI/Pd/Pr/Type 2 problems. In the design of the new core problem (TI/Pd/Pr=Assbly/Type3), the aim will be to simultaneously form assembly (P11) and modular product platforms (P5). The modules considered will be COTS (Q1) (Rai and Allada [43], Fujita *et al.* [11]). Different types of demand pattern scenarios can be considered. The objective will be to minimize the design and development costs (F2) of product platforms while simultaneously minimizing the assembly costs (F3) to form assembly platforms (P11). Assembly sequences (X4) will be the guiding factor for the determination of assembly costs (F3) (Siddique [48]). The new core problem could have the following CAC scheme:

ICAC - H2/Q1
MCAC: V2/U1/A1/N2/G2/C1/M2/S2/X3
OCAC- Dom: P5/O1/P11
OCAC – Obj: F2/F3

9. CONCLUSIONS

This paper presents a preliminary taxonomy to organize and classify various product platform problems into three major categories (S/Pd, T/Pd, and TI/Pd/Pr) that mimic the product development process starting from the fuzzy end design through the actual design process to the downstream activities after the design. The strategic problems are typically encountered during the fuzzy end stage of the product platform development process, while the tactical problems are encountered during the engineering design stage (conceptual and detail design phases) and downstream phases. Each of the three general problem categories is further divided into sub-problems. These sub-problems contain different problem variants. We have also analyzed the implications of the taxonomy for product platform problems by identifying benchmark problems under each problem category. We used the CAC scheme to visually inspect and devise three types of benchmark problems i.e. core problems from existing literature, corresponding problem variants from existing literature, and design of fundamentally new core problems.

Thus, the meta-data for the product platform problems presented in this paper is an effort to classify the problems from a broader perspective, yet giving a detailed insight for each kind of problem. The argument made in this paper is that effective categorization of benchmark problems could help the research community to disseminate, verify and validate research results. This proposed framework is an essential first step to foster further evolution.

We predict future research progress in this field to proceed in the following three phases: (a) Phase 1: Continued coverage of S/Pd and T/Pd problems with focus on building new models by relaxing some of the problem conditions and assumptions, solving new case-specific test problems, and using new and superior problem solving techniques to benchmark existing problem sets (b) Phase 2: Gradual shift to solve TI/Pd/Pr/Type 3 problems that include concurrent product and process platform design, (c) Phase 3: Undertaking a much wider scope of Strategic + TI/Pd/Pr Type 3 problems in which the upstream design activities (such as fuzzy-end), the engineering design, and the downstream design activities are all viewed as one integrated problem set. We believe that taxonomy has to be fully tested and validated against current literature before full-scale use by the research community.

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APPENDIX

Table A1: CAC Scheme for Product Platform Problems

Strategic & Tactical level parameters and their codes					
A	Planning Horizon	Not considered	A1		
		Planning horizon considered	A2		
B	Market segmentation (Cost, Performance, Number of Competitors, Demand, etc.)	Given a priori	B1		
		Market segments determined (conceptually and analytically)	B2		
C	Demand	Deterministic	C1		
		Stochastic	C2		
D	Competition	Number of competitors	D1		
		Market share	D2		
E	Time considerations	Time to market	E1		
		Design and development time	E2		
		Process lead time (Manufacturing cycle time, Supplier lead time, assembly time etc.)	E3		
F	Cost Considerations (Cash Flow)	Total life cycle cost	F1		
		Platform and/or derivative design and development cost	F2		
		Process costs (such as manufacturing, assembly, inventory costs, etc.)	F3		
		Net Present Value (NPV)	F4		
		Internal Rate of Return (IRR)	F5		
		Return on Investment (ROI)	F6		
G	Product type	Innovative	G1		
		Matured	G2		
H	Number of product families	Single product family	H1		
		Multiple product families	H2		
I	Diffusion time of the various products introduced in the market	Given a priori	I1		
		Has to be determined using analytical models	I2		
J	Product variant/platform introduction to the market place	Single firm introduces a single product variant/platform/s at a given time period	J1		
		Single firm introduces a multiple product variant/platform/s at a given time period	J2		
		Multiple firms introduces a multiple product variant/platform/s at a given time period	J3		
K	Customer needs/rating/importance considered	Basic	K1		
		Excitement	K2		
		Customer importance ratings	K3		
		Customer utility	K4		
		Level of performance	K5		
L	Types of functions considered	Basic	L1		
		Auxiliary	L2		
M	Type of key product technologies	Blue Sky technology	M1		
		Technology-of-the-shelf	M2		
		Incremental technology	M3		
N	Design for variety strategy	Top down	N1		
		Bottom Up	N2		
		Hybrid	N3		
O	Number of platforms	Single Platform	O1		
		Multiple platform, Single Platform at a given time period	O2		
		Concurrent platform	O3		
P	Types of platforms	Product Platforms	Customer-need platform	P1	
			Functional platform	P2	
			Functional-technology (FT) platform	P3	
			Technology-based platform	P4	
			Component/Module Platform	P5	
			Scalable platform (P6)	Scaling and common variables	P61
				Scaling and common variables determined	P62
			Hybrid Platform	P7	
			Interface platform	P8	
			Brand Platform	P9	
		Process Platforms	Manufacturing	P10	
			Assembly	P11	
			Supply Chain/Logistics	P12	
		Organization Platforms	Remanufacturing, Recycling, Reuse	P13	
Organization Platforms	P14				

Q	Component/Module types (Customized or Component-of-the-shelf modules in the Product Architecture)	Component-of-the shelf	Q1
		Customized modules	Q2
R	Component Configuration	Shape-based	R1
		Geometry-based	R2
		Material-based	R3
		Tolerance-based	R4
S	Types of modular architecture	Bus Architecture	S1
		Sectional Architecture	S2
		Slot-Modular Architecture	S3
T	Interfaces/interactions	Functional	T1
		Physical	T2
U	Platform evaluation metrics (such as product variants per platform)	Given a priori	U1
		To be determined (e.g. Commonality index computation papers)	U2
V	Trade-off	Parameters belonging within one perspective (e.g., functional parameters such as power vs. mass)	V1
		Parameters belonging to two or more perspectives (e.g., functional and manufacturing parameters such as power vs. manufacturing cost)	V2
W	Target constraints/Objective function values	Single Value	W1
		Range based	W2
X	Manufacturing and Assembly Parameters considered	Batch Size	X1
		Type of manufacturing process	X2
		Sequence	X3
		Material Consideration	X4
		Process Capability	X5
		Scheduling	X6
		Material flow (Plant Layout)	X7
		Process plan	X8
		Workstations	X9
		Throughput rate	X10
		Assembly and fastening scheme	X11
Y	Supply chain issues	Number of tiers	Y1
		Number of suppliers	Y2
		Type of relations: arm length or strategic	Y3
		Supply chain network considered	Y4
Z	End-of-Life (EOL)	Environmental issues considered	Z